Impacts of Regional Development on Emissions in China's Transport Sector

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Impacts of Regional Development on Emissions in China's Transport Sector

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Abstract

In recent years, China has repeatedly stated that CO_2 emissions should reach a peak by 2030 and be carbon neutral by 2060. China’s transport sector is playing an important role in meeting China’s targets, as the emissions of CO_2 from it grow steadily. We apply the LMDI to analyze the impact of regional development patterns on emissions in China’s transport sector. Based on the Kaya identity, eight factors (including carbon intensity, energy structure, energy intensity, turnover intensity, traffic intensity, regional structure, per capita traffic activity and population size) are decomposed. The period 1997-2017 is divided into four phases according to the growth rate of carbon emissions. The driving factors of CO_2 emission characteristic were varied by periods. The degree of driving factors’ influence also varies by region. The change in output growth rate of the regional transport sector is positively correlated with the change in the share of output value added, which is positively correlated with the change in emissions.

Keywords: CO_2 emissions; LMDI; Transport sector; Regional development; Regional structure; Driving factors

1. Introduction

Climate change and global warming have attracted more and more attention and become a serious challenge for many countries. Rising concentrations of greenhouse gases in the atmosphere are a major cause of global climate change. In order to curb the trend of global warming, the seventh World Government Summit, held in Dubai in February 2019, called for a more sustainable and inclusive “Globalization 4.0” to address the risks and challenges ahead. As the world’s largest carbon emitter, China’s rapid growth in carbon emissions over the past 40 years has attracted global attention (Guo et al., 2018). From the General Debate of the UN General Assembly at its seventy-five session in September 2020 to the Climate Ambition Summit in December 2020, China has repeatedly stated its goal of reaching a peak in carbon emissions by 2030, carbon neutral by 2060 (Li et al., 2021). The 2020 Central Economic Work Conference (CEWC) also identified achieving peak carbon and carbon neutrality as one of the eight key tasks of the 2021 (Liu et al., 2021).

Under the severe background of carbon emission reduction in China, the responsibility of emission reduction should be divided into industries and regions. Transport is an important sector for the emission reduction in China. According to the China Automotive Industry Development Report (2020), from 2005 to 2017, CO_2 emissions from China's transport sector maintained a steady growth trend, rising from 8% to 10%. With the acceleration of emissions in China from 349.00 Mt in 2005 to 723.87 Mt in 2017, analyzing emissions from China's transport is necessary for reducing the total emissions in China.

At present, the research methods of drivers of carbon emissions mainly focus on the decomposition analysis and regression analysis. For example, Timilsina & Shrestha (2009) found that energy intensity, per capita GDP, energy mix, population growth and carbon efficiency were the main factors that affect transport carbon emissions in 20 countries in Asia and Latin America. V.Andreoni's analysis (2012) of the main determinants of carbon emissions from European shipping and air transport in 2001-2008 shows that economic growth was the most important driver. Li (2016) used the LMDI to analyze the impact factors of carbon emissions in China's transport sector. The results show that income was the leading factor of the increase in the emissions in transport sector, and energy intensity was the main inhibiting factor of carbon emissions. Using the STRIPATA model, Gao et al. (2014) calculated the elastic coefficients of the driving factors such as population, GDP per capita, energy consumption per GDP, transport investment and the number of private cars. Liang et al. (2018) analyzed Beijing data from 1900 to 2016 by selecting seven driving factors, including passenger mileage, freight mileage and total vehicle volume. Using STIRPAT model and ridge regression method, Dong et al. (2017) analyzed the factors affecting the growth of carbon emission from transport sector in Xinjiang and found that the carbon emissions of transport sector in Xinjiang mainly came from the consumption of diesel and gasoline, and the population density played a leading role in the growth of carbon emissions.

However, in the study of transport sector carbon emissions, most of the literature ignored the regional differences in development patterns. China has a vast territory. There is a big gap in the development of various regions, and the level of development of the transport industry is unbalanced. Therefore, studying the driving factors of transport emissions from the perspective of regional development model is of great significance to the implementation of emission reduction responsibilities in the transport sector. In this case, through the regional analysis of carbon emissions in China's transport sector from 1997 to 2017, the LMDI model is used to study the regional differences in CO_2 emissions in order to fill these gaps.

2. Literature Review

Some scholars studied the CO_2 emissions from the transport sector from the national perspective. Lakshmanan and Han (1997) analyzed energy consumption and CO_2 emissions in the U.S. transport sector from 1970 to 1991 and found that GDP, population, and propensity to travel were the most important drivers of energy consumption and emissions. Lopez et al. (2018) considered the availability and limitations of data in developing countries, using population, transport activities, energy intensity, fuel structure and emission intensity as driving factors. The results showed that the most important emission reduction factor was transport activity. Saeed Solaymani (2019) analyzed the carbon emissions of seven major transport-sector CO_2 emitting countries, showing that in most countries the main inhibiting contributor of CO_2 emissions was carbon intensity, while the main drivers of the increase in CO_2 emissions were the electricity structure and economic output.

In addition, many researchers explored the drivers of CO_2 emissions from the China's transport sector. Liang et al. (2017) quantitatively analyzed the effects of energy structure, energy efficiency, transport patterns, transport development, economic development and population size from 2001 to 2014. Li (2016) found that the income led to the increase in carbon emissions, while the energy intensity effect caused the decrease in carbon emissions. The changes of traffic mode, traffic intensity and population had positive effects on the emissions of transport sector, but the effect was relatively small. Feng et al. (2020) considered two new factors, namely spatial pattern and age structure, and found that their effects were relatively small.

However, because of China's vast territory and different regional development, some scholars have analyzed the factors that affect the carbon emissions in specific regions. Dong et al. (2017) used the LMDI to identify driving factors of CO_2 emissions in Xinjiang's transport sector from 1990 to 2014. The results show that economic growth, population size, industrial structure, internal structure and energy structure can promote the increase of CO_2 emission. Guo and Meng (2019) studied Beijing-Tianjin-Hebei as representative of China's developed regions. The results show that transport energy intensity and economic effect were the main factors for the increase of CO_2 emissions, while energy structure, turnover of goods per unit of industrial output and industrialization were the main factors for the reduction. Gu et al. (2019) used the extended LMDI model and the system dynamics (SD) model to explore the determinants of CO_2 emissions in Shanghai from 1995 to 2016. They considered new factors such as car ownership, the structure of the city's tourism, and income levels and concluded that GDP per capita was the main positive driver of the increase in CO_2 emissions.

