



Spatial–temporal characteristics and decoupling effects of China’s transportation CO₂ emissions

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Abstract

Both the realization of the “double carbon” goal and the low-carbon economy development requires a focus on transportation CO₂ emissions. Calculating Chinese transportation CO₂ emissions and exploring its principles are essential for achieving high-quality development of the transportation industry. Firstly, we use a “top-down” method to assess carbon emissions from transportation operations from 2003 to 2019. Secondly, the study decomposes the influencing factors of transportation CO₂ emissions in China using the log-average weight decomposition method. Thirdly, the Tapio decoupling model is applied to study the decoupling effect of transportation CO₂ emissions in each province of China. The findings suggest that China’s transport carbon emissions are growing at an annual rate of roughly 16%. All GDP per capita, transportation energy intensity, and population size increase the growth of transportation CO₂ emissions. Contrastly, energy use per unit of turnover and transportation intensity decrease the growth of transportation CO₂ emissions. There is much variation in China’s carbon emission decoupling index from year to year. Policy recommendations are proposed in response to the study of the above findings and the differences in carbon reduction potential among provinces.

Keywords Decoupling effects · Driving factors · Transportation CO₂ emissions · Spatial–temporal characteristics

Introduction

Climate warming is a common problem facing the world at present. Carbon emissions have caused a sharp increase in greenhouse gasses, causing irreversible losses to the ecology, society, and economy. Countries worldwide are

reducing carbon emissions through international agreements and policies, and China has also set targets for reducing carbon emissions. The transportation sector is a key strategic industry in many countries’ economies and social-economic growth. It consumes around 60% of the world’s oil (IPCC 2013), emits 24.34% of total carbon emissions, and is also the industry with the highest growth in carbon emissions; as a result, it is a critical industry for meeting emission reduction targets (Cohan et al. 2016; IEA 2018; Shao and Wang 2021). According to the International Energy Agency, global transportation CO₂ emissions will reach 50% in 2030 and 80% in 2050 (IEA 2009). Because of the small and mobile nature of transportation sources, reducing carbon emissions is more complex and challenging than in other industries. Therefore, it is of positive significance to focus on carbon reduction in transportation for the overall carbon reduction of cities and even air pollution control.

Accelerating the achievement of the goal of carbon neutrality has become a global consensus to address climate change. It is also China’s solemn commitment to the international community. In 2020, the Chinese government set the strategic goal of achieving carbon peaking by 2030 and carbon neutrality by 2060. This goal has been incorporated

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Table 1 Typical literature on transportation CO₂ emission research

Literature	Method	Results
Zhu and Gao (2019)	Panel data model	In the “Belt and Road Initiative,” per capita GDP, urbanization level, and energy consumption structure have positive effects on transportation CO ₂ emissions. In contrast, technology level and trade openness negatively affect transportation CO ₂ emissions
Azlina et al. (2014)	VECM	Malaysia’s continued economic growth was the main reason for its increased transportation CO ₂ emissions
Zhang and Su (2020)	LMDI	In China, per capita GDP and population size encourage carbon emissions, whereas transportation intensity, energy intensity, and unit turnover energy consumption limit carbon emissions
Zeng et al. (2020)	The geographically weighted regression model	They found a positive spatial correlation between transportation CO ₂ emissions and vehicle ownership, GDP, freight turnover, and passenger turnover
Xu and Lin (2017)	Quantile regression model	Urbanization, economic growth, and private car ownership are the main drivers of growth in transportation CO ₂ emissions, while transportation energy efficiency effectively reduces carbon emissions
Xie et al. (2017)	STIRPAT	The population scale effect of transportation infrastructure is conducive to decreasing carbon emissions. Economic growth and the technological innovation of transportation infrastructure increase carbon emissions
Song et al. (2022)	GFI	Economy and land urbanization are the most critical factors hindering carbon emission reduction, while population urbanization, traffic intensity, and energy structure promote carbon emission reduction
Wang et al. (2020a, b)	Theil index and semi-variogram analysis	Transportation CO ₂ emission intensity of Central and Western Asia and North Africa is significantly higher than that of other regions along the belt and road, and there is a strong spatial correlation in Southeast Asian countries

into the overall layout of ecological civilization construction. As the world’s top carbon emitter, China’s transportation sector is not only one of the major emitters of greenhouse gasses but also one of the sectors with the most rapid growth in carbon emissions. In recent years, China’s transportation CO₂ emissions have increased. Transportation CO₂ emissions are predicted to reach more than four times the 2000 level in 2030 (Li et al. 2021). With the vision of achieving the goal of carbon peaking and carbon neutrality in China, reasonable and practical emission reduction in the transportation sector has become a hot topic for scholars to study.

The analysis of the drivers of transportation CO₂ emissions is mainly to verify the influence of demographic and economic factors on carbon emissions. Generally, we first analyze the possible factors that impact transportation CO₂ emissions from a theoretical perspective and screen the characterization indicators. Then, quantitative analysis is used to statistically test the significance of the impact, identify the factors that play a significant influence, and determine the direction and affecting intensity. Many studies, summarized in Table 1, have adopted different methods to analyze the influencing factors of transportation CO₂ emissions. These models include such as the LMDI, STIRPAT, VECM, geographically weighted regression model, quantile regression model, and GFI. We find scholars mainly analyzed the effects of factors such as per capita

GDP, urbanization level, economic growth, transportation infrastructure, traffic intensity, and energy structure on transportation CO₂ emissions. They show that per capita GDP, urbanization level, economic growth, and population size have positive effects on transportation CO₂ emissions, while transportation infrastructure, traffic intensity, and energy structure negatively affect transportation CO₂ emissions (Zhu and Gao 2019; Azlina et al. 2014; Zeng et al. 2020; Xu and Lin 2017; Xie et al. 2017; Wang et al. 2022; Song et al. 2022). Despite great research results analyzing the impact factors of transportation CO₂ emissions, because transportation is a complex system with many influencing factors and interconnections, an overly comprehensive and targeted analysis of the impact factors often only yields broad and generalized conclusions. It is not difficult to find that the factors affecting transport carbon emissions involve economic, social, and industrial development. It is necessary to analyze the driving mechanism and factors of transportation CO₂ emissions from the internal structure of transportation based on the existing studies. Based on the research of Papiez et al. (2021), Zeng et al. (2020), and Jaehun (2017), this paper fully considers the relationship between various factors and decomposes the traffic carbon emissions from GDP per capita, transportation energy intensity, population size, energy use per unit of turnover, and transportation intensity.

