RESEARCH ARTICLE

Decoupling and decomposition analysis of transportation carbon emissions at the provincial level in China: perspective from the 11th and 12th Five-Year Plan periods

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Abstract

Based on the Tapio decoupling model, this paper calculates the decoupling indexes of the transportation output and the transportation carbon emissions of China's 30 provinces and municipalities from 2006 to 2015. The research period (2006–2015) is divided into the 11th Five-Year Plan period (FYP) (2006–2010) and the 12th FYP period (2011–2015). On this basis, we conduct a comparative analysis to describe the spatial-temporal evolution of the decoupling states of transportation output and transportation carbon emissions. Furthermore, in order to deeply analyze the reasons for the evolution of the decoupling states during the 12th FYP period compared with the 11th FYP period, the LMDI decomposition method is used to decompose and compare the factors affecting the transportation carbon emissions in the two periods. The results show the following: (1) from the national point of view, the decoupling relationship between transportation output and transportation carbon emissions improved gradually, with small fluctuations from 2006 to 2015; (2) from the provincial point of view, their decoupling states mainly were expansive negative decoupling and weak decoupling, and the spatial evolution of the two decoupling states is significantly different; (3) the reductions in the transportation energy intensity and transportation intensity were the main factors inhibiting the increase of transportation carbon emissions in the 11th and 12th FYP periods, respectively. The growth of per-capita wealth was the decisive factor driving the increase in transportation carbon emissions in the two periods; (4) in contrast to the causes of decreases in the carbon emission variations in the 11th FYP period, in the 12th FYP period, the significant reduction in transportation intensity is the main reason causing the significant decrease of carbon emission variations. However, the transportation energy intensity and the transportation intensity fail to reduce simultaneously in the two periods.

Keywords Transportation carbon emissions · Transportation output · Decoupling · Driving factor · LMDI · Spatial-temporal evolution

Introduction

Since 2007, China has exceeded the USA and become the largest CO_2 emitter in the world. In China, the transportation industry has become the third largest energy consuming industry and the important source of carbon emissions (Lu et al. 2017b). Therefore, China's transportation carbon emission reduction is of great significance for China and the world.

As such, issues related to China's transportation carbon emissions have become hot topics in the field of environmental economics. Specifically, having made many achievements in studies in this area, scholars have carried out a great deal of research on the calculation of China's transportation carbon emissions (He et al. 2005; Wang et al. 2011; Li et al. 2013), the decoupling relationship between China's transportation carbon emissions and economic growth (Zhao et al. 2016; Wang et al. 2017; Dong et al. 2017; Zhu and Li 2017), the factors affecting China's transportation carbon emissions (Wang et al. 2011; Li et al. 2013; Xu and Lin 2015; Lin and Benjamin 2017; Zhang et al. 2018), etc.

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However, most of the above research on the decoupling relationship between China's transportation carbon emissions and economic growth has focused on one or several provinces of China as research areas. Moreover, previous research has only studied the trend of the decoupling relationship over time, without considering the spatial heterogeneity and the spatial evolution characteristics of the decoupling relationship among different regions in development stages. For example, Wang et al. (2017) and Zhu and Li (2017) respectively examine the temporal evolution characteristics of the decoupling relationship between economic growth and transportation carbon emissions in Jiangsu Province and Beijing-Tianjin-Hebei region; Zhao et al. (2016) and Dong et al. (2017) respectively measure and analyze the temporal change in the decoupling relationship between transportation economic development and transportation carbon emissions in Guangdong and Xinjiang, China.

On the basis of the examination of the decoupling status between the transportation carbon emissions and transportation economic growth, it is very important to explore the factors influencing the evolution characteristics of the decoupling relationship. Meanwhile, the change in the transportation carbon emissions is a vital cause of the change in the decoupling status. In view of this, scholars have conducted a great deal of research on the influencing factors of the transportation carbon emissions.

According to the research methods, the existing research on factors affecting China's transportation carbon emissions can be classified into two types. The first type of research uses traditional econometric regression models to examine the factors affecting transportation carbon emissions. For example, Xu and Lin (2015) employ the dynamic vector autoregressive model to analyze the factors affecting the change in China's transportation CO_2 emissions; Lin and Benjamin (2017) use quantile regression to investigate the impacts of per-capita GDP, energy intensity, carbon intensity, and total population on China's transportation CO_2 emissions; taking Changzhou as an example, Zhang et al. (2018) combine regression analysis with a traffic assignment model, a carbon emissions evaluation model, land use pattern, and landscape metrics analysis methods, to study the relationship between land use planning and transportation carbon emissions.

When exploring the long-term equilibrium relationship between variables, an econometric regression model is an effective tool. However, the weights of the factors affecting transportation carbon emissions in total effects will change in different periods, and the traditional econometric regression model has difficulty describing this short-term change process to some extent. Hence, scholars gradually adopt the second type, i.e., the index decomposition method, to dynamically describe the impacts of various affecting factors on transportation carbon emissions (Wang et al. 2011; Li et al. 2013).

After a comprehensive comparison by Ang (2004), it has been found that the LMDI (Logarithmic Mean Divisia Index) decomposition method has obvious advantages in theoretical foundation, adaptability, ease of use, and results in interpretation; thus, it is widely used in the study of factors affecting China's transportation carbon emissions (Wang et al. 2011; Lu et al. 2017b; Luo et al. 2017; Wang et al. 2018).

However, in the abovementioned studies on the factor decomposition of the transportation carbon emissions in China, the impacts of some important variables, such as the transportation intensity, the transportation energy intensity, and the industrial structure, are not taken into account simultaneously, which makes it impossible to examine the impacts of these factors on China's transportation carbon emissions. For example, Wang et al. (2011) and Wang et al. (2018) considered the transportation intensity effect and some other effects, but did not consider the transportation energy intensity effect and the industrial structure effect. In the study by Luo et al. (2017), none of the three factors is taken into account. Moreover, it is worth noting that Fan and Lei (2016) and Lu et al. (2017b) used the multivariate generalized Fisher index (GFI) decomposition model and the LMDI decomposition model to examine the influence factors of the transportation carbon emissions in Beijing and the Yangtze River Economic Belt, respectively. These two researches took into account the transportation intensity and the transportation energy intensity, but they did not consider the industrial structure effect; thus, it is impossible to examine the influential effect of the change in the industrial structure on the transportation carbon emissions.

In addition, Zhang et al. (2015) and Zhao et al. (2016) find that China's Five-Year Plan, causing transportation carbon emissions to show a five-year periodic fluctuation, has a significant impact on transportation carbon emissions. Therefore, it is very important to take the impact of the FYP into account when studying China's transportation carbon emissions. Since the economic development's focus and goals and the governments' attention to a reduction in carbon emissions vary in different FYP periods, the decoupling relationship between China's transportation carbon emissions and the economic development of the transportation sector and the factors affecting transportation carbon emissions may also be different in these FYP periods. In the abovementioned researches on the decoupling relationship, only a few take the impact of the FYP into account, and very few simply compare the decoupling relationships in different FYP periods (Zhao et al. 2016; Dong et al. 2017). However, these researches do not conduct further comparative studies from the perspective of a spatial-temporal evolution in different FYP periods; in the above researches on the factor decomposition, the FYP is not taken into account, and these studies do not perform an in-depth exploration of the differences in the influential effects of these factors in different FYP periods.

Based on the above analysis, taking the 30 provinces and municipalities in China as the research samples, this paper calculates the transportation carbon emissions in each province from 2005 to 2015, and then uses a Tapio decoupling elasticity index method to investigate the spatial-temporal evolution characteristics of the decoupling states of transportation economic development and transportation carbon emissions in China as a whole and the various provinces and municipalities. On this basis, the research period herein is divided into an 11th FYP period and a 12th FYP period, and the spatial-temporal evolution characteristics of the decoupling relationship in the two periods are compared. Next, this paper employs a LMDI method to examine the impacts of the carbon emissions coefficient effect, the transportation energy structure effect, the transportation energy intensity effect, the transportation intensity effect, the industrial structure effect, the per-capita wealth effect, and the population size effect on transportation carbon emissions. Additionally, in order to further explore the reasons for the improvement of the decoupling status during the 12th FYP period compared with the 11th FYP period, the differences of the impacts of these effects in the two periods are analyzed. Finally, this paper summarizes the main research conclusions and puts forward the corresponding policy recommendations for reducing China's transportation carbon emissions.

Model and methodology

Calculation of transportation carbon emissions

At present, there is no official statistical agency that directly issues the data on China's transportation carbon emissions. Hence, top-down and bottom-up approaches are commonly used in calculating transportation carbon emissions. As the bottom-up approach requires complete data (Li et al. 2013; Xie et al. 2016), this paper adopts the top-down approach to calculate the transportation carbon emissions according to the final energy consumption of the transportation sector. With reference to the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, the carbon emissions are calculated via Eq. (1):

$$c = \sum_{i}^{8} e_i \times v_i \times ce_i \times r \qquad (1)$$

where c is the total transportation carbon emissions, i is the fuel type, e is the fuel consumption value, v is the average low calorific value of fuel, ce is the carbon emission coefficient of fuel, and r is the carbon oxidation rate. The consumption data and the average low calorific values of various fuels are derived from *the China Energy Statistical Yearbooks 2006–2016*, and the carbon emission coefficients of various fuels are derived from the *2006 IPCC Guidelines for National*

Greenhouse Gas Inventories. Furthermore, we assume that the oxidation reaction is complete; thus, $r = 1$ in this paper. The carbon emission coefficients and the average low calorific values of various fuels are shown in Table 1.

