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Original Research

Decomposition and Decoupling of Transportation CO_2: A Comparison of Areas with Different Economic Development in China

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Abstract

The gap between relatively developed and less developed areas in China has become more evident with economic development. However, only a few investigations have compared factors of transportation CO_2 emissions in relatively developed and less developed areas at the micro level. Factors differ for transportation CO_2 emissions between areas. To assess their differences, we select Guangdong and Guangxi provinces in China as examples. This study conducted a decoupling research between transportation CO_2 emissions and economic output based on the Logarithmic Mean Divisia Index (LMDI) decomposition and Tapio decoupling model during 2000-2017. The LMDI model successfully quantified the effects of six factors, focusing on technology-related factors, i.e., research and development (R&D) efficiency and per capita R&D expenditure. Different factors of transportation CO_2 emissions in the two provinces were then compared. Results were as follows: (1) Four decoupling states appeared in the two areas. (2) Per capita R&D expenditure was the primary contributor to increased CO_2 emissions, followed by population size. Relative to those in Guangdong, the two effects were weaker in Guangxi. (3) Energy intensity was the major inhibitor of CO_2 emissions in Guangdong, followed by R&D efficiency. The two effects can reduce CO_2 emissions in Guangxi, although the inhibitory effects were relatively small. (4) Freight transportation intensity in Guangdong increased CO_2 emissions, whereas it decreased CO_2 emissions in Guangxi due to the extremely weak inhibitory effect. Finally, the study provides valuable suggestions for the development of low-carbon transportation in different areas.

Keywords: CO_2 emissions, relatively developed and less developed areas, decoupling, LMDI, transportation

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Introduction

Environmental changes and their effects on the society and economy of countries have become a global concern in the 21st century, threatening human life in the long run. These problems arise from the burning of fossil fuels, with transportation being a major contributor to global CO_2 emissions, accounting for 29% of the world's total energy consumption and 65% of world's oil product consumption [1]. Therefore, attention should be given to transportation CO_2 emissions while promoting the economy.

Transportation has achieved tremendous achievements in China through continuous development. However, it will also face increasing problems. China's transportation has become the third largest energy-consuming sector in the country and a significant source of CO_2 emissions under the background of rapid development [2]. Moreover, disparities in transportation development between different areas are becoming increasingly emphasized, particularly in relatively developed and less developed areas. Data from the Guangdong and Guangxi Bureau of Statistics indicate that freight turnover increased from 306.45 billion ton km in 2000 to 2819.22 billion ton km in 2017 in Guangdong and from 77.06 billion ton km in 2000 to 461.33 billion ton km in 2017 in Guangxi. Exploring factors related to CO_2 emissions is interesting with significant regional differences. Identifying potential CO_2 reduction factors and taking effective measures will provide significant references for the early achievement of carbon neutrality in relatively developed and less developed areas.

China has a vast territory with evident regional differences in terms of economic development and CO_2 emissions. Regional differences have been considered in relevant studies. Zhang and Zeng [3] adopted a spatial econometric model to analyze the spatial and temporal patterns and evolutionary trends of transportation CO_2 emissions. Lu et al. [2] utilized the Theil index to investigate the regional disparities of average transportation CO_2 emissions from three aspects in the Yangtze River Economic Belt. Ma et al. [4] conducted global and local spatial autocorrelation analysis to study regional disparities and temporal and spatial changes in the ecological pressure of carbon footprint for passenger transport in China. Liu et al. [5] quantified the role of spatial pattern when investigating the relationship between transportation CO_2 emissions and economic development by using the LMDI and Tapio decoupling models. Peng et al. [6] as an industry with high energy consumption and high carbon emissions, plays an increasing role in achieving the goal of carbon emissions reduction in China. Understanding the situation of the transport sector's carbon emissions efficiency and the relevant dominating driving forces is an important prerequisite for formulating carbon emissions reduction polices. This study evaluated the transport sector carbon emissions efficiency of 30 provinces in China from 2004 to 2016 using the Super slacks-based measure (Super-SBM evaluated the transportation carbon emissions efficiency of 30 provinces in China in 2004-2016 by the Super slacks-based measure model and spatial econometric approaches. And Peng et al. [7] employed the methods of exploratory spatial data analysis to examine the spatial distribution characteristics and influencing factors of transport CO_2 emissions. Wang et al. [8] examined the spatial and temporal characteristics of the relationship between transportation CO_2 emissions and economic growth by applying the standard deviational ellipse and Tapio decoupling method. Wang et al. [9] established an integrative framework to investigate the spatiotemporal characteristics and driving mechanism of regional atmospheric pollutant emissions for road transportation in China. From the above, many studies have focused on spatial and regional analysis of transportation CO_2 emissions in China, however, these studies did not further distinguish research areas and comparative analysis on transportation CO_2 emissions is limited. Research has yet to systematically investigate factors related transportation CO_2 emissions in relatively developed and less developed areas.