Developing low-carbon transportation aims to decouple carbon emissions from economic growth. The key to building a low-carbon economy is to study the decoupling relationship between transportation CO₂ emissions and economic growth. Using the Tapio decoupling model to study the relationship between macroeconomic activities and environmental pollution has become a focus of academic research thanks to in-depth and extensive investigation. Freitas and Kaneko (2011) and Engo (2018) used the Tapio decoupling model to study the decoupling index and characteristics of economic growth and environmental pressure in Brazil and Cameroon, respectively. Due to the continued evolution of the Tapio decoupling mode, many scholars are using the Tapio decoupling model to measure the relationship between industrial development and environmental pressure in industries like building, electrical power, equipment manufacture, and logistics (Xiao et al. 2013; Xie et al. 2019; Wan et al. 2016). Li et al. (2019) used the Tapio model to examine the relationship between China's transportation industry development and carbon emissions. They found that compared with developed and coastal provinces, underdeveloped provinces are more prone to weak decoupling than others. Zhu and Li (2017) researched the rise of transportation CO₂ emissions in the Beijing-Tianjin-Hebei region. They found that transportation CO₂ emissions are not always synchronized with economic growth. Transportation economic development, carbon emissions, and government policies are all linked, according to Liu et al. (2021). Sikder et al. (2022) find that a 1% increase in energy use, economic growth, industrialization, and urbanization increases CO₂ emissions by 0.23%, 0.17%, 0.54%, and 2.32%.

Many scholars have studied transportation CO₂ emissions, and the results show that the influencing factors of transportation CO₂ emissions are gradually increasing, and the decoupling effect is becoming more and more obvious (Jaehun 2017; Papiez et al. 2021). But compared with high-emission industries such as industry and power, there are some papers that focus on the drivers of transportation CO₂ emissions in China. Due to the vast territory of China, the increasing frequency of travel between provinces will continue to release a large number of logistics and transportation demands, and the effect of the same carbon emission constraint policy varies for different regions.

Therefore, it is necessary to provide an in-depth analysis of the drivers and the decoupling trend of transportation CO₂ emissions in each province of China. This paper is a supplement to the existing research on the change in carbon emissions from the transport industry in developing countries represented by China. Compared with existing studies, this paper mainly has the following innovations. Firstly, most current articles only use a few energy sources, such as coal, diesel, crude oil, and natural gas, to account for energy consumption. This paper expands the scope of accounting for transportation

energy consumption. It measures transportation CO₂ emissions using 16 types of energy consumer products such as raw coal, cleaned coal, other coal washing, briquette, coke, coke oven gas, crude, gasoline, kerosene, diesel fuel, fuel oil, lubricating oil, solvent oil, asphalt, liquefied petroleum gas, other petroleum products, natural gas, liquified natural gas and steam, and electricity. Secondly, the decomposition of the influencing factors in this paper includes transportation energy intensity, unit turnover energy consumption, transportation intensity, the GDP per capita of vehicles, and employees in the transportation industry. Compared with existing studies, the decomposition results of this study are more comprehensive. Thirdly, we analyze the spatial and temporal distribution characteristics of the decoupling trend of transportation CO₂ emissions and analyze the dynamic relationship between transportation CO₂ emissions and economic development at the provincial level by combining industry development characteristics. Thus, we can make reference suggestions for realizing China's economic transformation and sustainable development.

The rest of the paper is organized as follows. “Methodology and data” section presents the methodologies and data definitions. “Results and discussion” section discusses the empirical results. “Conclusions and policy implications” section concludes the paper and puts forward some policy recommendations.

Methodology and data

Transportation carbon emission estimation method

The “top-down” input–output approach and the “bottom-up” process analysis approach are the most commonly used methods for measuring carbon emissions (Zhang et al. 2019a, b). Ideally, the bottom-up calculation method should consider real-time data for the transportation industry. These data did not include the current statistics system of China, which may lead to inaccurate results. In addition, there are also many differences in the types of transportation energy consumption in different provinces. This study uses the top-down method established by the Intergovernmental Panel on Climate Change (IPCC) to estimate carbon emissions from transportation energy consumption to sure the convenience of the evaluation and the accuracy of the results. The formula for this procedure is:

$$C = \sum_i C_i = \sum_i E_i \times K_i \times F_i \times \frac{44}{12} \quad (1)$$

where E_i is the physical energy consumption of the i th transportation type; K_i is the coefficient for converting the i th energy into standard coal; and F_i is the carbon emission coefficient of the i th power. Energy consumption in the transportation industry involves coal (such as raw coal, coke oven

Table 2 Standard coal coefficients and carbon emission coefficients for energy conversion

Energy type	Standard coal conversion factor (kg/kg)	Carbon emission factor (kg/kg)
Raw coal	0.7143	0.756
Cleaned coal	0.9	0.765
Other coal washing	0.45	0.808
Briquette	0.6	0.798
Coke	0.9714	0.855
Coke oven gas	0.5714	0.354
Crude	1.4286	0.585
Gasoline	1.4714	0.401
Kerosene	1.4714	0.571
Diesel fuel	1.4571	0.592
Fuel oil	1.4286	0.618
Lubricating oil	1.2	0.812
Solvent oil	1.4672	0.585
Asphalt	1.3307	0.775
Liquefied petroleum gas	1.7143	0.504
Other petroleum products	1.2	0.585
Natural gas	12.143	0.448
Liquified natural gas	0.7572	0.571
Steam	0.0341	0.252
Electricity	1.229	0.290

(1) To calculate the missing value, the carbon emission coefficient of energy employs the IPCC carbon emission value; (2) The original data is in unit J, which is consistent with the statistical data unit. The energy unit is converted to standard coal, with a conversion coefficient of 1 kg of conventional coal equaling 29,271 kJ

gas, coke, briquette, cleaned coal, and other washed coal), oil products (such as diesel, gasoline, crude oil, fuel oil, kerosene, petroleum pitch, solvent oil, liquefied petroleum, gas, lubricating oil, and other petroleum products), natural gas, liquefied natural gas, thermal energy, electricity, and other energy sources. This paper adopts the IPCC’s determination standard of carbon emission coefficients (Table 2).

IPAT equation and LMDI method

The IPAT equation takes into account both environmental and human influences. It effectively examines the interaction of three primary variables of population, wealth, and technology, as well as their impact on the environment. The equation can express as follows:

$$I = PAT \tag{2}$$

where *I* stand for the human impact. *P*, *A*, and *T* stand for population, affluence, and technology, respectively.