Moreover, some scholars studied the regional differences in emissions in China. Zhang and Nian (2013) used STIRPAT model and provincial panel data to study CO_2 emissions from China's transport sector at the national and regional perspectives between 1995 and 2010. The results showed that passenger transport dominates CO_2 emissions from transport sector, and its impact declines from west to east. Luo et al. (2016) analyzed regional differences in CO_2 emissions from freight transport in China and used the Gini coefficient to analyze inequality in regional economic development. The results show that economic structure is the key driver of the change in emissions. Significant regional differences and inequalities in freight transport emissions were revealed. Xu and Lin (2016) used panel data model to analyze the regional differences and driving factors of China's transport CO_2 emissions, and found that different investment and management efficiencies led to different degree of emission reductions from energy efficiency improvements in the eastern, central and western regions. Later, they used quantile regression model (2018) to discuss the main drivers of CO_2 emission differences at high, medium and low development levels. Liu et al. (2017) used a non-radial DEA model to measure the CO_2 emission efficiency of land transport and found that eastern China has the highest environmental efficiency, followed by central and western China. Yang and Ma (2019) have decomposed and decoupled the CO_2 emissions model of China's international maritime transport. They revealed that economic growth was the main driving factor for the increase of CO_2 emissions, while the overall effect of energy intensity and commodity structure played an important role in the reduction of CO_2 emissions.

In summary, the available literature has discussed the drivers of China's CO_2 emissions in detail, but limitations remain. Firstly, the impact of regional development patterns on transport emissions have not been fully discussed. Secondly, the LMDI method has not been used effectively to analyze the regional differences of specific driving factors. Therefore, based on the LMDI, we decompose CO_2 emissions into 7 driving factors. particularly we analyze the impact of regional development pattern on transport emissions in China. Moreover, we focus the regional differences in the contributions of 7 driving factors in China, such that different emission reduction strategies are formulated based on different driving mechanisms of carbon emissions in different regions.

3. Methods and data

3.1. LMDI

In this paper, we use the extended Kaya equation to decompose the CO_2 emissions of China's regional transport sector (C^t) as follows:

$$\begin{aligned} C^t &= \sum_i \sum_r \frac{C_{ir}}{E_{ir}} \times \frac{E_{ir}}{E_r} \times \frac{E_r}{CT_r} \times \frac{CT_r}{IV_r} \times \frac{IV_r}{Y_r} \times \frac{Y_r}{Y} \times \frac{Y}{P} \times P \\ &= \sum_i \sum_r COE_{ir} \times ES_{ir} \times EI_r \times CI_r \times TI_r \times RS_r \times TA \times P \end{aligned} \tag{1}$$

where, C_{ir} is the CO_2 emissions of the transport sector in province r by fuel type i, E_{ir} is the energy consumption of the transport sector in province r by fuel type i, CT_r is the transport turnover of province r, IV_r is the transport mileage of province r, which represents investments in transport; Y_r stands for the increase in output of r's transport sector; and P is the total population.

Thus, based on Eq. (1), C^t is represented by seven factors, as follows:

(1) $COE = \frac{C_{ir}}{E_{ir}}$ is the carbon intensity factor of fuel type i in province r, that is, the carbon emission coefficient of various transport energy;

(2) $ES = \frac{E_{ir}}{E_r}$ is the energy structure factor of province r, which represents the proportion of each energy source in the total energy consumption of transport sector;

(3) $EI = \frac{E_r}{CT_r}$ is the energy intensity of province r, which represents the energy consumption per unit turnover;

(4) $CI = \frac{CT_r}{IV_r}$ is the turnover intensity of province r, indicating the turnover amount per unit mileage;

(5) $TI = \frac{IV_r}{Y_r}$ is the transport intensity of province r, i.e. the ratio of mileage to the added value of transport sector's output;

(6) $RS_r = \frac{Y_r}{Y}$ is the regional structure of province r, which represents the share of the added value of transport sector in the country.

(7) $TA = \frac{Y}{P}$ is a per capita transport activity, that is, the added value of per capita output of transport sector;

(8) P is the population.

The formula is decomposed by LMDI method, and the difference between base period and T period is called total effect $\Delta C = C^t - C^{t-1}$.

$$\begin{aligned} \Delta C^t &= C^t - C^{t-1} \\ &= \Delta C^t_{COE} + \Delta C^t_{ES} + \Delta C^t_{EI} + \Delta C^t_{CI} + \Delta C^t_{TI} + \Delta C^t_{RS} + \Delta C^t_{TA} + \Delta C^t_{P} \end{aligned} \quad (2)$$

where, ΔC^t_{COE}, ΔC^t_{ES}, ΔC^t_{EI}, ΔC^t_{CI}, ΔC^t_{TI}, ΔC^t_{TA} and ΔC^t_{P} denote respectively the effects of carbon intensity, energy structure, energy intensity, turnover intensity, traffic intensity, per capita traffic activity and population size. The effects can be decomposed year by year as follows:

$$\Delta C^t_{COE} = \sum \frac{C^t_{ir} - C^{t-1}_{ir}}{\ln(C^t_{ir} - C^{t-1}_{ir})} \times \ln(\frac{COE^t}{COE^{t-1}}) \quad (3)$$

$$\Delta C^t_{ES} = \sum \frac{C^t_{ir} - C^{t-1}_{ir}}{\ln(C^t_{ir} - C^{t-1}_{ir})} \times \ln(\frac{ES^t}{ES^{t-1}}) \quad (4)$$

$$\Delta C^t_{EI} = \sum \frac{C^t_{ir} - C^{t-1}_{ir}}{\ln(C^t_{ir} - C^{t-1}_{ir})} \times \ln(\frac{EI^t}{EI^{t-1}}) \quad (5)$$

$$\Delta C^t_{CI} = \sum \frac{C^t_{ir} - C^{t-1}_{ir}}{\ln(C^t_{ir} - C^{t-1}_{ir})} \times \ln(\frac{CI^t}{CI^{t-1}}) \quad (6)$$

$$\Delta C^t_{TI} = \sum \frac{C^t_{ir} - C^{t-1}_{ir}}{\ln(C^t_{ir} - C^{t-1}_{ir})} \times \ln(\frac{TI^t}{TI^{t-1}}) \quad (7)$$

$$\Delta C_{RS}^{t}=\sum\frac{C_{ir}^{t}-C_{ir}^{t-1}}{\ln(C_{ir}^{t}-C_{ir}^{t-1})}\times\ln(\frac{RS^{t}}{RS^{t-1}}) \tag{8}$$

$$\Delta C_{TA}^{t}=\sum\frac{C_{ir}^{t}-C_{ir}^{t-1}}{\ln(C_{ir}^{t}-C_{ir}^{t-1})}\times\ln(\frac{TA^{t}}{TA^{t-1}}) \tag{9}$$

$$\Delta C_{P}^{t}=\sum\frac{C_{ir}^{t}-C_{ir}^{t-1}}{\ln(C_{ir}^{t}-C_{ir}^{t-1})}\times\ln(\frac{P^{t}}{P^{t-1}}) \tag{10}$$

3.2. Data sources

We conducted in 30 provinces from 1997 to 2017, excluding Tibet, Hong Kong, Macau and Taiwan. The 30 provinces are divided into eight Chinese regions (Feng et al., 2013), including Beijing-Tianjin (Beijing and Tianjin), North (Hebei and Shandong), Northeast (Liaoning, Jilin and Heilongjiang), Central Coast (Shanghai, Jiangsu and Zhejiang), Central (Shanxi, Anhui, Jiangxi, Henan, Hubei and Hunan), South Coast (Fujian, Guangdong and Hainan), Southwest (Guangxi, Chongqing, Sichuan, Guizhou and Yunnan) and Northwest (Inner Mongolia, Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang).