Tapio decoupling evaluation model

The relationship between economic growth and ecological environment has always been an important issue in the field of environmental economics, and the existence of the environmental Kuznets curve has been a controversial topic among scholars (Bakirtas and Cetin 2017; Churchill et al. 2018; Sarkodie and Strezov 2019). To further explore the relationship between economic growth and the environment, decoupling was first introduced from physics in the early twenty-first century (Zhang 2000). The Organization for Economic Cooperation and Development (OECD) then proposed the first decoupling model (OECD 2002). For further analysis of the factors affecting the decoupling relationship, Tapio (2005) has put forward an elasticity analysis model, in which the decoupling states are classified into eight types, as shown in Table 2. This model currently is widely used in the study of the relationship between carbon emissions and economic growth and is also the basis for the calculation of the decoupling indexes in this paper. The equation is as follows:

$$de_t = \frac{(ce_t - ce_{t-1})/ce_t}{(gdp_t^{tra} - gdp_{t-1}^{tra})/gdp_t^{tra}} = \frac{\triangle ce_t/ce_t}{\triangle gdp_t^{tra}/gdp_t^{tra}} \qquad (2)$$

where de_t denotes the decoupling index from year $t-1$ to year t, ce_t denotes the transportation carbon emissions in year t, and gdp_t^{tra} is the transportation output, i.e., the added value of the transportation sector in year t, $\triangle ce_t$ denotes the variation of transportation carbon emissions from year $t-1$ to year t, and $\triangle gdp_t^{tra}$ denotes the transportation output variation from year $t-1$ to year t.

LMDI model

The LMDI method can be stated in a multiplicative decomposition form and in an additive decomposition form. According to the research achievements by Ang (2004, 2005), this paper uses the additive decomposition method. The previous decomposition studies have not considered the transportation energy intensity, the transportation intensity, and the industrial structure simultaneously, while the three factors have the important impact on the transportation carbon emissions, and the effects are even greater than that of other influencing factors (Wang et al. 2011; Zhang and Nian 2013). Meanwhile, due to the difference in the focus of the economic policy, the three

Table 1 Some coefficients of fuels

Fuel type	Raw coal	Coke	Crude oil	Fuel oil	Gasoline	Kerosene	Diesel oil	Natural gas
Carbon emission coefficient	25.8	29.2	20	21.1	18.9	19.6	20.2	15.3
Average low calorific value	20,908	28,435	41,816	41,816	43,070	43,070	42,652	38,931
Conversion coefficient of standard coal	0.714	0.971	1.429	1.429	1.471	1.470	1.457	1.214

The carbon emission coefficient of natural gas is expressed in m^3/GJ, and the carbon emission coefficients of other fuels are expressed in kg/GJ. The average low calorific value of natural gas is expressed in KJ/m^3, and the average low calorific values of other fuels are expressed in KJ/kg

factors may show a significant difference in the 11th and 12th FYP periods. Hence, in order to measure the difference of the driving effect of the factors in the two FYP periods, it is very necessary to take the three factors into account simultaneously. In view of this, this paper finally decomposes the factors driving the increase of transportation carbon emissions into seven factors, including the carbon emission coefficient, the transportation energy structure, the transportation energy intensity, the transportation intensity, the industrial structure, the per-capita wealth, and the population size. The equation is expressed as follows:

$$\mathrm{CE}^t = \sum_i \mathrm{CE}_i^t = \sum_i \frac{\mathrm{CE}_i^t}{E_i^t} \times \frac{E_i^t}{E^t} \times \frac{E^t}{\mathrm{TS}^t} \times \frac{\mathrm{TS}^t}{\mathrm{GDP}_{tra}^t} \times \frac{\mathrm{GDP}_{tra}^t}{\mathrm{GDP}^t} \times \frac{\mathrm{GDP}^t}{\mathrm{POP}^t} \times \mathrm{POP}^t$$

$$= \sum_i \mathrm{CI}_i \times \mathrm{ES}_i \times \mathrm{ET} \times \mathrm{TG} \times \mathrm{IS} \times \mathrm{PC} \times \mathrm{POP} \quad (3)$$

where t indicates the year and i denotes the fuel type consumed in the transportation sector. CE denotes the total transportation carbon emissions, and CE_i^t denotes the transportation carbon emissions caused by the consumption of fuel i in year t. E_i^t denotes the consumption of fuel i in the transportation sector in year t (all types of fuel consumption are converted into standard coal for further calculation; the specific conversion coefficients are shown in Table 1.), E^t denotes the total transportation energy consumption in year t, and TS represents the transportation turnover. GDP_{tra}^t is the transportation output, POP denotes the population size, CI denotes the carbon emission coefficient, and ES represents the transportation energy structure. ET denotes the energy consumption per unit transportation turnover, i.e., the transportation energy intensity, and TG denotes the transportation turnover per unit transportation output, i.e., the transportation intensity. IS represents the proportion of transportation output to the national GDP, i.e., the industrial structure, and PC denotes the per-capita GDP.

We assume that carbon emissions are CE^0 at the beginning and that they then become CE^t after t years. According to the additive decomposition of the LMDI model, the carbon emission variation ($\Delta\mathrm{CE}^t$) is decomposed into the carbon emission coefficient effect CI_{effect}, the transportation energy structure effect ES_{effect}, the transportation energy intensity effect ET_{effect}, the transportation intensity effect TG_{effect}, the industrial structure effect IS_{effect}, the per-capita wealth effect PC_{effect} and population size effect P_{effect}. The equation is as follows:

$$\Delta\mathrm{CE}^t = \mathrm{CE}^t - \mathrm{CE}^0 \quad (4)$$

$$= \Delta\mathrm{CI}_{effect} + \Delta\mathrm{ES}_{effect} + \Delta\mathrm{ET}_{effect} + \Delta\mathrm{TG}_{effect}$$

$$+ \Delta\mathrm{IS}_{effect} + \Delta\mathrm{PC}_{effect} + \Delta P_{effect}$$

Table 2 Decoupling types based on the Tapio model

de_t	$\triangle ce_t$	$\triangle gdp_t^{tra}$	Decoupling state
$(-\infty, 0)$	<0	>0	Strong decoupling (SD)
(0,0.8)	>0	>0	Weak decoupling (WD)
$(1.2, +\infty)$	<0	<0	Recessive decoupling (RD)
$(-\infty, 0)$	>0	<0	Strong negative decoupling (SND)
(0,0.8)	<0	<0	Weak negative decoupling (WND)
$(1.2, +\infty)$	>0	>0	Expansive negative decoupling (END)
(0.8,1.2)	<0	<0	Recessive coupling (RC)
(0.8,1.2)	>0	>0	Expansive coupling (EC)

where

$$\Delta CI_{effect} = \sum_i L\left(CE_i^t, CE_i^0\right) \times \ln\frac{CI^t}{CI^0} \quad \Delta ES_{effect} = \sum_i L\left(CE_i^t, CE_i^0\right) \times \ln\frac{ES^t}{ES^0} \quad \Delta ET_{effect} = \sum_i L\left(CE_i^t, CE_i^0\right) \times \ln\frac{ET^t}{ET^0} \quad \Delta TG_{effect}$$

$$= \sum_i L\left(CE_i^t, CE_i^0\right) \times \ln\frac{TG^t}{TG^0} \quad \Delta IS_{effect} = \sum_i L\left(CE_i^t, CE_i^0\right) \times \ln\frac{IS^t}{IS^0} \quad \Delta PC_{effect} = \sum_i L\left(CE_i^t, CE_i^0\right) \times \ln\frac{PC^t}{PC^0} \quad \Delta P_{effect}$$

$$= \sum_i L\left(CE_i^t, CE_i^0\right) \times \ln\frac{P^t}{P^0} \quad L\left(CE_i^t, CE_i^0\right) = \begin{cases} \left(\dfrac{CE_i^t - CE_i^0}{\ln CE_i^t - \ln CE_i^0}\right) & \text{if } CE_i^t \times CE_i^0 \neq 0 \\ 0 & \text{if } CE_i^t \times CE_i^0 = 0 \end{cases}$$

Data sources

In this paper, the data pertaining to various types of energy consumption in the transportation sector of China's 30 provinces and municipalities in 2005–2015 is derived from the energy balance tables in the *China Energy Statistical Yearbook*. Due to the lack of data for their areas, Tibet, Taiwan, Hong Kong, and Macao are beyond the research scope of this paper. The economic data, including the transportation output, the GDP, the population size, and transportation turnover, is derived from the *China Statistical Yearbook* compiled by the National Bureau of Statistics of the People's Republic of China, of which the transportation output and GDP are converted from the current price to the constant price in 2005. The passenger traffic turnover of different transportation modes is converted to a freight traffic turnover (unit 100 million tons/km), using different coefficients. On the basis of the study carried out by Lu et al. (2017a), the specific coefficients for the conversion of railway, road, and waterway passenger traffic turnover to freight traffic turnover are 1, 0.1, and 1, respectively.