The regional ecological environment is affected by the two significant factors of population and economy, and at the same time, is destroyed by a specific technology. The LMDI model,

based on the IPAT model, establishes a transportation CO₂ emission decomposition model by connecting the regional environment with various influencing variables in a chain product. Therefore, this paper adopts the LMDI method to complete the factor decomposition of China’s transportation CO₂ emissions. The total carbon emissions *C* is calculated as follows:

$$C = \frac{C}{E} \times \frac{E}{TT} \times \frac{TT}{GDP} \times \frac{GDP}{P} \times P \tag{3}$$

where *TT* represents transportation turnover after conversion, and the conversion coefficients of passenger turnover of railways, highways, waterways, and aviation used to convert freight turnover are 1, 0.2, 0.3, and 0.083, respectively (Zhang et al. 2019a, b). *C/E* represents the transportation energy intensity, that is, the number of carbon emissions released per unit of transportation energy consumption. This ratio is closely related to the energy structure. *E/TT* indicates unit turnover energy consumption and is used to assess the technological level of vehicle energy conservation and emission reduction. *TT/GDP* represents the intensity of transportation, that is, the total transportation turnover per unit of GDP. This ratio reflects the level of transportation efficiency. *GDP/P* represents the GDP per capita of vehicles. *P* denotes the number of people employed in the transportation industry of some regions.

The formula is decomposed without a residual error in the LMDI approach proposed by Ang et al. (2015). The total effect of the difference in transport carbon emissions from the base period to the *t* period is expressed as $\Delta C = C^t - C^0$.

$$\Delta C^t = \Delta C_{ce}^t + \Delta C_{et}^t + \Delta C_{tg}^t + \Delta C_{gp}^t + \Delta C_p^t \tag{4}$$

$$\Delta C_{ce}^t = \frac{C^t - C^0}{\ln C^t - \ln C^0} \ln \left(\frac{C_e^t}{C_e^0} \right) \tag{5}$$

$$\Delta C_{et}^t = \frac{C^t - C^0}{\ln C^t - \ln C^0} \ln \left(\frac{E_t^t}{E_t^0} \right) \tag{6}$$

$$\Delta C_{tg}^t = \frac{C^t - C^0}{\ln C^t - \ln C^0} \ln \left(\frac{T_g^t}{T_g^0} \right) \tag{7}$$

$$\Delta C_{gp}^t = \frac{C^t - C^0}{\ln C^t - \ln C^0} \ln \left(\frac{G_p^t}{G_p^0} \right) \tag{8}$$

$$\Delta C_p^t = \frac{C^t - C^0}{\ln C^t - \ln C^0} \ln \left(\frac{P^t}{P^0} \right) \tag{9}$$

where ΔC_{ce}^t denotes the traffic energy intensity effect, ΔC_{et}^t denotes the energy consumption effect per unit turnover, ΔC_{tg}^t denotes the transportation intensity effect, ΔC_{gp}^t denotes

Table 3 Degree of decoupling and classification standard

Degree of decoupling		$\Delta C/C$ and $\Delta E/E$	ϵ	Implication
Decoupling	Strong decoupling	$\Delta C/C < 0; \Delta E/E > 0$	$\epsilon < 0$	The value-added of the transportation industry's GDP increases, while carbon emissions decline
	Weak decoupling	$\Delta C/C > 0; \Delta E/E > 0$	$0 < \epsilon < 0.8$	The value-added of the transportation industry's GDP increases, while carbon emissions decline less rapidly than economic growth
	Recession decoupling	$\Delta C/C < 0; \Delta E/E < 0$	$\epsilon > 1.2$	The value-added of the transportation industry's GDP declines at a much slower rate than carbon emissions declining
Connection	Growth connection	$\Delta C/C > 0; \Delta E/E > 0$	$0.8 < \epsilon < 1.2$	The increasing rate of value-added of the transportation industry's GDP is similar to the growth of carbon emissions
	Weak connection	$\Delta C/C < 0; \Delta E/E < 0$	$0.8 < \epsilon < 1.2$	The reducing rate of value-added of the transportation industry's GDP is similar to carbon emissions declining
Negative decoupling	Weak negative decoupling	$\Delta C/C < 0; \Delta E/E < 0$	$0 < \epsilon < 0.8$	The declining rate of value-added of the transportation industry's GDP is higher than carbon emissions declining
	Strong negative decoupling	$\Delta C/C > 0; \Delta E/E < 0$	$\epsilon < 0$	The value-added of the transportation industry's GDP declines, while carbon emissions increase
	Growth negative decoupling	$\Delta C/C > 0; \Delta E/E > 0$	$\epsilon > 1.2$	The value-added of the transportation industry's GDP increases at a much slower rate than carbon emission growth

the GDP per capita effect, and ΔC_p^t denotes the population size effect. These five measures show the contributions of various factors to changes in transportation CO₂ emissions.

Tapio decoupling model

“Decoupling” means economic growth brings less environmental pressure or consumes fewer resources. The Tapio decoupling model cannot only avoid uncertainty caused by base period selection but also judge multiple types of decoupling states based on the range of elastic value changes (Huang et al. 2021). At the same time, the LMDI model can well settle the residual and zero value problems and satisfy other conditions of “perfect decomposition approaches.” Then it has become one of the most extensively used methods in decomposing CO₂ emission changes (Yu et al. 2015). This study uses incremental data in the Tapio decoupling model to investigate the relationship between transportation CO₂ emissions and economic development over a long period, to completely characterize the volatility and accuracy of the decoupling condition of the transportation industry. Based on the connotations of decoupling theory, combined with existing transportation CO₂ emission-related research, this paper uses the transportation industry's GDP to characterize the industry's economic development. It constructs a decoupling model of transportation CO₂ emissions. The specific calculation formula is as follows:

$$\epsilon = \frac{\Delta C/C}{\Delta E/E} \quad (10)$$

where ϵ is the decoupling index; ΔC represents the current carbon emissions minus the previous carbon emissions; C is the current period's carbon emissions; ΔE indicates the difference between the transportation industry's GDP for the current period and the last period; and E represents the transportation industry's GDP for the current period. According to Tapio's division of the elastic value change range (Tapio 2005), we can decompose decoupling states into three types: decoupling, connection, and negative decoupling. According to the value of decoupling elasticity, they can be further classified into eight types, as shown in Table 3. The strong decoupling shows that the economic development of transportation is not based on resource consumption and environmental damage, and the negative decoupling and connection states are both non-ideal coupling states.