China Emission Accounts and Datasets (CEADs) is the source of energy consumption and carbon emission data for the provincial (municipal) transport sectors used in this paper. The CEADs database was developed by NSF, the Chinese Academy of Sciences, and other research institutions. Its data is based on peer-reviewed academic studies, all of which are fully developed and available (Liu, et al., 2015). These data are consistent with national greenhouse gas inventories and previous studies (Guan, et al., 2012; Shan, et al., 2016). The reference coefficients of energy conversion standard coal are obtained from China Energy Statistics Yearbook. The data of carbon emission coefficient are from China Statistical Yearbook and 2006 IPCC Guidelines for national greenhouse gas inventories. Data on drivers of carbon emissions in the transport sector, including passenger turnover, mileage, transport output and population, are from China Statistical Yearbook.

4. Results

4.1. Changes of CO_2 emissions from China's transport sector

In the 20 years from 1997 to 2017, China's CO_2 emissions in the transport sector rose 546%, from 107.2Mt to 705.38Mt (Fig.1). From 1997 to 2005, China's transport sector experienced a quick increase in total CO_2 emissions. Growth in emissions were, on average, 15.49% per year during 1997-2005, decreasing 8.80% per year between 2005 and 2012. These trends mirror the evolution of the Chinese transport sector during this time period: growth of the Chinese GDP from transport sector accelerated, reaching an average GDP growth of over 10.16% per year between 1997 and 2005 (NBS, 2006). The high growth rate of Chinese GDP from transport sector led to a rise in CO_2 emissions as fast transport development increased investment in building transport networks, driving the energy consumption from the transport sector. Although the CO_2 emissions from the transport sector declined in 2013, they showed a strong rebound from 596.08 Mt in 2013 to 709.97 Mt in 2017, with an average annual growth rate of 4.47%. Thus, during the whole period 1997-2017, China's CO_2 emissions can be divided into four stages: high growth period (1997-2005), slow growth period (2005-2012), recession period (2012-2013), and stable growth period (2013-2017).

Fig.1 shows the significant changes over 1997-2017 in the emission shares of fossil fuels and regions in the total emissions from Chinese transport sector. The oil was a key source of the total CO_2 emissions through all years, peaking at 95.03% of emissions in 2007 (Fig.1a). The CO_2 emissions from coal decreased quickly from 1997 to 2005, decreasing from 19.57% in 1997 steadily to 5.98% of all emissions by 2005. During 2005-2012, the CO_2 emissions from coal showed a stable proportion over time, accounting for less than 5.98% of emissions. The CO_2 emissions from natural gas developed rapidly during 2005-2017, growing from 0.60% in 2005 to 3.64% by 2017. Between 1997 and 2017, the central and central coast regions had the largest share, accounting for 21.03% and 17.38% of the total in 2017 (Fig.1b). During 1997-2004, the emission share of Beijing-Tianjin region increased from 5.95% to 6.07%, and during 2005-2012 it is stable at more than 4.63% of the total emissions, increasing to 4.67% by 2017. The southwest's share grew steadily from 10.68% in 1997 to 14.80% in 2017, exceeding the south coast (13.62%) and northeast regions (10.35%).

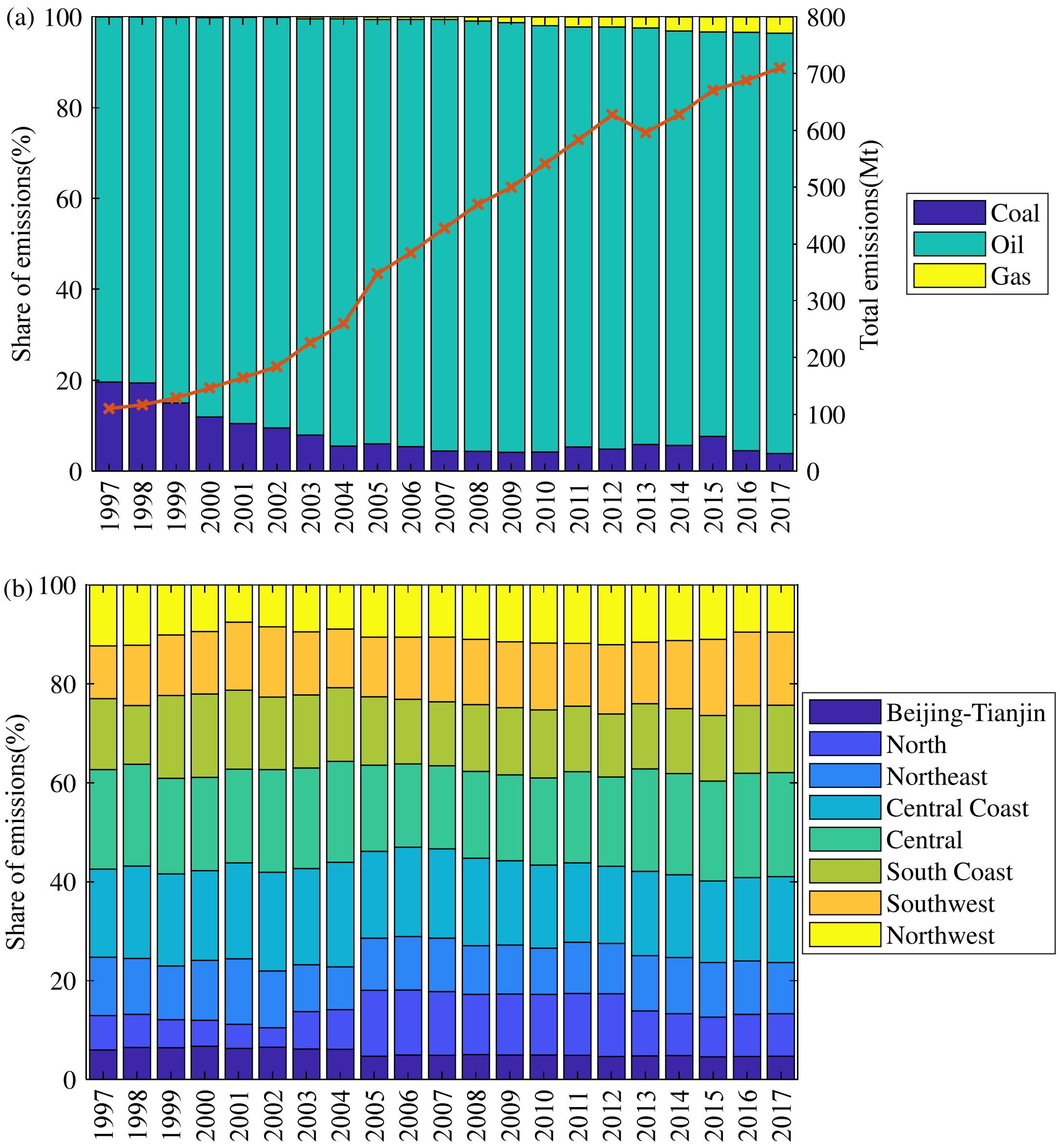

Fig. 1. Changes of CO_2 emissions in China's transport sector. (a) Total CO_2 emissions in China's transport sector from 1997 to 2017 and shares of CO_2 emissions from three fossil fuels; (b) Shares of CO_2 emissions from eight regions.