Spatial-temporal evolution of decoupling relationship

Analysis of national-level decoupling relationship

First, the total transportation output and the total transportation carbon emissions of China's 30 provinces and municipalities in each year from 2005 to 2015 are calculated. Then, the variation rates of the total transportation output and the total transportation carbon emissions in each year are obtained. Their decoupling indexes are calculated via Eq. (2), as shown in Table 3. The following can be seen from Table 3: (1) In 2006–2015, the transportation output increased from RMB 1278.9 billion to RMB 2914.5 billion, with an average annual growth rate of 9.58%. The transportation output maintained a growth rate of more than 10% before 2008. However, its growth rate decreased significantly after 2008, as the outbreak of the financial crisis had a huge negative impact on domestic investment and international trade, which seriously affected the development of the transportation sector. With the implementation of China's Four Trillion Investment Policy and the gradual recovery of national economy, the transportation sector has greatly developed and its growth rate has improved significantly. However, as China's economic downward pressure has increased constantly in recent years, the growth rate of the transportation sector has gradually decelerated. (2) In 2006–2015, the transportation carbon emissions increased from 107.61 million tons to 181.37 million tons, with an average annual growth rate of 5.97%. In comparison with the growth of the transportation output, the variation rate of transportation carbon emissions has fluctuated widely, and the growth rate has decreased on the whole. Especially, the carbon emissions in 2013 decreased by 5.49% more than those in 2012 did. (3) The decoupling state of transportation output and transportation carbon emissions has gradually optimized. The decoupling state was expansive coupling before 2009, followed by weak decoupling. Especially in 2013, the decoupling state was strong decoupling due to the decrease in transportation carbon emissions. The phenomenon of the reduction of carbon emissions from transportation in 2013 has also been confirmed in other scholars' research (Song et al. 2017; Wang et al. 2018). The reasons are mainly as follows: first, in order to save energy, China has implemented a tax reform on resource taxes since the end of 2011. Oil and natural gas have been changed from specific taxes to ad valorem taxes. Coupled with the time lag effect of the policy, this reform ultimately led to a decline in energy use in the transportation sector in 2013 and a reduction in carbon emissions from transportation. Second, in 2013, the Chinese government included environmental assessment for the first time in the assessment of official promotion. In order for local officials

Table 3 Transportation output, transportation carbon emissions and the decoupling relationship in 2005-2015

Year	CE (million tons)	GDP$_{tra}$ (billion)	ΔCE(%)	ΔGDP$_{tra}$ (%)	de$_t$	State
2005	97.40	1137.06				
2006	107.61	1278.90	10.480	12.474	0.840	EC
2007	119.70	1446.85	11.233	13.133	0.855	EC
2008	131.07	1590.78	9.499	9.948	0.955	EC
2009	139.42	1703.59	6.371	7.091	0.898	EC
2010	150.04	1904.85	7.618	11.814	0.645	WD
2011	162.74	2103.70	8.467	10.439	0.811	EC
2012	173.45	2302.73	6.577	9.461	0.695	WD
2013	163.92	2489.88	− 5.492	8.127	− 0.676	SD
2014	173.88	2706.19	6.073	8.688	0.699	WD
2015	181.37	2914.52	4.311	7.698	0.560	WD
2006–2015	–	–	5.972	9.584	0.623	WD

to obtain political promotion, they will inevitably impose stricter carbon emission reduction measures (Ru 2018) on important carbon emission sectors such as transportation, thus limiting carbon emissions in transportation and other sectors.

Comparison of provincial-level decoupling states between the 11th and 12th FYP periods

The 11th FYP and the 12th FYP were implemented in the years 2006–2010 and 2011–2015, respectively, and the focus on economic development was different in the two periods. Specifically, in the 11th FYP period, more attention was paid to the economic aggregate, while in the 12th FYP period, more attention was paid to the economic structure and quality. Hence, it is necessary to compare the decoupling relationship between transportation output and transportation carbon emissions in the two periods. For China's 30 provinces and municipalities in the 11th and 12th FYP periods, Table 4 lists the variation rates of transportation output and transportation carbon emissions, as well as their decoupling relationship. Moreover, in order to more intuitively express their decoupling changes, ArcGIS is used to visualize the decoupling states of 30 provinces and municipalities described in Table 4. See Fig. 1.

First, we analyze the decoupling states in the 11th FYP period. In this period, the international financial crisis broke out. In response to the crisis, the Chinese government took a series of measures to stimulate domestic demand. Therefore, a large number of government funds flowed into the infrastructure construction, including railway and road construction. As shown in Table 4, the national average annual growth rate of transportation output reached 10.47%, while the national average annual growth rate of transportation carbon emissions was 8.67%. The national decoupling index was 0.827, and the national decoupling state was the expansive coupling state, which was not optimistic. The growth rates of the transportation output and the transportation carbon emissions varied

greatly in different provinces. The growth rate of transportation output decreased from the eastern region to the western region. The average growth rates of the eastern, central, and western provinces were 10.60%, 10.14%, and 8.91%, respectively. The growth rates of carbon emissions in the eastern provinces fluctuated slightly, but they were quite different in the western provinces. From the calculated results, it can be seen that the standard deviation of the carbon emission growth rate in the eastern provinces was 4.17, while that in the western provinces was 8.57. Moreover, the decoupling states of various provinces and municipalities were characterized by obvious spatial heterogeneity, of which the Heilongjiang and Xinjiang's decoupling states were strong due to the negative growth of transportation carbon emissions. There were 11 provinces in a weak decoupling state, which were mainly concentrated in the eastern coastal region (Liaoning, Hebei, Shandong, Tianjin, Jiangsu, and Zhejiang) and the area adjacent to the central and southwestern regions (Hubei, Hunan, Guangxi, and Yunnan). The provinces in the expansive coupling state were Inner Mongolia, Chongqing, Guizhou, Jiangxi, and Guangdong. There were 12 provinces in the expansive negative decoupling state, including five discontinuously distributed provinces and municipalities in the eastern region (Jilin, Beijing, Shanghai, Fujian, and Hainan) and seven in the central and western regions (Anhui, Henan, Shanxi, Shaanxi, Sichuan, Gansu, and Qinghai), of which Qinghai was in the worst decoupling state, with a decoupling index of up to 3.365, due to the high growth rate of carbon emissions.

Second, we analyze the decoupling states in the 12th FYP period. The national average annual growth rate of transportation output decreased from 10.47% in the 11th FYP period to 8.49% in the 12th FYP period. Meanwhile, the national average annual growth rate of transportation carbon emissions decreased from 8.67 to 2.75%. Although their growth rates decreased simultaneously, the decrease in the growth rate of

Table 4 Comparison of decoupling states between the 11th and 12th FYP periods

Province	Region	11th FYP period				12th FYP period			
		ΔCE(%)	ΔGDP$_{tra}$(%)	de$_t$	State	ΔCE(%)	ΔGDP$_{tra}$(%)	de$_t$	State
Shanxi	C	18.257	12.169	1.500	END	3.432	8.593	0.399	WD
Inner Mongolia	C	14.356	15.103	0.951	EC	− 3.249	7.020	− 0.463	SD
Jilin	C	14.835	10.401	1.426	END	6.509	5.010	1.299	END
Heilongjiang	C	− 0.425	6.584	− 0.065	SD	5.826	5.988	0.973	EC
Anhui	C	10.897	8.941	1.219	END	14.670	5.688	2.579	END
Jiangxi	C	6.314	7.662	0.824	EC	9.666	5.144	1.879	END
Henan	C	10.739	4.375	2.455	END	8.606	5.932	1.451	END
Hubei	C	5.604	12.962	0.432	WD	− 1.444	10.500	− 0.138	SD
Hunan	C	7.283	13.107	0.556	WD	9.836	6.741	1.459	END
Beijing	E	10.470	6.645	1.575	END	3.919	6.193	0.633	WD
Tianjin	E	6.750	12.796	0.527	WD	− 2.739	9.605	− 0.285	SD
Hebei	E	5.434	12.418	0.438	WD	− 2.206	9.469	− 0.233	SD
Liaoning	E	4.962	12.670	0.392	WD	2.728	8.418	0.324	WD
Shanghai	E	5.503	3.820	1.440	END	1.541	5.555	0.277	WD
Jiangsu	E	9.988	14.168	0.705	WD	7.330	9.725	0.754	WD
Zhejiang	E	7.419	12.942	0.573	WD	4.293	9.545	0.450	WD
Fujian	E	16.869	8.007	2.107	END	5.242	10.595	0.495	WD
Shandong	E	6.516	13.293	0.490	WD	− 9.057	9.425	− 0.961	SD
Guangdong	E	8.306	9.273	0.896	EC	1.735	9.799	0.177	WD
Guangxi	E	8.636	12.414	0.696	WD	2.510	5.820	0.431	WD
Hainan	E	18.431	8.770	2.102	END	− 2.250	9.579	− 0.235	SD
Chongqing	W	12.608	10.736	1.174	EC	9.697	8.598	1.128	EC
Sichaun	W	11.707	5.071	2.309	END	2.186	9.507	0.230	WD
Guizhou	W	16.868	15.473	1.090	EC	7.988	11.522	0.693	WD
Yunnan	W	7.952	11.946	0.666	WD	2.579	10.060	0.256	WD
Shaanxi	W	19.068	9.571	1.992	END	− 5.180	6.004	− 0.863	SD
Gansu	W	5.326	4.050	1.315	END	9.817	1.227	8.004	END
Qinghai	W	29.212	8.680	3.365	END	5.500	5.045	1.090	EC
Ningxia	W	3.948	7.216	0.547	WD	4.840	2.920	1.657	END
Xinjiang	W	− 0.840	7.421	− 0.113	SD	14.335	16.487	0.869	EC
China	–	8.665	10.473	0.827	EC	2.746	8.491	0.323	WD