Data source

The data used in this article come primarily from China Statistical Yearbooks (2003–2019), China Transportation Yearbooks (2003–2019), China Energy Statistical Yearbooks (2003–2019), China Environment Yearbooks (2003–2019), and the National Bureau of Statistics website.¹ There are

¹ <http://www.stats.gov.cn/tjsj/ndsj/>

Table 4 The indicators and their sources

Indicators	Source
Energy consumption in the transportation industry	China Energy Statistical Yearbook (2003–2019); China Environment Yearbook (2003–2019)
Passenger and freight turnover volumes	China Transportation Yearbook (2003–2019)
Transportation energy consumption	China Transportation Yearbook (2003–2019)
Total transportation turnover	China Transportation Yearbook (2003–2019)
Population size	China Statistical Yearbook (2003–2019)
The added value of transportation GDP	China Statistical Yearbook (2003–2019)

Energy consumption in the transportation industry involves coal (such as raw coal, coke oven gas, coke, briquette, cleaned coal, and other washed coal), oil products (such as diesel, gasoline, crude oil, fuel oil, kerosene, petroleum pitch, solvent oil, liquefied petroleum, gas, lubricating oil, and other petroleum products), natural gas, liquefied natural gas, thermal energy, electricity, and other energy sources

many missing data in Tibet, Hong Kong, Macau, and Taiwan, so these studies did not include the four provinces. We only study the remaining 30 provinces. The indicators and their sources are shown in Table 4. In addition, based on data from previous years, we apply interpolation and gray correlation forecasting algorithms to estimate some missing values of indicators.

Results and discussion

Measurement results and analysis of China's transportation CO₂ emissions

Using the data collected and the calculation formula for transportation CO₂ emissions, we calculated CO₂ emissions for the provinces of China from 2003 to 2019. The trend in transportation CO₂ emissions is consistent with Guo et al. (2014) and Li et al. (2019). Furthermore, most research recognizes geographic closure as the primary requirement for regional grouping (Zhang et al. 2020), and many studies claim that China has regional technical heterogeneity (Yang et al. 2015; Wang et al. 2013). Therefore, to more clearly analyze the changing trend of China's regional transportation CO₂ emissions, we group the 30 provinces studied according to the classification of NBSC.² As illustrated in Fig. 1, this study splits China's 30 provinces into four major regions: northeast, eastern, central, and western.

Figure 2 depicts the CO₂ emissions from transportation in China's various regions from 2003 to 2019. It can be seen that all four areas have an increasing trend in vehicle CO₂ emissions. Especially from 2003 to 2012, China's transportation CO₂ emissions showed a rapid growth trend, mainly due to China's increased investment in

the construction of transportation networks. Although China's transportation CO₂ emissions appeared to decline in 2012–2013, they rebounded in the following years. This is mainly due to the particular survey on economic statistics in China's transportation industry in 2013. The statistical scope of road, waterway, passenger, and freight transportation data was adjusted, which led to a significant decrease in transportation CO₂ emissions. Transportation CO₂ emissions in the eastern, central, western, and northeastern regions grew by 5477×10^4 t, 3521×10^4 t, 1954×10^4 t, and 1559×10^4 t, respectively, from 2003 to 2019. As the east part develops rapidly, the transportation of CO₂ emissions in the east region becomes the primary source of CO₂ emissions. As of 2019, the transportation CO₂ emissions of Shanghai, Shandong, and Guangdong provinces in the eastern region exceeded the 1000×10^4 t mark, ranking among the top three in the country. The main reason for the small total carbon emissions in the northeast is that the region includes only three provinces and has a small economic scale. This brings about a low dynamic in the transportation industry and low transportation CO₂ emissions. However, in terms of per capita transportation CO₂ emissions, the northeast is much higher than the central and western regions. In addition, carbon dioxide emissions from transport in the central region continued their slow but steady upward trend.

Figure 3 shows that from 2003 to 2019, the transportation CO₂ emissions in all studied provinces of China increased vastly. Most eastern provinces generate more CO₂ emissions than other provinces. In 2019, the three eastern provinces of Guangdong, Shandong, and Shanghai posted the highest carbon dioxide emissions. Guangdong's CO₂ emissions reached 13.04 million tons in 2019, around 20 times that of Ningxia. Furthermore, coastal provinces' carbon emissions are much higher than inland provinces. This may be because water transportation in coastal provinces is a massive part of the transportation industry. By the same, fuel oil pollution and carbon emissions from water transportation are higher than

² http://www.stats.gov.cn/zjtj/zthd/sjtjr/dejtjkfr/tjkg/201106/t20110613_71947.htm

Fig. 1 Classification of China's three major regions

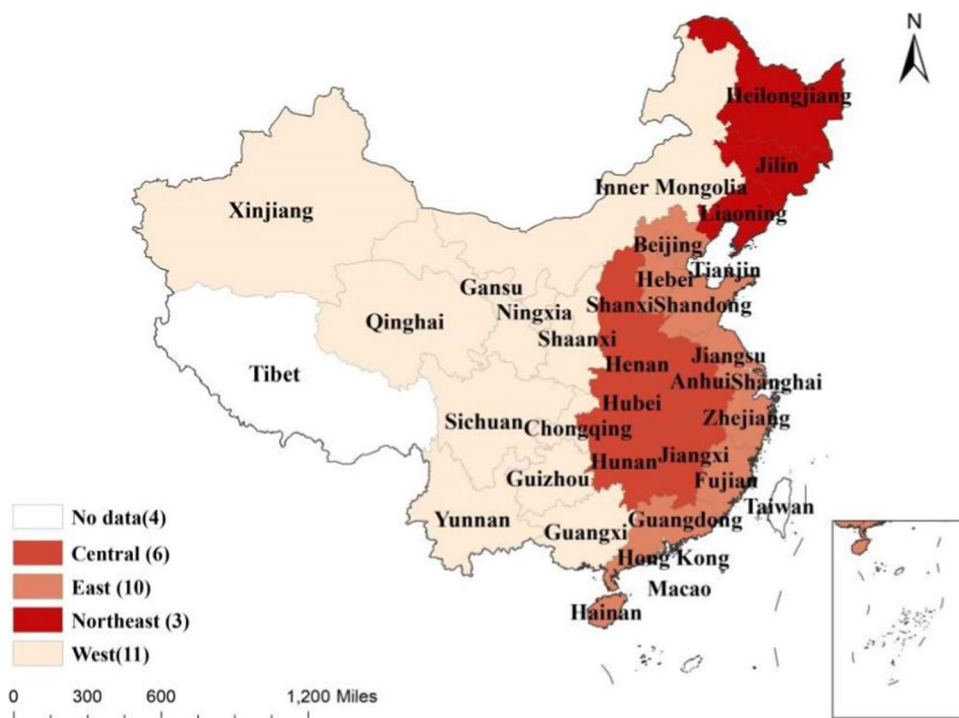
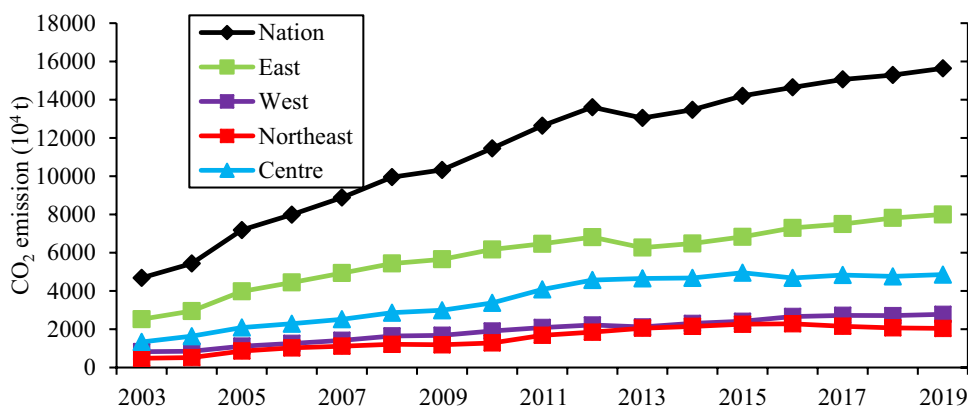