4.2 Driving factors of CO_2 emissions from China's transport sector

Fig. 2 presents the decomposition of total emissions into energy structure, energy intensity, turnover intensity, transport intensity, regional structure, per capita transport activity, population size and carbon intensity. Overall, the total emissions from transport sector grew at an average rate of 15.49% yr^{-1} between 1997 and 2005 (Fig.3), more than three times over the period. Per capita transport activity and energy intensity contributed 9.0% yr^{-1} and 7.8% yr^{-1} of this growth, respectively. Conversely, transport intensity resulted in an average -4.7% yr^{-1} decrease in emissions. During 2005-2012, China saw the strongest per capita transport activity, which contributed to emission increases of 12.0% yr^{-1}. Transport intensity drove the largest emissions decrease (-2.4% yr^{-1}), but policies to decreasing transport intensity seem unlikely to cancel the positive emission impact of per capita transport activity. Although energy intensity had a large positive impact on the total emissions during 2012-2013, driving a 18.3% yr^{-1} increase in emissions, the total CO$_2$ emissions declined at -5.0% yr^{-1}. This was mainly because that per capita transport activity growth in the China slowed down, resulting in an increase in emissions of “only” +4.1% yr^{-1}, and was offset by the emission contribution of turnover intensity (-25.8% yr^{-1}) over this period. During 2013-2017, the total emissions continued to increase, at +4.5% yr^{-1}, which was mainly driven by the fast per capita transport activity and energy intensity increase, driving increasing emissions of 6.6% yr^{-1} and 3.0% yr^{-1}, respectively. Moreover, we find a steeper reduction due to further reduction in transport intensity (-5.4% yr^{-1}) during this period.

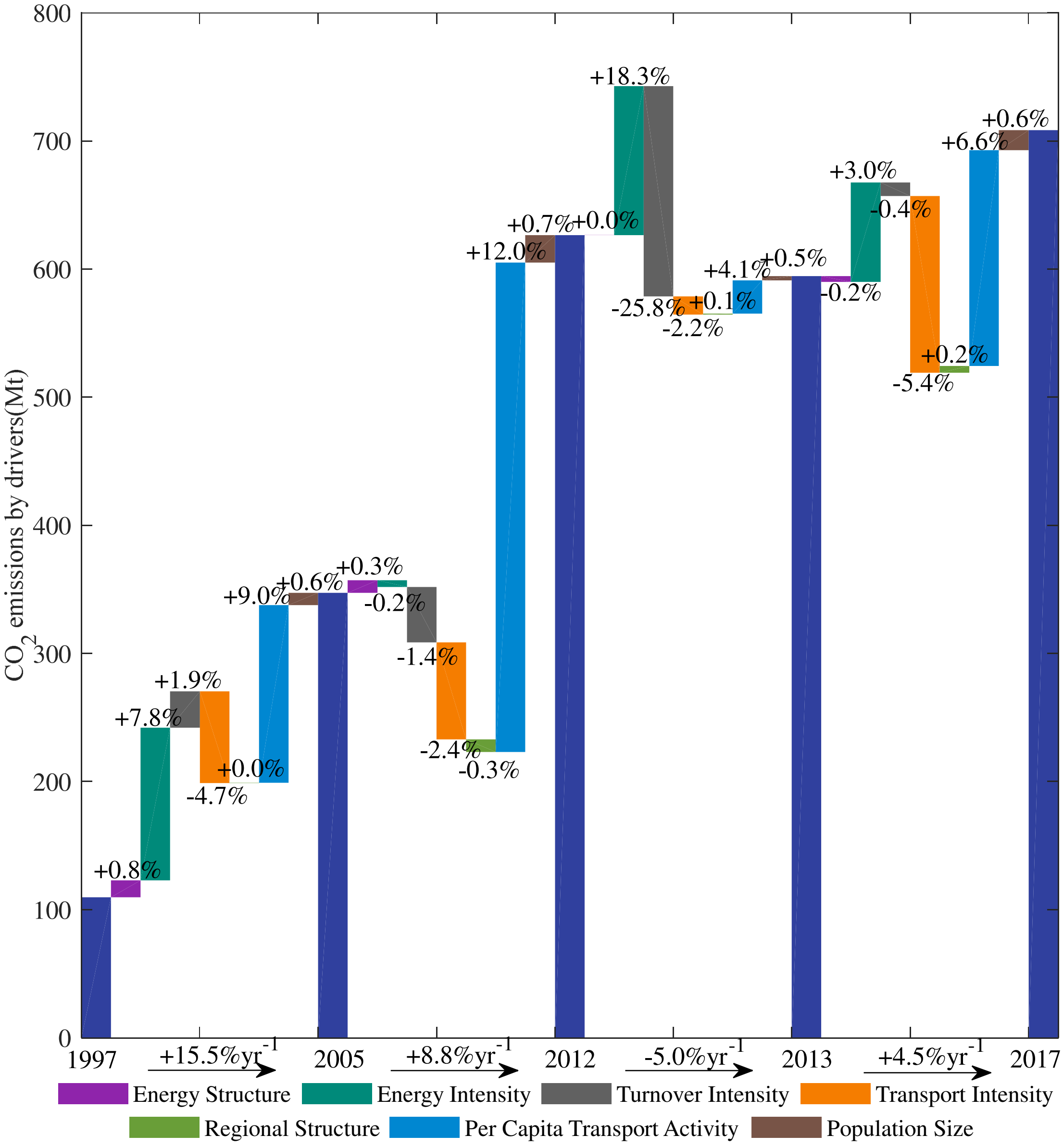

Fig. 2. Contributions of seven drivers to the change in CO_2 emissions. The selected periods include 1997-2005,2005-2012,2012-2013 and 2013-2017, and the lengths of the bars reflect the contributions of factors during each period.