C, E, and W indicate the central region, eastern region, and western region, respectively

carbon emissions was more significant. Furthermore, the national decoupling state improved from an expansive coupling to a weak decoupling. In this period, the growth rates of transportation output and transportation carbon emissions also varied considerably in various provinces and municipalities. Specifically, the growth rates of the transportation output of Xinjiang (with a highest growth rate) and Gansu (with a lowest growth rate) were 16.49% and 1.23%, respectively, and the former's growth rate was 13.41 times the latters. The decoupling states of various provinces and municipalities were also characterized by obvious spatial heterogeneity. The number of provinces in strong decoupling state increased from two in the 11th Five-Year period to seven in the 12th

Five-Year period, including Tianjin, Hebei, Inner Mongolia, Shandong, Hubei, Hainan, and Shaanxi. Other than Hainan, the geographic spatial distribution pattern of the remaining six provinces followed an inverted U-shaped pattern. The number of provinces in weak decoupling state increased to 12, which were mainly distributed in the eastern coastal region (Liaoning, Beijing, Jiangsu, Shanghai, Zhejiang, Fujian, and Guangdong) and southwestern region (Sichuan, Guizhou, Yunnan, and Guangxi), following a U-shaped pattern. It can be seen that all eastern coastal provinces reached the weak decoupling state or strong decoupling state. Xinjiang and Heilongjiang manifested a strong decoupling state in the 11th FYP period and deteriorated to an expansive coupling
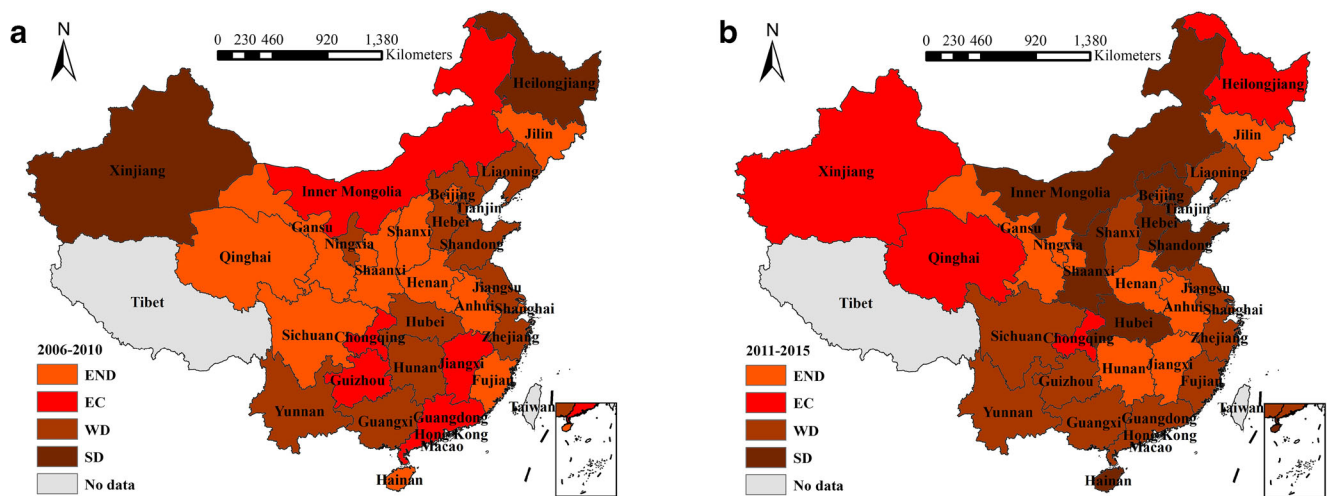
Fig. 1 Spatial distribution of decoupling states in the 11th and 12th FYP periods. **a** Decoupling states in the 11th FYP period. **b** Decoupling states in the 12th FYP period

state in the 12th FYP period. In addition, Qinghai and Chongqing also showed an expansive coupling state. The number of provinces in an expansive negative decoupling state decreased from 12 in the 11th FYP period to 7 in the 12th FYP period, and these provinces were mainly distributed in the northwestern region (Gansu and Ningxia) and central region (Henan, Anhui, Hubei, and Jiangxi).

From Table 4, it can be seen that most provinces' decoupling indexes declined significantly in the 12th FYP period. From Fig. 1, it can be found that the numbers of provinces in a strong decoupling state and a weak decoupling state increased in the 12th FYP period. The above shows that the decoupling relationship between the transportation output and the transportation carbon emissions improved in the 12th FYP period. Meanwhile, it should be noted that the decoupling indexes of some provinces in the central and western regions (Heilongjiang, Anhui, Jiangxi, Hunan, Gansu, Ningxia, and Xinjiang) increased sharply.

Spatial-temporal evolution of decoupling states

Based on the data of each province and municipality in 2005–2015, we use the Eq. (2) to determine the decoupling states of China's 30 provinces and municipalities. Table 5 shows the calculated results. Although the decoupling state is classified into eight types, most of the provinces are in the expansive negative decoupling state, expansive coupling state, weak decoupling state, and strong decoupling state. Since the reform and opening up in 1978, China's economy has maintained a rapid growth momentum. As an important part of the national economy, the transportation sector also has maintained a growth trend on the whole. Therefore, the provinces' decoupling states mainly have been expansive negative decoupling states, expansive coupling states, weak decoupling

states, and strong decoupling states, with $\triangle GDP_t^{tra} > 0$. In 2007 and 2008, the decoupling states of Shanghai, Henan, and Sichuan were ones of strong negative decoupling, due to the negative growth in transportation output caused by the financial crisis.

To intuitively describe the decoupling relationship and its changes with respect to the current development status in China, in this paper, a strong decoupling state and a weak decoupling state are defined as good states. Therefore, in Fig. 2, the annual number of provinces and municipalities in a good state with respect to the decoupling relationship, in the eastern region, the central region and the western region are summarized respectively and their changes in the three regions are shown. From the national perspective, the number of provinces in a good state shows an upward trend as a whole and exhibits a periodical characteristic. Specifically, the number of provinces in a good state shows a downward trend in 2006–2008, no significant change in 2008–2009, a rapid increase in 2009–2012, and a slight fluctuation after 2012. During the financial crisis, the economic growth rate of China's transportation sector declined. As a result, the number of provinces in a good state also declined slightly. However, after the outbreak of the financial crisis, the Chinese government adopted a series of fiscal policies in a timely manner to invest large amounts of funds in infrastructure construction, such as transportation, so that the economic growth of transportation sector could quickly recover. In the 12th FYP period, the growth rate of transportation carbon emissions in many provinces decreased, which may be related to the higher requirements on fuel efficiency and environmental quality proposed by the Chinese government. The recovery of the economic growth rate of the transportation sector and the decrease in the growth rate of transportation carbon emissions resulted in the increase in the number of provinces in a good state.

Table 5 Decoupling states of provinces and municipalities in 2006–2015

Region	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Beijing	END	END	END	END	WD	EC	WD	WD	EC	WD
Tianjin	WD	SD	EC	EC	WD	WD	WD	SD	WD	SD
Hebei	WD	WD	SD	SD	END	EC	WD	WD	SD	SD
Liaoning	WD	EC	WD	WD	WD	WD	WD	SD	END	WD
Shanghai	END	END	END	SNC	WD	SD	WD	SD	SD	WD
Jiangsu	WD	WD	EC	WD	EC	WD	EC	WD	EC	WD
Zhejiang	EC	EC	EC	WD	WD	EC	WD	WD	WD	WD
Fujian	WD	END	END	END	EC	EC	WD	WD	WD	WD
Shandong	WD	WD	WD	END	SD	EC	EC	SD	WD	WD
Guangdong	WD	EC	EC	EC	EC	WD	WD	SD	WD	WD
Guangxi	END	END	WD	END	WD	WD	END	SD	END	WD
Hainan	SD	EC	END	END	WD	WD	WD	SD	SD	WD
Shanxi	WD	WD	END	WD	WD	WD	WD	WD	SD	WD
Inner Mongolia	END	WD	EC	END	EC	WD	END	SD	WD	WD
Jilin	END	END	END	WD	WD	WD	WD	END	END	END
Heilongjiang	END	WD	SD	END	SD	END	WD	EC	END	END
Anhui	EC	END	WD	EC	EC	END	END	END	END	WD
Jiangxi	WD	WD	SD	END	END	END	WD	EC	WD	END
Henan	WD	END	SNC	END	END	END	END	END	WD	END
Hubei	WD	WD	EC	SD	WD	END	SD	SD	WD	WD
Hunan	WD	WD	SD	END	WD	WD	SD	END	END	END
Chongqing	WD	END	EC	SD	END	WD	END	EC	SD	END
Sichaun	END	END	END	SNC	SD	SD	EC	SD	END	SD
Guizhou	END	EC	END	WD	END	WD	END	SD	WD	WD
Yunnan	END	WD	WD	WD	END	WD	WD	SD	END	SD
Shaanxi	EC	END	END	END	END	WD	WD	SD	EC	SD
Gansu	WD	SD	EC	END	END	END	END	END	WD	RC
Qinghai	END	END	END	END	END	WD	WD	EC	WD	END
Ningxia	END	EC	SD	EC	EC	WD	WD	WD	END	SNC
Xinjiang	END	WD	WD	SD	SD	WD	WD	END	WD	END