Fig. 2 Regional changes in China's transportation CO₂ emissions from 2003 to 2019



from road transportation. During the study period, China's transportation CO₂ emissions increased by nearly 16% on average. In terms of the average yearly rise rate of emissions in each province, Henan Province had the highest rate (35.69%), followed by Heilongjiang Province (30.14%). On the other hand, Ningxia had the slowest growth rate (3.22%).

Analysis of driving factors of China's transportation CO₂ emissions

The above analysis shows significant spatial and temporal, and regional differences in transportation CO₂ emissions among the 30 Chinese provinces. So, what factors play a crucial role in transportation CO₂ emissions? This paper uses the LMDI model from the traffic energy intensity effect

(ΔC_{ce}^t), energy consumption effect per unit turnover (ΔC_{et}^t), transportation intensity effect (ΔC_{ig}^t), GDP per capita effect (ΔC_{gp}^t), and the population size effect (ΔC_p^t) to decompose the drivers of transportation CO₂ emissions in 30 provinces. Equations (4) to (8) calculate the decomposition results, as shown in Table 5.

Table 5 shows that the growth in GDP per capita from 2003 to 2019 resulted in 112,705,700 tons of carbon emissions from transportation, with an average annual increase of about 7 million tons. The overall rate of GDP per capita contribution to carbon emissions shows a rising and then dropping trend. It demonstrates that the transportation industry's ongoing GDP expansion has resulted in rapid development and a significant increase in energy consumption, putting additional pressure on carbon emissions.

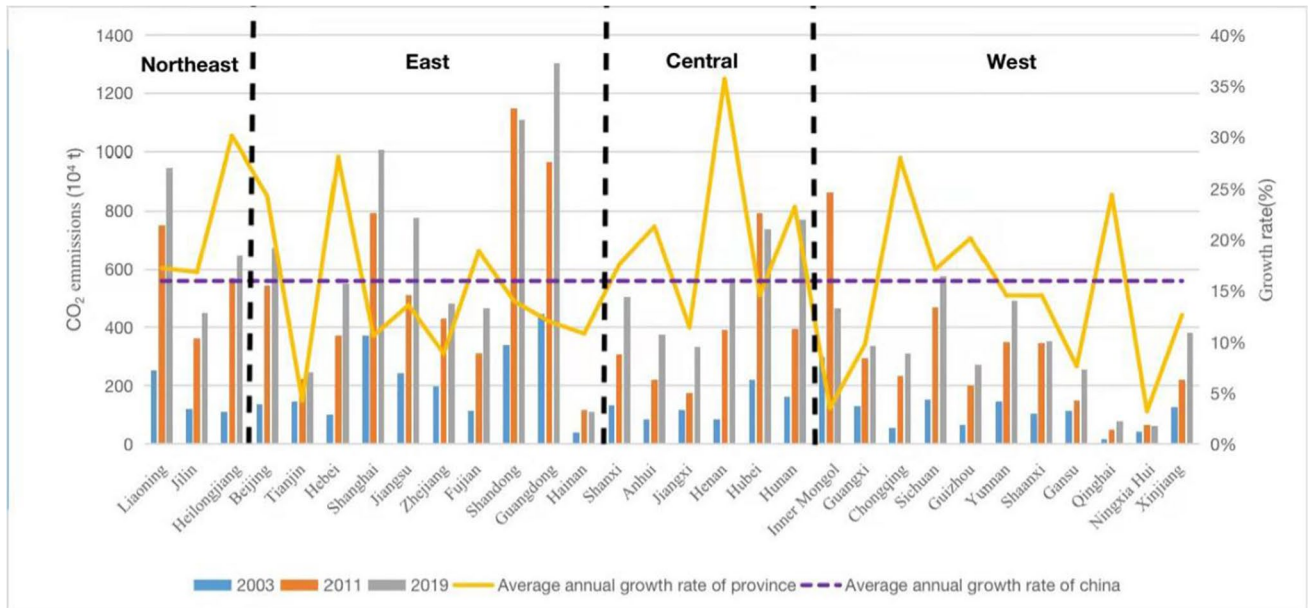


Fig. 3 Changes in transportation CO₂ emissions in China

Table 5 Decomposition results of transportation CO₂ emissions (10⁴ t)

Year	ΔC_{ce}^t	ΔC_{et}^t	ΔC_{tg}^t	ΔC_{gp}^t	ΔC_p^t	ΔC
2003–2004	-72.68	-306.48	1032.41	134.30	29.80	817.35
2004–2005	227.14	737.43	719.59	203.20	36.93	1924.29
2005–2006	118.85	-12.23	-521.15	1228.43	40.01	853.91
2006–2007	58.90	-278.30	-12.76	1053.01	43.55	864.40
2007–2008	269.55	-44.99	-443.33	1219.03	47.79	1048.06
2008–2009	-191.70	-479.41	340.66	-4.06	49.36	-285.16
2009–2010	143.85	-696.32	-16.38	1730.02	52.15	1213.33
2010–2011	242.31	-569.83	-224.64	1224.94	57.67	730.44
2011–2012	171.50	-23.14	-549.24	1267.91	64.96	931.99
2012–2013	24.15	448.00	-2106.82	-1514.27	65.57	-3083.37
2013–2014	-283.54	-827.28	795.42	362.15	68.99	115.74
2014–2015	137.33	1235.85	-1398.40	780.55	68.59	823.93
2015–2016	-297.97	-128.58	128.06	719.24	84.62	505.36
2016–2017	-209.93	-1177.40	418.03	1448.25	78.95	557.90
2017–2018	-11.52	-462.68	30.87	602.18	57.75	216.60
2018–2019	-92.90	-233.92	-236.49	815.69	51.66	304.04
2003–2019	233.34	-2819.28	-2044.17	11,270.57	898.35	7538.81

Transportation CO₂ emissions increased by 8,983,500 tons due to population changes from 2003 to 2019, with an average annual growth of roughly 561,469 tons. An inverted U-shape showed the overall contribution rate of population size to carbon emissions and its promotion effect.