4.3 Changes in emissions from regional structure

Although regional structure, measured by shares of regional transport output is a small driving factor on the emissions from transport sector, its driving impact on emissions is increasing. The regional structure drove emissions at 0.21% yr^{-1} during 2013-2017. Thus, we further investigate the emission contribution of regional structure for different regions. Between 1997 and 2005, as the Northwest, North and Southwest regions experienced the development of transportation, regional structural in these regions contributed CO_2 emissions increases, all at around 0.20% yr^{-1}. Among them, the contribution of Southwest was mainly driven by Guizhou province (see Table S1), in which the average annual emission contribution of regional structure was 0.18% yr^{-1}. The decrease in the transport value added of South Coast region led to a CO_2 emission reduction of -0.53% yr^{-1}, with large reduction from Fujian (-0.10% yr^{-1}), Guangdong (-0.41% yr^{-1}) and Hainan (-0.02% yr^{-1}) provinces. Between 2005 and 2012, the emissions impact of regional structure only for Northwest (+0.22% yr^{-1}), North (+0.16% yr^{-1}) and Southwest (+0.00% yr^{-1}) regions remained positive. The largest contribution of regional structure to emission reduction was in Central Coast region, which decreased from -0.03% yr^{-1} during 1997-2005 to -0.30% yr^{-1} during 2005-2012. The inhibitory effect of South Coast region decreased to -0.09% yr^{-1}, and compared with that in 1997-2005, the decreasing extent of its share of transport value added was reduced. The contribution of regional structure to CO_2 emissions in Beijing-Tianjin region changed from positive (+0.04%) during 1997-2005 to negative (-0.07%) during 2005 to 2012 due to Beijing's negative inhibiting impact at -0.08% yr^{-1}.

Between 2012 and 2013, regional structure started to increase CO_2 emissions by 0.10% yr^{-1}. This is mainly because continuing transport development drives emissions at 1.13% yr^{-1} in Central region, of which 0.72% yr^{-1} in Henan and 0.43% yr^{-1} in Hubei. Moreover, we find steeper increase due to further transport development in Southwest (+0.86% yr^{-1}). However, since transport development in North and Northwest regions was relatively weak during this period, the emission reductions resulting from regional structure in these two regions were relatively high, at -1.80% yr^{-1} and -0.24% yr^{-1} respectively. Between 2013 and 2017, we saw a larger emission increase due to regional structure (at 0.21% yr^{-1}). This is mainly from the emissions increases caused by the regional structure impacts in Southwest and South Coast regions, which contributed to emission changes of +0.48% yr^{-1} and +0.42% yr^{-1}, respectively. At the same time, Northeast (-0.53% yr^{-1}) and Northwest (-0.29% yr^{-1}) regions were the regions with the largest inhibiting emissions effects of regional structure.

The changes in emissions caused by regional structure were due to the changes in the shares of regional transport value added because regional structure reflects the relative contributions of different regions to national transport value added. Thus, we future analyze the relationship between the changes in emissions caused by regional structure and the changes in the share of regional transport value added (Fig. 3b). We found that there is a positive correlation between the changes of emissions by regional structure and the changes in the share of regional transport value added. The greater the change in the share of regional transport value added, the greater the change in emissions. However, we need to consider the difference in the regional emissions per unit of transport value added. This means that an effective measure to reduce the emissions by regional structure is to increase the relative value added shares of regions with low emissions per unit of transport value added, and meanwhile decrease the relative value added shares of regions with high emissions per unit of transport value added.

Moreover, since the regional shares of transport value added change with the regional growth rate of transport value added, we further analyze the relationship between the changes in the regional shares of transport value added and the changes in the growth rate of regional transport value added. We found that the change of the share of regional transport value added is positively related to the change in the growth rate of regional transport value added (Fig.3c). As a result, the greater the increase in the growth rate of regional transport value added, the greater the increase in its share, and the greater the increase in its transport emissions.

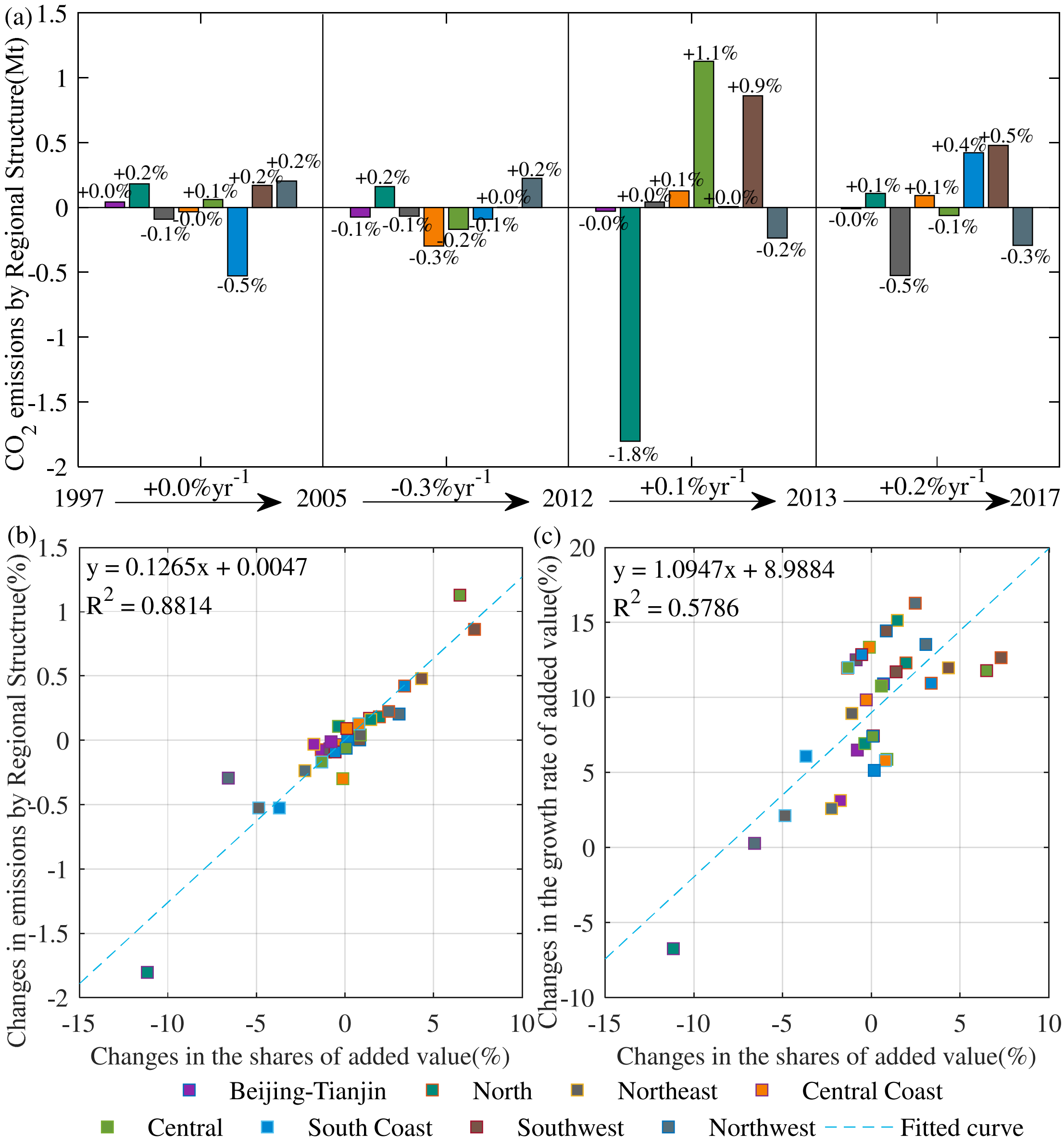

Fig.3. Changes in CO_2 emissions caused by regional structure. (a) Contribution of emissions by regional structure; (b) Relationship between the change of emissions by regional structure and the changes in the regional share of transport value added (c) Relationship between the change in the regional growth rate of transport value added and the change in the regional share of transport value added