From the regional perspective, the change in the number of provinces in a good state varied greatly among the eastern, central, and western regions. In the eastern region, the number of provinces in good state changed in a consistent manner with the trend of the whole country, showing a clear upward trend on the whole. The western region showed a slow upward trend, with a significant fluctuation in 2009–2012. The central region has been relatively stable on the whole, only showing a slight fluctuation. It is worth emphasizing that the number of provinces in a good state in the western region still increased during the financial crisis. We can see that the impact of the financial crisis on the transportation sector in the western region was far weaker than that in the eastern region. This is consistent with the characteristics of China's regional economic development. In China, the eastern coastal region has always been ahead of the central and western regions

in terms of the economic development. Meanwhile, in the eastern coastal region, the scale of international trade and foreign investment has been relatively large, the financial industry has been developing rapidly, and the degrees of marketization and openness to the outside world has been relatively high due to the superiority of its geographic location (Fan et al. 2011; Yang et al. 2018). However, this also means that the industries in the eastern coastal areas have been more vulnerable to the global economic situation than those in central and western regions have been.

To visually describe the spatial-temporal evolution of the decoupling relationship of the various provinces and municipalities, ArcGIS is used to visualize the decoupling relationship in 2006, 2011, and 2015 in Table 5, as shown in Fig. 3. From a combination of Table 5 and Fig. 3, the following can be seen (1) in 2006, the decoupling states mainly were expansive negative decoupling and weak decoupling. There were 12
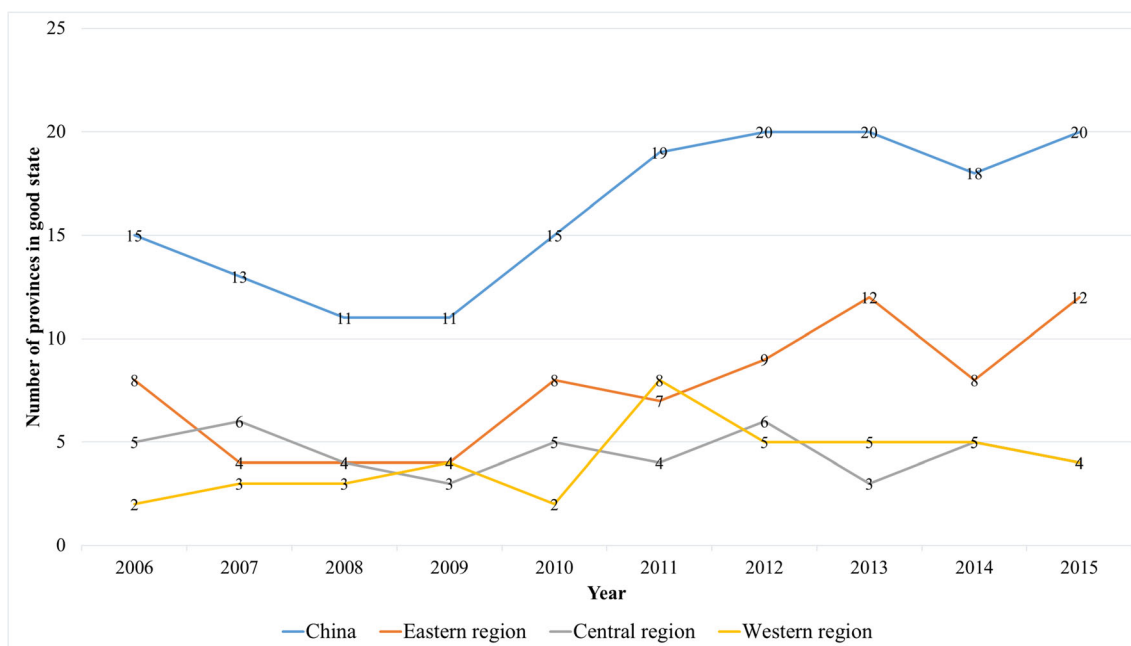
Fig. 2 Changes in the number of provinces in a good state

provinces in expansive negative decoupling states, and most of them were distributed in the western and northern regions, showing a tilted L-shape pattern. Concentrated in the eastern coastal and central regions, 14 provinces were in weak decoupling states. (2) In 2011, the numbers of provinces in weak decoupling states and expansive coupling states increased, and the provinces in expansive coupling states were concentrated in the eastern coastal region. The number of provinces in weak decoupling states increased from 12 in 2006 to 19 in 2011 and they shifted from the central and eastern regions to the western and northern regions, while the provinces in expansive negative decoupling states are concentrated in the central region. The number of provinces in expansive coupling states increased from 3 to 5, and all of them were in the eastern coastal region. (3) In 2015, there was no province in an expansive coupling state and there was an increase in the number of provinces that were in strong decoupling states. Weak decoupling states were evident again in the central and eastern coastal regions. In 2006–2011, the expansive negative decoupling states manifested in the western and northern regions had shifted to the central region, and then to the northwest and northeast regions in 2015. In the early stages, few provinces showed a strong decoupling state, but the number of provinces exhibiting strong decoupling states showed an upward trend. Moreover, although only one province (Hainan) manifested a strong decoupling state in 2006, a strong decoupling state was exhibited by two provinces (Sichuan and Shanghai) in 2011 and five provinces (Sichuan and Yunnan in the southwest, Hebei and Tianjin in the Beijing-Tianjin-Hebei region, and Shaanxi in the northwest) in 2015.

Factor decomposition analysis on transportation carbon emissions

In the above analysis, we have known that, compared with the 11th FYP period, the decoupling state between the transportation carbon emissions and the transportation output during the 12th FYP period showed a significant improvement. Through the definition of the decoupling index (see Eq. (2)), we can know that the improvement of the decoupling states can come from two sources, one is the increase in the transportation output, and the other is the decrease in the transportation carbon emissions. Meanwhile, it can be seen from Table 4 that the decrease in the transportation carbon emissions during the 12th FYP period is more obvious, thus it is the main reason for the improvement of the decoupling state. In order to get a better understanding of the evolution characteristics of the decoupling relationship, it is very necessary to explore and compare the driving factors of the transportation carbon emissions in the 11th and 12th FYP periods.

Next, the LMDI method is applied to decompose the factors affecting the transportation carbon emissions into the carbon emission coefficient, the transportation energy consumption structure, the energy consumption per unit transportation turnover (transportation energy intensity), the transportation turnover per unit output (transportation intensity), the industrial structure, the per-capita wealth, and the population size, according to the Eq. (3). The energy consumption per unit transportation turnover and the transportation turnover per unit
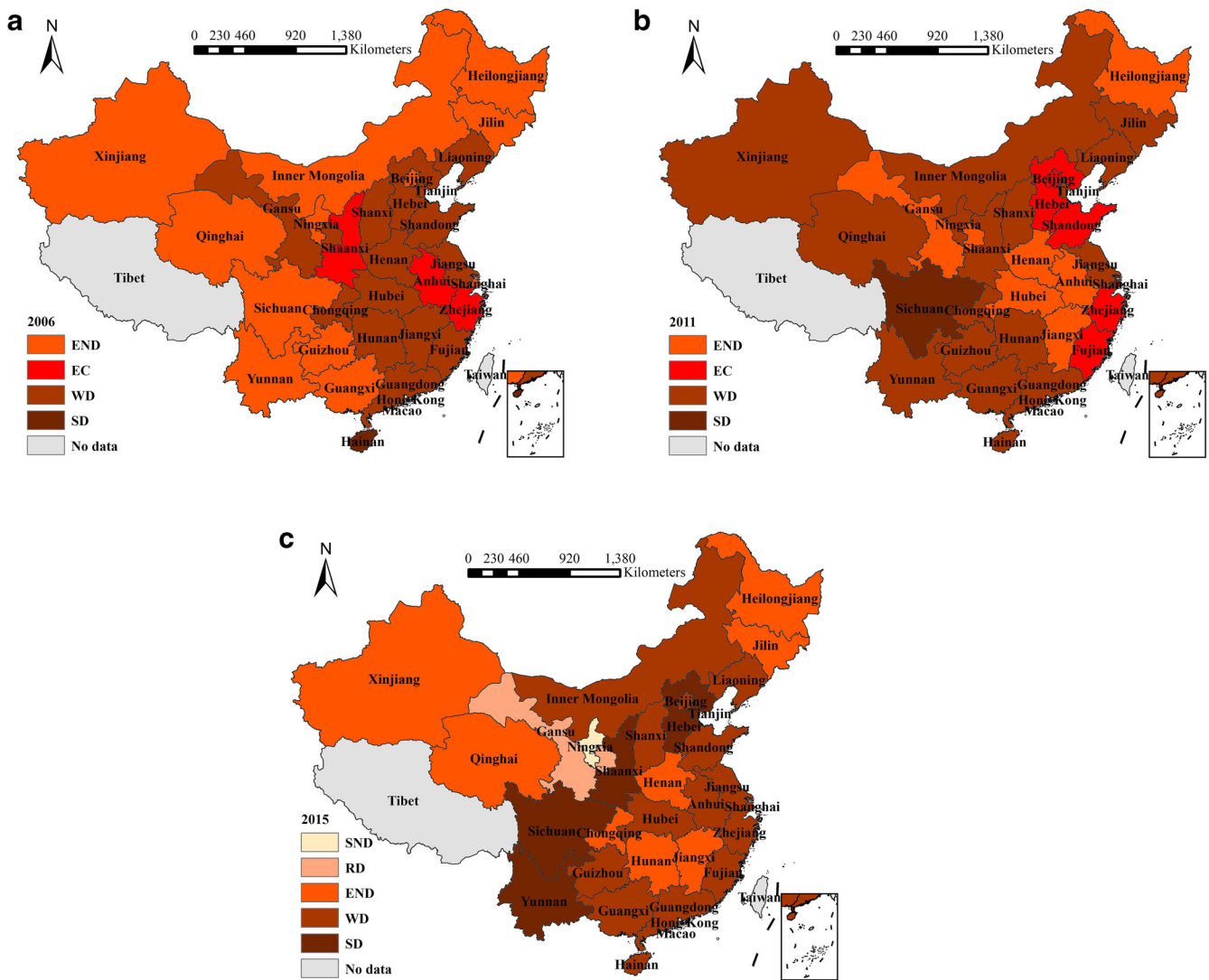
Fig. 3 Spatial distribution of the decoupling states in 2006, 2011 and 2015. **a** Decoupling states in 2006. **b** Decoupling states in 2011. **c** Decoupling states in 2015