Another aspect influencing transportation CO₂ emission rise is transportation energy intensity. The increased energy intensity of transportation has resulted in a total increase of 2.3 million tons of carbon emissions. It may be because of continuous improvement in the structure of transportation

energy consumption, and the increase in the use of new energy vehicles, which means the transportation energy intensity does not promote carbon emissions.

Energy consumption per unit of turnover has achieved cumulative reductions of 28,192,800 tons, and an average annual reduction of 1,762,100 tons. This is mainly because, in recent years, China has used energy conservation and reducing emissions as its main goal to adjust its transport structure and improve the efficiency of continuous transport. This has, to some extent, effectively slowed the trend of rising carbon emissions.

Table 6 Decoupling characteristics of China's transportation CO₂ emissions

Year	Environmental pressure ($\Delta C/C$)	Economic growth ($\Delta G/G$)	Decoupling elasticity (ϵ)	Decoupling type
2003–2004	0.1492	– 0.1006	– 1.4839	Strong negative decoupling
2004–2005	0.3217	0.1349	2.3840	Negative growth decoupling
2005–2006	0.1122	0.1747	0.6422	Weak decoupling
2006–2007	0.1117	0.1427	0.7825	Weak decoupling
2007–2008	0.1204	0.1468	0.8204	Growth connection
2008–2009	0.0380	0.0724	0.5249	Weak decoupling
2009–2010	0.1089	0.1684	0.6467	Weak decoupling
2010–2011	0.1031	0.1548	0.6656	Weak decoupling
2011–2012	0.0768	0.1102	0.6967	Weak decoupling
2012–2013	0.0437	0.2105	0.2074	Weak decoupling
2013–2014	0.0327	0.0575	0.5678	Weak decoupling
2014–2015	0.0542	0.0562	0.9657	Growth connection
2015–2016	0.0312	0.0528	0.5912	Weak decoupling
2016–2017	0.0285	0.0979	0.2914	Weak decoupling
2017–2018	0.0151	0.0452	0.3345	Weak decoupling
2018–2019	0.0228	0.0608	0.3756	Weak decoupling

Transportation intensity has resulted in a total reduction of 20,441,700 tons of carbon emissions, with an average annual decrease of 1,277,600 tons. It is mainly because China's transportation structure has been relatively stable for 20 years. Then reducing transportation CO₂ emissions through continuous improvement of transportation intensity has become an essential measure of China's low-carbon transportation development.

Analysis of decoupling characteristics of China's transportation CO₂ emissions

Temporal changes of the decoupling characteristics

Using the Tapio decoupling model and Eq. (10), we calculate China's transportation industry's carbon emission decoupling index from 2003 to 2019 and assess the decoupling features time series from 2003 to 2019. Table 6 shows that during the study period, the relationship between transportation CO₂ emissions and the value added of the transportation sector in the 30 provinces experienced a trend from strong negative decoupling to weak decoupling. The transportation sector's reliance on fossil fuels has gradually diminished, and energy use efficiency has improved. This paper divides the sample interval into two phases (2003–2007 and 2007–2019). Then, the decoupling relationship between transportation CO₂ emissions and the economic growth of the transportation sector in each province is analyzed.

(a) From 2003 to 2007, transportation CO₂ emissions showed a fluctuating decline, whereas transportation GDP showed fluctuating growth. However, transportation CO₂ emissions, on the other hand, grew at a far

faster rate than transportation GDP in 2003 and 2004. During the sample period, carbon emission decoupling alternates between strong negative decoupling, growth negative decoupling, weak decoupling, and growth connection.

(b) From 2008 to 2019, China's transportation CO₂ emissions and GDP increased, although carbon emissions grew faster than the economy. Carbon emission decoupling takes the form of weak decoupling throughout this period. China's transportation CO₂ emissions and GDP growth rate fluctuated in a “low–high–low” pattern.

The decoupling index of transportation carbon emission in China fluctuates negatively. Despite promising results in reducing transportation CO₂ emissions, the transportation economy and carbon emissions are rising. Neither has reached the environmental Kuznets curve's inverted U-shaped inflection point. China's weak decoupling of transportation CO₂ emissions is expected to continue, and it is consistent with the scientific rule of thumb after the carbon peak. Therefore, it is especially critical to implement more muscular transportation energy efficiency and emission reduction policies.

Regional differences in decoupling characteristics

It is considering that each province in China's economic development level, transportation infrastructure, and energy consumption structure have significant differences. It is essential to explore regional differences in transportation CO₂ emissions by province. Figure 4 shows the decoupling