4.4 Regional emission changes by drivers

Overall, the per capita transport activity, energy intensity, population size and energy structure have played a positive role in promoting emissions.

Among them, the per capita transport activity's promotion function was the most obvious. Emissions increased in all four stages except for North region, where emissions decreased by -1.36% yr^{-1} during 2012 to 2013 (Fig.4a). The decline in North region was mainly due to Shandong province (-1.50% yr^{-1}) (Table S2), where a reduction in the value added of transport output led to a reduction in emissions. In the first three phases, Central region contributed the most, with more than 1.90% yr^{-1}. During 2013 to 2017, the emission contribution rate of Southwest region was the highest, reaching 1.37% yr^{-1}, mainly driven by Sichuan province (0.58% yr^{-1}). In recent years, the rapid increase in transport activity in Southwest region promoted the increase of emissions. The Central region, second only to Southwest, also contributed 1.32% yr^{-1} growth, with stable growth in value added of transport output leading to a steady rise in emissions.

For the whole development process, energy intensity also played a certain role in promoting regional emissions. But it helped to reduce emissions from 2005 to 2012 (Fig.4b). During 1997 to 2005, the contribution rate of North region was the highest, reaching 1.25% yr^{-1}, mainly driven by Shandong province (1.26% yr^{-1}) (Table S3), whose contribution rate was the highest in the country. During 2005-2012, energy intensity had an inhibiting impact on the total emissions. Energy intensity improved in the Beijing-Tianjin, South Coast, North and Central regions, with emissions of -0.33% yr^{-1}, -0.28% yr^{-1}, -0.26% yr^{-1} and -0.01% yr^{-1}, respectively. Beijing (-0.18% yr^{-1}), Tianjin (-0.15% yr^{-1}) and Shandong (-0.29% yr^{-1}), which are close to the capital, were the base areas with high energy consumption and became the primary task of environmental control. Therefore, these provinces should vigorously promote technological innovation and improve energy intensity to reduce carbon emissions. Moreover, the region with the largest contribution to CO_2 emissions was Northwest region, at just 0.29% yr^{-1}. However, between 2012 and 2013, there was a relatively large increase in the contribution of each region and the impact of energy intensity in all regions all turned positive. Central region contributed an increase of 5.20% yr^{-1} in emissions by energy intensity. This was mainly because the contribution of Henan and Anhui were 1.39% yr^{-1} and 1.19% yr^{-1} respectively, ranking the highest all the provinces. The annual contribution Southern Coast region also reached 4.69% yr^{-1}. Only in North and Northwest regions, the contribution was low (0.38% yr^{-1}), mainly because the contribution of Shandong (-0.12% yr^{-1}) and Inner Mongolia (-0.57% yr^{-1}) provinces were negative. From 2013 to 2017, the contribution of each region tended to level off. The region with the largest annual contribution was Southwest region (0.91% yr^{-1}), because of Sichuan's 0.64% yr^{-1} contribution ranked first in the country.

In addition, population and energy structure factors also played a role in the growth of emissions. The contribution rate of population was relatively stable, except for the emission reduction of -0.02% yr^{-1} in Northeast region during 2013 to 2017, the emission increased in the other stages and regions (Fig.4c). The reduction in emissions in Northeast region was driven by all provinces in Northeast, contributed -0.01% yr^{-1} respectively. The reduction in population size led to a reduction in carbon emissions from the transport sector. In the first two periods, Central Coast and South Coast regions had the largest emissions, mainly influenced by Shanghai and Guangdong (Table S4). After entering the recession period, the two regions that contributed the most to CO_2 emissions became the Central Coast and Beijing-Tianjin regions (0.12% yr^{-1}). During 2013 to 2017, the influence of Central region (0.12% yr^{-1}) increased significantly, and it had become a high-contribution region second only to South Coast (0.15% yr^{-1}). This shows that developed regions have higher population growth rates, leading to more contribution to CO_2 emissions. In addition, China's economic development and population are gradually expanding from the coastal areas to inland regions such as Beijing-Tianjin and Central regions.

Overall, the energy structure played a positive role in CO_2 emissions between 1997 and 2012 (Fig.4d). But between 2012-2013, the disincentive effect of the energy structure on CO_2 emissions began to emerge. This is because in the recession period, emission reductions were achieved by optimizing the energy structure in all regions except for Northeast (0.32% yr^{-1}) and Southwest (0.04% yr^{-1}) regions. Jilin (0.31% yr^{-1}) in Northeast region contributed the most to the increase in CO_2 emissions (Table S5). The largest contributor to CO_2 reduction was Southwest region (-0.25% yr^{-1}). All the provinces in the Southwest region, except for Chongqing, have promoted emission reduction, especially Sichuan province, with a contribution rate of -0.21% yr^{-1}, which ranked first among all provinces. From 2013 to 2017, the changes in the energy structure in all the regions helped reduce emissions. With the wide use of natural gas gradually replaced the use of coal and oil in transport sector, the emission reduction due to energy structure in Northwest region was the largest, which reached -0.07 yr^{-1}.

However, turnover intensity and transport intensity mainly played a negative role in affecting emissions. From 1997 to 2005, the turnover intensity led to a small increase in emissions. All regions had positive contribution rates (Fig.4e), with Central Coast and North regions having the highest contribution rates (0.50% yr^{-1}). In the early stages of economic development, emissions increased as a result of increased turnover per mile in all regions. With the continuous development of transport, only Beijing-Tianjin (0.49% yr^{-1}) and South Coast (0.37% yr^{-1}) regions increased their emissions between 2005 and 2012, whose urban traffic pressure was significant, while other regions reduced their emissions to varying degrees. The highest contribution rate to CO_2 reduction was -0.60% yr^{-1} in North region, which was mainly due to Shandong province's contribution rate of -0.41% yr^{-1} (Table S6). During 2012 to 2013, emissions were reduced in all regions. South Coast region (-5.46% yr^{-1}) had the highest contribution rate to reduction. Guangdong ranked first among provinces, with a reduction rate of -4.81% yr^{-1}. The continuous development of the transport industry improved the transport efficiency and alleviates the turnover density of the unit mileage. For 2013-2017, the negative impact of turnover intensity decreased in all regions, and the negative impact in Northwest region was relatively large, reaching -3.89% yr^{-1}. Central Coast (0.36% yr^{-1}), North (0.11% yr^{-1}) and South Coast (0.11% yr^{-1}) regions showed smaller increases in emissions. Visible in recent years, the development of traffic volume intensity has gradually entered the bottleneck.