output are usually used to measure the energy use efficiency of the transportation sector and the transportation output efficiency, respectively (Zhang and Nian 2013). In addition, no observable changes occur to the carbon emission coefficients of various fuels in the research period. Therefore, the effects of changes in carbon emission coefficients of various fuels are negligible (Tan et al. 2011; Wang et al. 2016; Jiang et al. 2017). Tables 6 and 7 show the specific decomposition results in the 11th and 12th FYP periods, respectively.

Transportation energy structure and industrial structure

The effect of the transportation energy structure on the increase of transportation carbon emissions varies greatly in different provinces and municipalities. The transportation

energy structure mainly plays an inhibitory role in the increase of carbon emissions in China, but its effect is weak. In the 11th FYP period, the optimization of the transportation energy structure reduced the national transportation carbon emissions by 0.193 million tons, accounting for 0.47% of the variation of transportation carbon emissions. Due to the transportation energy structure effect, 15 provinces' carbon emissions increased, meanwhile, the remaining 15 provinces' carbon emissions decreased. In the 12th FYP period, the optimization of the transportation energy structure reduced the national transportation carbon emissions by 1.568 million tons, accounting for 9.03% of the variation of transportation carbon emissions. The number of provinces where the transportation carbon emissions decreased due to the transportation energy structure effect also increased to 23. However, the effect of the transportation energy structure optimization on the reduction of carbon emissions was still relatively weak. The energy

Table 6 Decomposition results in the 11th FYP period

2006–2010	Region	ES	ET	TG	IS	PC	POP	Sum
Shanxi	C	− 6.15	68.87	6.20	14.81	110.63	17.87	212.23
Inner Mongolia	C	− 2.00	− 233.64	223.56	− 39.73	334.27	12.74	295.21
Jilin	C	− 20.29	− 12.20	53.94	− 32.89	113.08	1.82	103.47
Heilongjiang	C	− 7.12	− 111.24	38.86	− 58.12	132.47	0.77	− 4.37
Anhui	C	− 3.95	− 202.26	216.86	− 37.62	120.28	− 5.70	87.61
Jiangxi	C	− 1.06	− 132.00	122.34	− 44.76	102.62	6.05	53.19
Henan	C	5.52	− 212.35	298.58	− 113.69	177.97	0.52	156.56
Hubei	C	12.39	− 294.39	105.27	− 23.67	314.57	3.70	117.87
Hunan	C	1.78	− 73.10	− 15.32	− 16.81	200.23	14.16	110.94
Beijing	E	− 0.21	44.24	14.49	− 65.61	87.72	83.23	163.85
Tianjin	E	− 0.64	97.62	− 146.16	− 27.96	91.68	41.25	55.78
Hebei	E	0.84	− 60.68	− 43.02	16.62	155.62	16.98	86.36
Liaoning	E	7.91	− 432.12	212.72	− 33.31	374.50	18.12	147.81
Shanghai	E	− 6.06	− 93.10	165.02	− 264.85	255.44	161.60	218.05
Jiangsu	E	0.49	− 29.96	− 59.40	21.94	292.31	17.16	242.54
Zhejiang	E	0.97	− 107.37	− 2.57	30.41	196.28	38.92	156.64
Fujian	E	59.83	39.71	30.22	− 46.23	110.02	6.80	200.36
Shandong	E	3.95	− 429.88	127.76	26.88	547.10	36.09	311.90
Guangdong	E	− 11.28	− 24.51	− 17.93	− 113.83	426.30	123.65	382.40
Guangxi	E	− 20.44	− 164.80	119.03	− 19.24	188.27	− 8.04	94.79
Hainan	E	3.23	30.35	9.46	− 20.22	56.13	4.67	83.62
Chongqing	W	0.07	−98.89	115.78	− 42.11	135.46	6.63	116.95
Sichaun	W	− 34.42	− 45.31	155.07	− 136.55	228.10	− 6.57	160.32
Guizhou	W	− 1.15	54.75	− 44.83	20.40	106.47	− 11.78	123.86
Yunnan	W	5.75	− 4.65	− 57.53	2.17	171.34	10.69	127.76
Shaanxi	W	− 13.88	− 3.66	113.47	− 63.49	178.34	3.13	213.91
Gansu	W	1.97	− 43.58	50.39	− 39.86	63.16	0.77	32.85
Qinghai	W	1.12	1.20	25.86	− 6.11	17.88	1.04	40.99
Ningxia	W	− 1.39	− 64.26	56.59	− 14.95	32.41	3.53	11.93
Xinjiang	W	4.86	− 124.58	30.31	− 31.19	93.29	17.79	− 9.52
Total	–	− 19.34	− 2661.79	1905.04	− 1159.58	5413.93	617.60	4095.86

In Tables 6 and 7, C, E, and W indicate the central region, eastern region, and western region, respectively. ES, ET, TG, IS, PC, and POP represent the transportation energy structure effect, transportation energy intensity effect, transportation intensity effect, industrial structure effect, per-capita wealth effect, and population size effect, respectively

consumption structure of China's transportation sector has not been rationalized for a long time, and the petroleum energy products, such as gasoline, kerosene, and diesel oil, occupy a large absolute proportion (Yu et al. 2015). Furthermore, the optimization process of the transportation energy structure is very slow due to the constraints on resource endowments and technology (Fan and Lei 2016). Therefore, the transportation energy structure effect is very limited for reducing carbon emissions. However, it should also be noted that the transportation energy structure effect had significantly improved in the 12th FYP period compared with that in the 11th FYP period. In particular, governments have vigorously promoted the use

of green and clean energies, such as natural gas, in recent years (Fig. 4), which has accelerated the optimization of the transportation energy structure and further enhanced the inhibitory effect on carbon emissions.

Then, we analyze the industrial structure effect. Because this paper focuses on China's transportation sector, we measure the industrial structure by the proportion of the added value of the transportation sector to the GDP. The LMDI decomposition results (Tables 6 and 7) show that the adjustment of the industrial structure has inhibited the transportation carbon emissions as a whole. Specifically, due to the industrial structure effect, transportation carbon emission decreased by