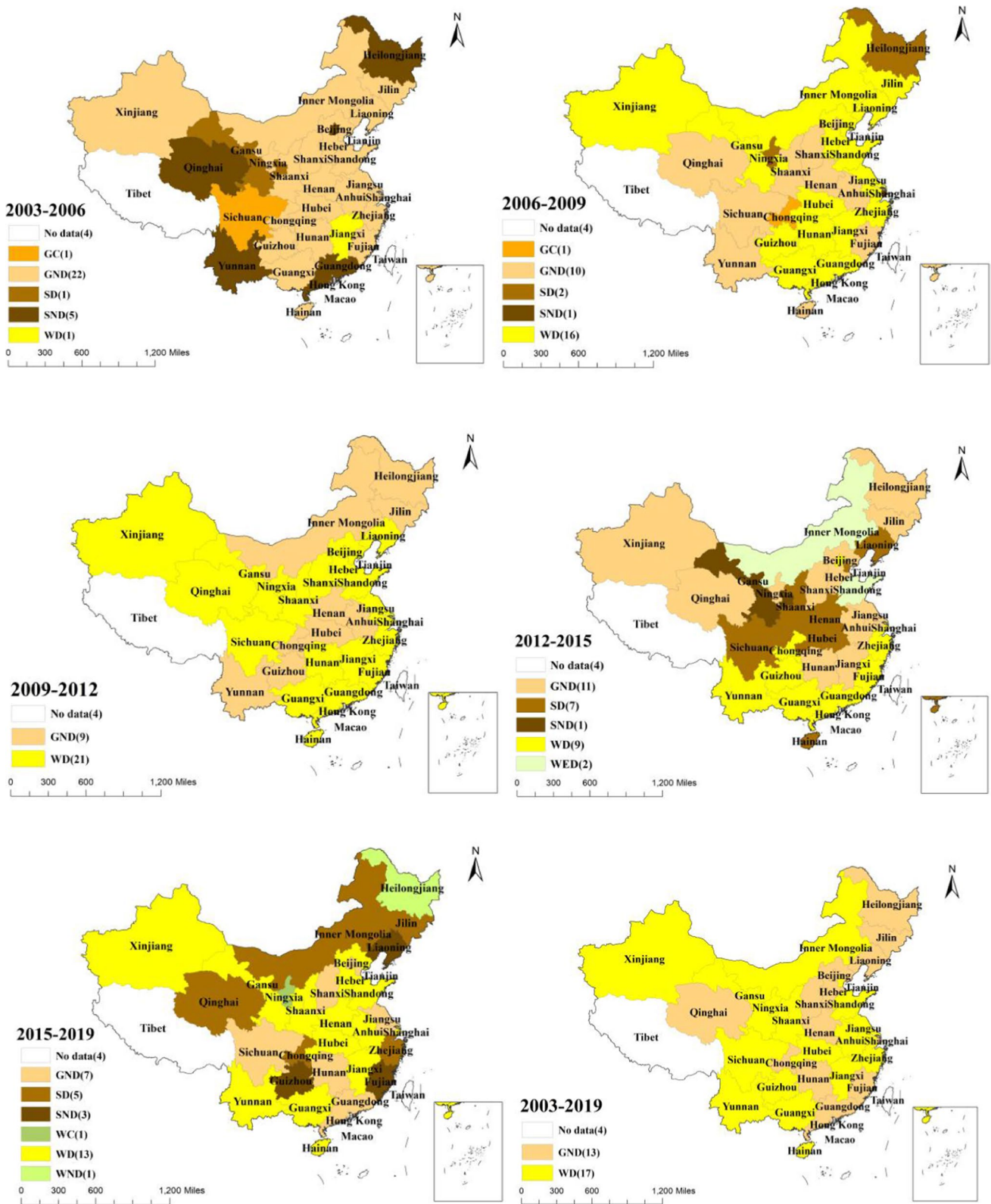


Fig. 4 Changes in the decoupling characteristics of transportation CO₂ emissions in China from 2003 to 2019 (GC, growth connection; GND, growth negative decoupling; SD, strong decoupling; SND,

strong negative decoupling; WD, weak decoupling; WED, weakening decoupling; WC, weak connection; WND, weak negative decoupling)

characteristics of transportation CO₂ emissions in the periods 2003–2006, 2006–2009, 2009–2012, 2012–2015, 2015–2019, and the entire sample period 2003–2019.

- (a) From 2003 to 2006, Beijing, Heilongjiang, Guangdong, Yunnan, and Qinghai showed strong negative decoupling. In contrast, Gansu showed strong decoupling, Jiangxi showed weak decoupling, Sichuan showed growth connection, and the remaining 22 provinces all showed negative growth decoupling. Yunnan had the highest degree of decoupling, with a decoupling elasticity value of -254.7539 . It may be because Yunnan has seized the strategic development opportunity of China's western development and continuously increased its transportation infrastructure investment. While promoting the value added to the transportation industry, it also boosts energy consumption, which drives the growth of carbon emissions. The lowest degree of decoupling is in Gansu Province, which has a decoupling elasticity value of -0.0799 and has reached the ideal coupling state of transportation economic development and carbon emissions. During this period, the decoupling state of transportation CO₂ emissions in various provinces in China was diversified, and the degree of decoupling was relatively high.
- (b) From 2006 to 2009, Shanghai showed a solid negative decoupling state, and its decoupling elasticity was -4.044 . Heilongjiang and Ningxia Hui Autonomous Region showed a strong decoupling state, and their decoupling elasticity was between -0.2 and 0 . Chongqing was in a state of growth connection, and its decoupling elasticity was 0.9129 . Beijing, Shanxi, Anhui, Fujian, Henan, Hainan, Sichuan, Yunnan, Shaanxi, and Qinghai all showed negative growth decoupling, whereas the remaining 16 provinces showed weak decoupling. Generally speaking, the decoupling of transportation CO₂ emissions in different provinces in China was diversified at this stage. The relationship between transportation CO₂ emissions and industry value shifts gradually from a negative decoupling to a weak decoupling relationship. It is consistent with the pre-peak characteristics of the EKC curve.
- (c) From 2009 to 2012, Inner Mongolia, Jilin, Heilongjiang, Anhui, Henan, Hubei, Chongqing, Guizhou, and Yunnan showed negative growth decoupling, and the remaining 21 provinces showed weak decoupling. Overall, at this stage, the state of decoupling and the degree of decoupling of China's provincial transportation CO₂ emissions became consistent. The relationship between transportation development and carbon emissions is at a reasonable stage.
- (d) From 2012 to 2015, Gansu showed a solid negative decoupling state, and its decoupling elasticity was -3.8515 . Tianjin, Liaoning, Henan, Hubei, Hainan, Sichuan, and Shaanxi showed strong decoupling. The two provinces of Inner Mongolia and Shandong showed decoupling. Hebei, Shanxi, Jilin, Heilongjiang, Jiangsu, Anhui, Jiangxi, Hunan, Qinghai, Ningxia, and Xinjiang all showed negative growth, whereas the remaining nine provinces showed weak decoupling. In general, the decoupling state of China's provincial transportation CO₂ emissions is diversified at this stage, and the editorial contribution of transportation development to the growth of carbon emissions is gradually weakening.
- (e) From 2015 to 2019, Liaoning, Fujian, and Guizhou showed strong negative decoupling. Inner Mongolia, Jilin, Zhejiang, Chongqing, and Qinghai were in solid decoupling. This decoupling process is consistent with the EKC curve. Heilongjiang showed weak negative decoupling, and its decoupling elasticity was 0.788 . Ningxia showed weak connecting, and its decoupling elasticity was 0.8754 . Beijing, Tianjin, Shanxi, Jiangsu, Hunan, Guangdong, and Sichuan showed negative growth decoupling, while the remaining 13 provinces showed weak decoupling. The four provinces of Shaanxi, Henan, Hubei, and Hainan, strongly decoupled in the previous period (2012–2015), all returned to a weakly decoupled state. It is in line with the scientific rule that there is a more extended plateau period after carbon peaking.
- (f) From 2003 to 2019, Beijing, Hebei, Shanxi, Liaoning, Jilin, Heilongjiang, Shanghai, Fujian, Henan, Hunan, Guangdong, Chongqing, and Qinghai all showed negative growth decoupling, and the relationship between transportation economy development and carbon emissions did not reach the ideal state. The remaining 17 provinces showed weak decoupling. It shows that most provinces have departed from the traditional development model of resource consumption and environmental destruction and have begun to engage in green development, but this transformation must be further strengthened.