In terms of transport intensity, emissions decreased in most regions between 1997 and 2017 (Fig.4f). In the first phase (1997-2005), the contribution of each region to CO_2 emissions was negative. The largest contribution rate of emission reduction was in Central (-0.82% yr^{-1}) and North (-0.81% yr^{-1}) regions. By 2005, the rate of emission reduction slowed down and the contribution rate of Central (0.09% yr^{-1}) and North (0.06% yr^{-1}) regions were positive. South Coast region saw the biggest drop in CO_2 emissions (-0.73% yr^{-1}). This reflects the increasing role of government investment in the region in promoting the output of transportation industry. Between 2012 and 2013, Central (-1.65% yr^{-1}) and Southwest (-1.11% yr^{-1}) regions contributed significantly more to emission reductions. The North region was the region that contributed most to the increase in carbon dioxide emissions (1.74% yr^{-1}). Shandong (1.71% yr^{-1}) had the highest contribution rate of transport intensity adjustment (Table S7). Since 2013, transport intensity had improved, and CO_2 emissions had decreased in all regions. The highest contribution rate of emission reduction was in Central Coast (-1.22% yr^{-1}) and South Coast (-1.10% yr^{-1}) regions. This is mainly because the contribution rates of Guangdong and Sichuan provinces reached -0.73% yr^{-1} and -0.53% yr^{-1} respectively, ranking the highest among all provinces. The lowest rate of reduction was in Northeast (-0.02% yr^{-1}) region. This is mainly because the reductions elsewhere were partly offset by the 0.29% contribution from Gansu. This also reflects the government investment to the transport industry output promotion function tends to smooth.

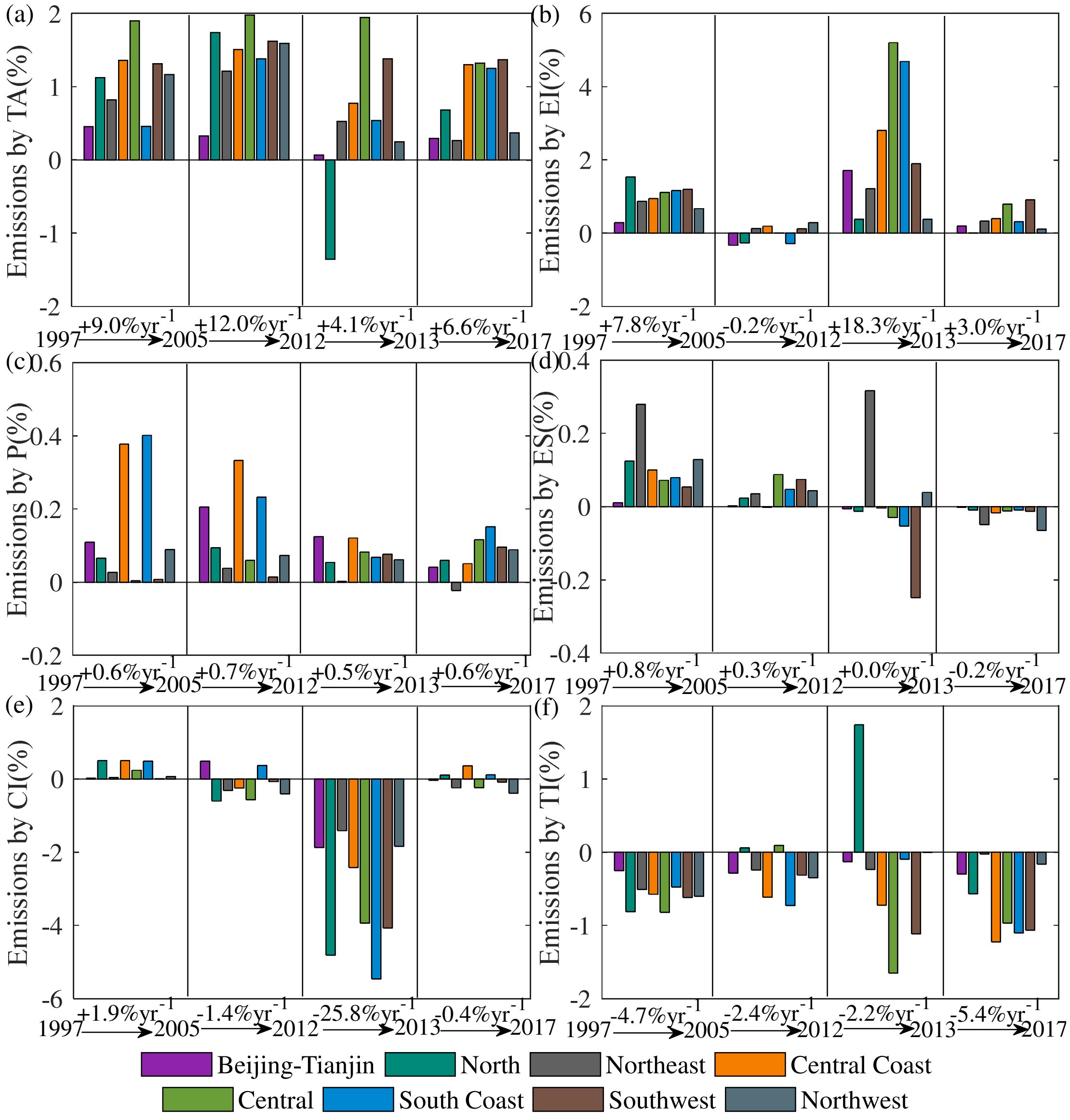

Fig.4. Changes in CO_2 emissions in China's transport sector caused by drivers at the regional level. (a) Region-specific contributions of energy structure to changes in national CO_2 emissions; (b) Region-specific contributions of energy intensity to changes in national CO_2 emissions; (c) Region-specific contributions of turnover intensity to changes in national CO_2 emissions; (d) Region-specific contributions of transport intensity to changes in national CO_2 emissions. The compound annual rate of total emissions (r) is related to the total rate (R) across n years as $r = \sqrt[n]{(1+R)}$-1, and compound annual contribution of a given factor (k) is $r \times S_k$ where S_k is the share of the contribution of the factor during the whole period.