Table 7 Decomposition results in the 12th FYP period

2011–2015	Region	ES	ET	TG	IS	PC	POP	Sum
Shanxi	C	− 1.21	11.80	− 105.07	33.70	115.87	9.44	64.54
Inner Mongolia	C	45.00	21.83	− 351.33	− 50.11	228.54	7.98	− 98.08
Jilin	C	19.28	62.55	− 65.37	− 38.90	100.98	0.47	79.00
Heilongjiang	C	− 3.60	259.94	− 259.43	− 28.81	167.33	− 3.34	132.09
Anhui	C	− 7.89	151.73	− 6.54	− 69.23	150.74	12.32	231.14
Jiangxi	C	1.00	51.75	1.94	− 57.72	116.67	5.54	119.17
Henan	C	− 51.03	311.98	− 241.17	− 69.39	200.44	5.79	156.62
Hubei	C	− 62.18	− 284.94	− 14.20	14.30	285.97	12.69	− 48.37
Hunan	C	17.13	133.59	− 76.31	− 69.95	212.10	17.06	233.61
Beijing	E	− 0.70	127.71	− 176.19	− 25.80	121.60	41.45	88.06
Tianjin	E	− 3.40	302.46	− 414.79	− 15.49	71.81	31.85	− 27.55
Hebei	E	− 1.16	− 142.57	− 69.31	29.58	129.40	11.84	− 42.22
Liaoning	E	− 1.68	− 5.91	− 197.98	60.38	248.87	− 0.22	103.47
Shanghai	E	− 6.76	119.95	− 287.39	− 72.69	283.72	32.12	68.95
Jiangsu	E	− 1.98	98.88	− 179.85	17.36	325.00	9.19	268.59
Zhejiang	E	1.00	20.80	− 167.36	43.53	216.75	10.25	124.97
Fujian	E	− 6.09	− 125.81	33.93	4.96	180.63	15.74	103.35
Shandong	E	− 11.06	− 2.52	− 928.84	18.60	409.45	27.24	− 487.12
Guangdong	E	11.61	− 1035.35	547.91	95.99	437.53	50.31	107.99
Guangxi	E	− 52.37	− 25.83	− 28.35	− 61.53	148.55	14.33	− 5.22
Hainan	E	− 0.09	8.55	− 86.73	4.75	51.38	6.51	− 15.63
Chongqing	W	− 5.38	128.04	− 105.19	− 50.33	173.41	13.69	154.24
Sichaun	W	− 1.73	− 26.31	− 111.33	− 4.19	177.61	9.54	43.60
Guizhou	W	− 7.33	26.07	− 67.58	− 4.57	148.38	5.99	100.96
Yunnan	W	− 1.27	− 134.98	− 15.59	− 7.76	202.43	12.82	55.65
Shaanxi	W	− 20.90	− 156.78	− 43.29	− 72.44	171.36	5.97	− 116.09
Gansu	W	− 4.99	72.60	6.27	− 75.34	83.15	3.13	84.83
Qinghai	W	− 1.50	20.29	− 17.38	− 14.30	26.60	2.62	16.34
Ningxia	W	4.88	29.49	− 21.46	− 22.06	28.53	4.06	23.44
Xinjiang	W	− 2.44	146.95	− 172.78	85.03	132.17	26.38	215.31
Total		− 156.84	165.96	− 3620.74	− 402.44	5346.98	402.74	1735.66

11.596 million tons and 4.024 million tons in the 11th and 12th FYP periods, respectively. From the numerical point of view, in the 12th FYP period, the carbon emission reduction effect of the industrial structure declined significantly because the adjustment speed of the industrial structure has changed. In the twenty-first century, China's economy has maintained a rapid growth but also has been confronted with a challenge of economic transformation and upgrading. During this process, in most provinces, the proportion of other service industries in the national economy has increased significantly, but the proportion of the transportation sector in most provinces has decreased. By the 12th FYP period, after a period of decline, in most provinces, the proportion of the transportation output in the provincial GDP had stabilized. It could be reduced by a small margin and would not fall further, which resulted in the decline rates of the proportion in most provinces were smaller than those in the 11th FYP period. Therefore, the carbon emission reduction effect of the industrial structure had also declined. This phenomenon is particularly evident in the eastern coastal region where economic and scientific levels are highly advanced. Because the adjustment of the proportion of the transportation sector to the national economy in the eastern coastal region was quite limited, the industrial structure effect increased transportation carbon emissions in eight eastern provinces in the 12th FYP period but increased the transportation carbon emissions in four provinces in the 11th FYP period. However, in general, the industrial structure effect has played an important role in the reduction of transportation carbon emissions, whether in the 11th or the 12th FYP periods. The absolute values of the industrial structure effect accounted for 28.3% and 23.2% of the total carbon emission variation in the 11th and 12th FYP periods, respectively.
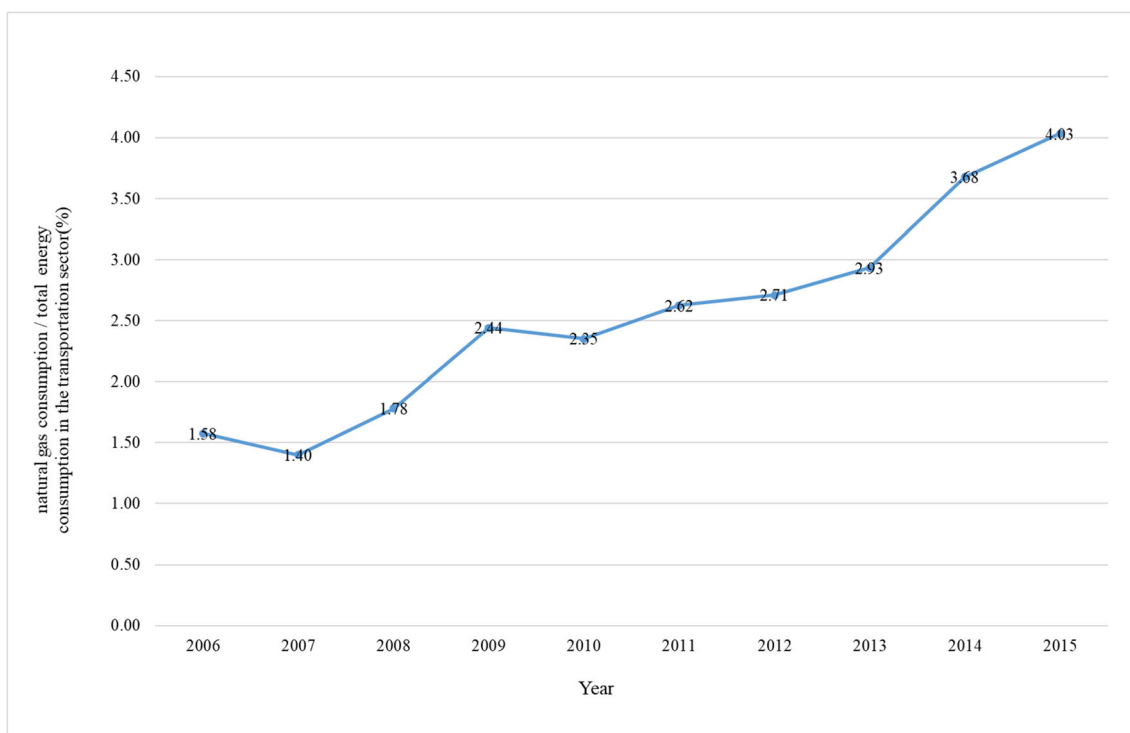
Fig. 4 The proportion of natural gas to total transportation energy consumption in China in 2006–2015

Transportation energy intensity and transportation intensity

In this paper, the energy consumption per unit transportation turnover (transportation energy intensity) and the transportation turnover per unit output (transportation intensity) are used to measure the transportation energy use efficiency and the transportation output efficiency, respectively. In the 11th FYP period, in 23 provinces, carbon emissions were reduced by a total of 26.618 million tons due to the overall improvement in transportation energy use efficiency caused by the transportation energy intensity effect. This is the main factor in curbing the increase of transportation carbon emissions. Liaoning had the largest emission reduction effect, with a reduction of 4.321 million tons of carbon emissions, while Tianjin increased carbon emissions by 0.976 million tons, due to the transportation energy intensity effect. This indicates that the transportation energy intensity effect varied greatly in the eastern provinces in the 11th FYP period. In the 12th FYP period, many provinces' energy consumption per unit transportation turnover failed to continue a downward trend, indicating that their energy intensities were dramatically changed, eventually resulting in an increase of 1.66 million tons of carbon emissions. Although the increase occupied a low percentage of the absolute value of the total carbon emission variation, we should note that Guangdong reduced 10.354 million tons of carbon emissions due to the significant negative energy intensity effect. Excluding Guangdong, the

positive energy intensity effect resulted in an increase of more than 12 million tons of carbon emissions in the 12th FYP period. This fully demonstrates the importance and necessity of improving energy use efficiency, especially after taking the transportation energy intensity effect into account in the 11th Five-Year period.

In the 11th FYP period, the transportation intensity effect led to an increase of 19.5 million tons of carbon emissions. It was the second largest factor leading to the increase of transportation carbon emissions, following the per-capita wealth effect. The increase of 19.05 million tons accounted for 46.5% of the total carbon emission variation. In the central and western regions, the positive transportation intensity effect led to an increase in carbon emissions, except for Hunan, Guizhou, and Yunnan. Therefore, the transportation intensities in these two regions did not significantly decline in the 11th FYP period. In the 12th FYP period, the transportation intensity effect became the decisive factor for the decrease of transportation carbon emissions. Compared with those in the 11th FYP period, the transportation intensities of most provinces declined significantly in the 12th FYP period, achieving a reduction of 36.207 million tons of carbon emissions. The reduction accounted for 208.6% of the total carbon emission variation.

In the 11th FYP period, although the national energy intensity declined, the transportation intensities of most provinces, especially in the central and western regions actually increased. In the 12th FYP period, the transportation intensities

of most provinces declined significantly, but their energy intensities increased. This indicates that efforts must be made both in transportation energy intensity and transportation intensity and to further reduce the transportation carbon emissions, measures should be taken to avoid the imbalanced development among regions.

Per-capita wealth

Consistent with the findings by many scholars (Wang et al. 2011; Fan and Lei 2016), the empirical results in this paper also indicate that the growth of per-capita wealth is the decisive factor leading to the increase of transportation carbon emissions. The results in Table 6 and 7 show that due to the per-capita wealth effect, the transportation carbon emissions increased by 54.139 million tons, which accounts for 132.2% of the total variations in transportation carbon emissions in the 11th FYP period. In the 12th FYP period, the increase of transportation carbon emissions caused by the per-capita wealth effect did not change greatly, maintaining a level of 53.47 million tons. Because the Chinese government stepped up efforts to protect the environment and developed a series of policies to save energy and reduce carbon emissions, the total increase of transportation carbon emissions decreased from 40.959 million tons in the 11th Five-Year period to 17.357 million tons in the 12th FYP period. Therefore, the increase of carbon emissions caused by the per-capita wealth effect is 3.08 times the total carbon emissions variation.