Discussion

This paper finds that the overall transportation CO₂ emissions of each province in China show a rising trend, and it is regionally characterized as high in the east, followed by the mid-west, and low in the northeast. The decoupling effects in each province of China showed a trend from strong negative decoupling to weak decoupling. Both the trend in transportation CO₂ emissions and its decoupling

characteristics are consistent with Guo et al. (2014), Li et al. (2019), and Song et al. (2022). However, this paper uses 16 kinds of fossil fuels to account for transportation CO₂ emissions, and the estimated results are more accurate than other papers. However, this paper selects GDP per capita, population size, transportation energy intensity, energy use per unit of turnover, and traffic intensity to decompose the influencing factors of transportation CO₂ emissions, which increases the innovation and operability of transportation carbon emission research. This paper found that GDP per capita and population size contribute to the growth of transportation CO₂ emissions. But energy use per unit of turnover and transportation intensity decrease transportation CO₂ emissions. These results are consistent with Zhu and Gao (2019), Zhang and Su (2020), Xu and Lin (2017), and Song et al. (2022). However, this paper found transportation energy intensity increases transportation CO₂ emissions. This result is inconsistent with Zhang and Su (2020). It may be because Zhang and Su (2020) take the Yellow River Basin in China as the study target, and the continuous increase in the proportion of clean energy shown in the Yellow River Basin after 2012 has slowed down the trend of carbon emission growth to some extent. However, this study has several limitations. On the one hand, we use the top-down approach advocated by the IPCC to measure carbon emissions, which may lead to biased estimates of the results; on the other hand, due to the vast size of China, transportation CO₂ emissions and regional economic development vary greatly. In the follow-up study, we must consider the changes in energy use technologies in different regions of China, narrow the scope of the study, and conduct more detailed research at the regional or provincial level.

Conclusions and policy implications

Conclusions

To establish energy conservation and emission reduction regulations in the transportation industry, it is critical to research transportation emissions in China and the elements that drive them. The Tapio decoupling model analyzes the dynamic decoupling effect of transportation CO₂ emissions in China's provinces from 2003 to 2019. It first estimated China's transportation CO₂ emissions using the "top-down" method from 2003 to 2019. Finally, the LMDI approach examines the factors influencing China's transportation CO₂ emissions. The study's main findings are listed below.

- (1) China's transportation CO₂ emissions are increasing by around 16% each year. Transportation CO₂ emissions in the eastern region are much greater than in the central and western regions, while carbon emissions in coastal

provinces are significantly higher than in inland provinces. Guangdong, Shandong, Shanghai, and Liaoning have always had higher transportation CO₂ emissions than other provinces, whereas Ningxia and Qinghai have the lowest. All Chinese provinces confront significant energy-saving and emission-reduction challenges in the transportation business.

- (2) Over time, China's transportation industry's carbon emission decoupling index has shifted dramatically. For a long time, the type of decoupling has evolved from strong negative decoupling to weak decoupling. Although China's green transportation development has yielded some achievements, it has yet to reach the inverted U-shaped inflection point of the environmental Kuznets curve. There is a significant gap between the strong decoupling of low-carbon transportation's leading indicators. The decoupling index of transportation CO₂ emissions has also varied throughout China's provinces. Anhui, Henan, and Yunnan provinces fared well, but Anhui, Henan, and Yunnan provinces did not.
- (3) GDP per capita is essential for raising China's transportation CO₂ emissions, whereas energy usage per unit turnover is the most critical factor for cutting emissions. Transportation energy intensity and population size have contributed to the transportation industry's carbon emissions, while transportation intensity has also helped reduce emissions.

Policy implications

- (1) Optimizing the energy structure and improving low-carbon travel for residents are vital initiatives to control transportation CO₂ emissions. All provinces in China should further optimize their energy structure and reduce the proportion of oil consumption as much as possible. At the same time, they should vigorously develop low-carbon energy sources such as natural gas and electricity and strengthen efforts to promote new energy vehicles. The government can encourage the use of new clean energy, such as natural gas and solar power, through financial subsidies and carbon trading policies and thus increase the share of clean energy in the transportation sector. In addition, we need to pay attention to demographic changes, raise people's awareness of environmental protection through various channels, and encourage the public to use public transportation.
- (2) Reducing energy consumption per unit turnover and increasing the intensity of transportation are the most important methods for solving the current transportation CO₂ emission problem. The rapid development of China's economy will inevitably lead to a gradual increase in total energy consumption, so we must pay

great attention to improving energy efficiency. On the one hand, the Chinese government should further encourage cooperation between industry, academia, and research in developing and promoting related technologies. Vigorously research, develop and promote energy-efficient means of transport, and promote green transportation development by reducing the energy efficiency level of transport. On the other hand, promoting and strengthening transportation intelligence is critical. To increase transportation efficiency, the Chinese government should actively construct intelligent systems such as logistics platform information services and multimodal transportation starting at the provincial level.

- (3) Each province should adopt differentiated carbon emission reduction initiatives to achieve the transformation of the transportation industry. In promoting the “double carbon” goal, the Chinese government should fully consider the differences in transportation carbon reduction potential among provinces and the decoupling effect of transportation CO₂ emissions and economic development, and then implement differentiated transportation carbon reduction measures and policies. The economic growth and technological innovation ability in the eastern provinces are relatively high; they should take advantage of their low-carbon technology to promote low-carbon transportation transformation. The central provinces have larger populations and high pressure on transportation trips. These provinces should strengthen the integration of public transportation to increase the proportion of public transportation in the population’s travel and reduce transportation energy consumption. The northeastern and western provinces face a mismatch between the development and consumption of resources. These provinces should promote the use of new energy vehicles and subsequently improve the energy consumption structure.

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Data availability All data used in this paper are from field research, then they are reliable and available.

Declarations

Ethical approval All analyses were based on previous published studies, thus no ethical approval are required.

Consent to participate All of the authors consent to participate in this paper.

Consent for publication All of the authors consent to publish in this paper.

Conflict of interest The authors declare no competing interests.

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