5. Discussion

Many scholars have discussed the driving factors of CO_2 emissions in the transport sector, but the differences in emission reduction effects due to the differences in the development models of various regions have not been discussed in detail. In this study, the regional structure was added to the division of impact factors. The impact of regional structure on the CO_2 emission of the national transport sector and the differences between the CO_2 emission factors of various regions are discussed.

The results show that the regional structure does not have a significant impact on the CO_2 emission of the national transport sector. However, at the regional level, driving factors under different regional development models have different contributions to CO_2 emission. From the comparison of the regional structure contribution rates of various regions in 2013-2017, the contribution rates of Southwest, South Coast, Central Coast and North regions were positive. The reason is that the growth rate of the output value of the transportation sector in these areas were relatively high. In Southwest region, due to the continued prosperity of tourism in recent years, transport consumption has increased. Chengdu and Chongqing also jumped into new first-tier cities. With the introduction of the concept of Chengdu-Chongqing Economic Circle, Southwest region has become increasingly connected. The continuous improvement of its internal transport network and the communication network with the outside world has resulted in the highest growth rate of the output value added of its transport sector in recent years. In addition, since the South Coast, Central Coast and North regions were more developed and had higher total consumption capacity, it is not surprising that the added value of the transport sector maintained a steady growth.

Different regional development models lead to great differences in the contribution of each region in per capita transport activity, energy intensity, population, energy structure, turnover intensity and transport intensity factors. In 2013-2017, the first three factors led to an increase in CO_2 emission in all regions. Energy structure and traffic intensity led to CO_2 emission reductions in all regions. However, in terms of turnover intensity, some regions promoted CO_2 emissions and some regions suppressed it. The regional difference in turnover intensity was consistent with that in regional structure. Only the Central Coast, South Coast and North regions promoted CO_2 emissions. It can be speculated that the contribution of turnover intensity was related to the level of economic development. The transport construction in developed regions was at the leading level in the country, but due to the increase in population, transport pressure was still relatively high. But at the same time, South Coast and Central Coast regions optimized transport intensity and contributed the most to reducing CO_2 emission. It can be seen that the transport in developed areas was more complete. Therefore, taking into account the different characteristics and different resources of each region, regions should strive to discover different factors that make emission reduction more efficient, and use its own advantages to achieve emission reduction. At the same time, all regions should strengthen cooperation to achieve complementary advantages and further promote the reduction of national CO_2 emissions.

By comparing the impact of regional development models on national total CO_2 emission (J. Zheng et al., 2019), the total average annual growth rate of CO_2 emissions from 2012 to 2016 was 1.7% yr^{-1}, but we found that the average annual growth rate of CO_2 emission from the transport sector reached 4.5% yr^{-1} in 2013-2017. It can be seen that in recent years, CO_2 emissions from the transport sector have become a major factor in the increase in China's total CO_2 emissions. The main factors leading to the increase of the total CO_2 emission of the country were economy and population. Consistent with this, we found that per capita transportation activities and population factors also contributed to the growth of CO_2 emission from the transport sector. The difference is that, energy efficiency contributed to emission reductions in terms of total CO_2 emission, but the energy intensity of the transport sector still promoted to emissions. This indicates that the energy efficiency of the transport sector needs to be improved. In addition, regional structure had a greater impact on total emissions and was the second most important factor. However, in terms of total emission, the positive correlation between the growth rate of output value and emission was still valid.

At the regional level, improvements in energy efficiency in all regions contributed to overall emission reduction in 2012-2016. However, energy intensity in all regions in 2013-2017 led to an increase in CO_2 emission from the transport sector. The North region contributed the largest to the reduction of total CO_2 emission, which was consistent with the least contribution of it to the increase of CO_2 emission in the transport sector. It can be seen that the energy efficiency improvement in the North region was at the leading level in the country. The Central and Southwest regions were also at the top of the list of contributors to total emission reduction, but contributed the largest to the emission increase in transport sector. It is clear that their energy efficiency improvement was concentrated in other sectors. In terms of the energy structure, each region contributed to reducing emission from the transport sector, but the South Coast, Northwest, Central Coast and North regions contributed to the increase in total emission. It can be seen that the energy restructuring of the transport sector was developing more rapidly than that of other sectors. The two emission reduction contribution rates of the Northwest region were both the highest, which indicates that the energy structure improvement of the northwest region was in a leading position of the country. However, the Northeast and Central Coasts, which were the second and third largest contributors to CO_2 reduction in the transport sector, accounted for the second and third largest increase in total CO_2 emission. The Beijing-Tianjin region contributed the second most to total CO_2 reduction in the country, but the least to the emission reduction in transport sector. These regions did not penetrated energy structure adjustments into various industries, which led to this imbalance.

6. Conclusion

The period 1997-2017 is divided into four phases according to the characteristics and growth rate of carbon emissions: the period 1997-2005 is a period of high growth, the period 2005-2012 is a period of low growth, the period 2012-2013 is a period of emission reduction, and the period 2013-2017 is a period of stable growth. Transport activity and energy intensity contributed the largest to the growth of carbon emissions in 1997-2005, but improvements in transport intensity helped to reduce emissions. In the second phase, per capita transport activity was the most active, offsetting the emission reduction effect of transport intensity, so that carbon emissions continued to increase. In 2012-2013, the slowdown in the growth of transport activity and the minimum contribution of turnover intensity to emission reductions offset the significant contribution of energy intensity, resulting in a reduction in total carbon emissions. Rapid improvements in per capita transport activity and energy intensity in 2013-2017 led to an increase in total emissions.

From regional perspective, in all stages, the regional structural adjustment in Southwest region resulted in a continuous increase in CO_2 emissions, with the largest contribution rate among all provinces. The regional structural adjustment in Northwest region led to an increase in CO_2 emissions in the first two stages, but resulted in the largest decrease in CO_2 emissions in the second two stages. Moreover, we found that the change in the rate of output growth of the regional transport sector is positively correlated with the change in the share of output value added, while the change in emissions by regional structure is positively correlated with the change in the share of output value added of the regional transport sector. As a result, the higher the rate of growth of output and the larger the share, the greater the increase in CO_2 emissions from the transport sector.

As far as the influencing factors of regional CO_2 emission change are concerned, the promoting effect of energy intensity is relatively continuous, but its contribution rate is relatively stable in recent years. The effect of energy structure gradually changed from promoting emissions in the first two stages to restraining emissions. The change of traffic intensity and turnover intensity can obviously restrain the regional emissions. In particular, transport intensity has maintained a high contribution rate to emission reduction in recent years, but the contribution rate of turnover intensity to emission reduction is slowly weakening.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

All data generated or analysed during this study are included in this published article [and its supplementary information files].

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

Yiwen Wu: Conceptualization, Formal analysis, Investigation, Software, Validation, Visualization, Writing - original draft; Rong Yuan: Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing - review & editing; Yuchen Pan: Data curation, Writing - review & editing.

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