Generally, the increase of transportation carbon emissions caused by per-capita wealth growth in the eastern region far exceeds that in the western region. In the 11th FYP period, Shandong, Guangdong, and Liaoning had the highest per-capita wealth effects, increasing carbon emissions by 5.471 million, 4.263 million, and 3.745 million tons, respectively. The three provinces cumulatively contributed 25.2% to the total per-capita wealth effects. Qinghai, Ningxia, and Hainan had the lowest per-capita wealth effects, increasing carbon emissions by 0.179 million, 0.324 million, and 0.561 million tons, respectively. The three provinces only cumulatively contributed 1.97% to the total per-capita wealth effects. In the 12th FYP period, Guangdong, Shandong, and Jiangsu had the highest per-capita wealth effects, increasing carbon emissions by 4.375 million, 4.095 million, and 3.25 million tons, respectively. The three provinces cumulatively contributed 21.9% to the total per-capita wealth effects. Qinghai, Ningxia, and Hainan had the lowest per-capita wealth effects, increasing carbon emissions by 0.266 million, 0.285 million, and 0.514 million tons, respectively. The three provinces only cumulatively contributed 2% to the total per-capita wealth effects.

Whether measured in the 11th FYP period or in the 12th FYP period, the provincial-level economy has been growing continuously and people's living level has improved gradually, changing people's lifestyles significantly. The large-scale freight transportation, the increase in private cars, and people's increasingly frequent travel undoubtedly have led to a significant increase of transportation carbon emissions. The increase of transportation carbon emissions caused by the per-capita wealth effect in the 11th FYP period is quite close to that in the 12th FYP period. This means that although the measures for environmental protection, energy saving, and emission reduction taken by the Chinese government have significantly impeded the increase of carbon emissions in the 12th FYP period, the decoupling relationship between economic growth and transportation carbon emissions has not improved significantly. There is still a high positive correlation between them.

Population size

The population size effect is an important factor for the increase of transportation carbon emissions. The increase in population will increase carbon emissions from social life activities. Tables 6 and 7 show that the increase of transportation carbon emissions due to the change of the population size was 6.176 million tons in the 11th FYP period, accounting for 15.1% of the total carbon emission variation. Although the carbon emissions decreased to 4.027 million tons in the 12th FYP period, the share due to the change in the population increased to 23.2%. Although the population size effect led to an increase of transportation carbon emissions in the two periods, the amount is still much less compared with the amount attributable to the per-capita wealth effect. This is because although China has a large population size, the population growth rate has declined significantly since the implementation of the one-child policy. The low birth rate inevitably determines that the population size effect will not be the decisive factor in the increase of transportation carbon emissions.

From Tables 6 and 7, we can find an interesting phenomenon. The population size effect in the eastern region is greater than that in the central and western regions as a whole. Particularly, in both the 11th and 12th FYP periods, the top three provinces with the highest increase in carbon emissions caused by the population size effect were Shanghai, Guangdong, and Beijing. This may have a close relationship with the characteristics of China's population migration. Although the population growth rate is not very high in the eastern coastal region of China, a large number of people migrate from the central and western regions to the eastern coastal region for employment. As a consequence, the eastern coastal region, especially the economically developed provinces, such as Beijing, Shanghai, and Guangdong, has always been the net labor force inflow region (Luo et al. 2016). The large inflows of the labor force have increased the population size in the eastern coastal region, resulting in an increase in transportation carbon emissions.

Conclusions and policy implication

Conclusions

In this paper, the energy consumption data of the transportation sector from 2005 to 2015 is used to calculate the decoupling indexes of the transportation output and the transportation carbon emissions of China's 30 provinces and municipalities. Then, the spatial-temporal evolution of the decoupling states in the 11th and 12th FYP periods is analyzed comparatively. Moreover, in order to further analyze the reasons for the evolution of the decoupling states during the 12th FYP period compared with the 11th FYP period, the LMDI model is employed to decompose and compare the factors driving transportation carbon emissions in the two periods. The main conclusions are as follows:

(1) In the 11th and 12th FYP periods, the national-level decoupling state was dominated by expansive coupling and weak decoupling, respectively, and the decoupling relationship improved gradually. From the provincial-level perspective, the decoupling indexes of most provinces in the 12th FYP period declined by comparison with those in the 11th FYP period. However, few central and western provinces showed a sharp rise in the decoupling index.

(2) In this paper, a weak decoupling state and a strong decoupling state are defined as good states. In 2006–2015, the number of provinces in a good state generally showed an upward trend. Moreover, the trend in the number of provinces in a good state varied significantly among the eastern, central, and western regions.

(3) In 2006–2015, the decoupling states at the provincial level were mainly the expansive negative decoupling and weak decoupling states. The number of provinces in expansive negative decoupling state was on a downward trend, and this state shifted from the western and northern regions to the central region, and then diverged from the central region to the northwestern and northeastern regions; The weak decoupling state evolved from the eastern and central regions to the western and northern regions, and then returned to the eastern coastal region. Moreover, the number of provinces in a strong decoupling state also showed an upward trend. By 2015, a total of five provinces were in a strong decoupling state and they were mainly located in the southwestern and Beijing-Tianjin-Hebei regions.

(4) In the 11th FYP period, the transportation energy structure, the transportation energy intensity, and the industrial structure had an inhibitory effect on transportation carbon emissions, of which the transportation energy intensity had the strongest inhibitory effect; transportation intensity, per-capita wealth, and population size played a catalytic role, of which the per-capita wealth was the decisive factor. In the 12th FYP period, the transportation energy structure, the transportation intensity, and the industrial structure had an inhibitory effect on transportation carbon emissions, of which the transportation intensity had the strongest inhibitory effect; transportation energy intensity, per-capita wealth, and population size played a catalytic role, of which the per-capita wealth was the decisive factor.

(5) The increase of transportation carbon emissions in the 12th FYP period dropped significantly in comparison with that in the 11th FYP period. The transportation intensity effect was the decisive factor for the significant decrease in total carbon emission variation in the 12th FYP period. Moreover, at present, China's transportation intensity and transportation energy intensity are not declining simultaneously.

Policy implication

Based on the above conclusions, this paper proposes the following policy suggestions:

(1) To avoid unbalanced development, differentiated emission reduction measures should be taken to improve the decoupling relationship of different provinces and municipalities simultaneously. This differentiated policy is mainly reflected in the degree of economic development and the completeness of transportation infrastructure. In areas with low economic development and underdeveloped transportation infrastructure, in order to promote economic development, more energy consumption and pollution emissions are not subject to legal constraints. Hence, the government should adopt more administrative control measures to reduce carbon emissions from transportation. On the one hand, it should complete local traffic control laws and regulations, limiting the continuous increase in total carbon emissions. For example, the quota for the sale of private cars will be set, and the minimum utilization index of new energy vehicles will be stipulated. On the other hand, the construction of transportation infrastructure should be strengthened, the bicycle rental system should be built and improved, and more fiscal revenues could be used to invest in the construction of bus lanes to speed up the track. For regions with high levels of economic development, perfect infrastructure, and better population quality and human capital, more encouragement and guidance policies are

needed. For example, more leaflets, advertisements, and other measures are taken to promote the use of energy-saving and emission-reducing vehicles, to cultivate low-carbon awareness among residents, and to set up special funds for low-carbon transportation development.

(2) The R&D investment in energy-saving technologies related to transportation should be increased to simultaneously decrease the transportation energy intensity and transportation intensity. The development of new energy-saving technologies mainly depends on the government's reasonable incentives and support policies, as well as the improvement of the technical level of R&D institutions. For policy implementers, first, the government should set up special financial subsidies to provide financial support for scientific research departments or enterprises that research and develop new technologies and create a favorable policy environment for creating sophisticated technologies; second, strengthen the technology for low-carbon transportation. The protection of intellectual property rights provides a reasonable profit margin for technology developers. In this respect, it is necessary to improve the reporting channels for patent technologies, simplify administrative approval procedures, and improve patent protection related bills. For technology creators, on the one hand, development of composite materials should be carried out to improve the level of technological research; on the other hand, starting from the transportation tools themselves, more popularization and manufacturing of clean energy vehicles and charging buses could be adopted.

(3) The proportion of new energy should be increased to optimize the transportation energy structure. The optimization of the transportation energy structure can restrain the increase of transportation carbon emissions to a certain extent, indicating that governments at all levels should also take measures to optimize the transportation energy structure (for example, accelerate the implementation of China's "coal to gas" policy, strengthen the resource tax reform, and realize the transition from the specific tax to ad valorem tax excessive). The energy products used in China's transportation sector have long been dominated by petroleum products, such as gasoline, kerosene, and diesel oil. Moreover, the optimization process of the energy structure is very slow, which has seriously hindered the reduction of transportation carbon emissions. Therefore, governments at all levels should gradually promote the use of new energy sources, such as electricity and natural gas, as well as increase the R&D investment in clean energy technologies (such as solar energy, biomass energy), allowing these technologies to be widely applied in the transportation sector. In addition, the Chinese governments should adopt subsidy policies to encourage people to use new energy vehicles.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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