Many scholars have used different methods to investigate factors associated with transportation CO_2 emissions. The econometric model is a frequently used method by scholars. Okada [10] found an inverted U-shaped relationship between aging populations and CO_2 emissions from road transportation by using a first-order differential equation. Saboori et al. [11] adopted the fully modified ordinary least squares method and determined a positive bidirectional relationship among CO_2 emissions, road energy consumption, and economic growth. Xu and Lin [12] developed a dynamic nonparametric additive model and found that the nonlinear effect of economic growth on CO_2 emissions is in accordance with the environmental Kuznets curve hypothesis based on provincial data in China. Lin and Benjamin [13] adopted quantile regression to study the effects of carbon intensity, per capita gross domestic product (GDP), energy intensity, and total population on transportation CO_2 emissions in China. Wang et al. [14] established an extended Stochastic Impact by Regression on Population, Affluence, and Technology model and determined that socioeconomic factors are the major contributors to the increase in transportation CO_2 emissions. Rasool et al. [15] used the autoregressive distributed lag model and the vector error correction model to study the determinants of transportation CO_2 emissions in Pakistan. Their results showed that oil prices and economic growth reduced CO_2 emissions, whereas population density, energy intensity, and road transport can increase such emissions.

Decomposition methods are more common than econometric methods in the transport sector.

The concept of decoupling is frequently adopted to determine whether a region is growing economically while reducing CO_2 emissions. Many studies on decoupling relationship have focused on the driving factors of CO_2 emissions [16-20] while the transportation sector accounts for a major share of CO_2 emissions. The analysis of transportation sector CO_2 emissions is help to decrease CO_2 emissions. Thus the purpose of this paper is to investigate the potential factors influencing the change of transport sector CO_2 emissions in China. First, the transport sector CO_2 emissions over the period 1985-2009 is calculated based on the presented method. Then the presented LMDI (logarithmic mean Divisia index. The LMDI model has been widely used due to its solid theoretical foundation and adaptability. On the one hand, previous studies used LMDI from the macro perspective. Such studies included [21] for China, India, Indonesia, Republic of Korea, Malaysia, Pakistan, Sri Lanka and Thailand, [22] for Moroccan, [23-25] for China, [26] for Korea, [27]the nature of operating the transportation sector in the country requires an excessive amount of fossil energy which causes the rise of CO_2 emissions. Ascertaining the impending factors and technologically to conserve energy, as well as governing CO_2 emissions from this sector, are essential to attain sustainable development. The paper endeavors to determine the decomposition of driving factors that affect the relationship between Bangladesh's transport sector development and CO_2 emissions due to energy consumption from the year 1990 to 2017 using the Logarithmic-Mean Divisia Index (LMDI for Bangladesh, [28] for the Eurasian corridor (29 countries). On the other hand, the scope of these studies is China from the regional perspective [29-37]. Most studies have covered several provinces. These studies frequently divide indicators into economic growth, economic structure, energy structure, population scale, and other factors, while failing to emphasize the roles of technology-related factors, such as R&D efficiency and per capita R&D expenditure. Only a few studies have attempted to explore the role of technological development in transportation CO_2 emissions. To the best of our knowledge, only one study determined the effect of technology-environmental innovation on transportation CO_2 emissions [38]. Transportation is closely related to energy consumption. Studies have shown that technological development can reduce transportation energy intensity [39, 40]. Furthermore, R&D expenditure can facilitate the development of low-carbon technologies in transportation. At present, technological innovation is at a critical stage in China, and the role of technological development in transportation CO_2 emissions is worth exploring comprehensively in this context.

In accordance with the above literature review, we identify two issues to further explore. First, limited related factors have been considered and only a few studies have explored the role of technological development in transportation CO_2 emissions. Whether R&D promotes economic growth decoupling from transportation CO_2 emissions remains unaddressed. Second, seldom studies have been conducted to compare the drivers of transportation CO_2 emissions in relatively developed and less developed areas at the micro level. Whether the magnitude of the impact is the same for each factor has not been determined in different areas. Given this context, Guangdong and Guangxi represent relatively developed and less developed areas, respectively. we make three major contributions to complete the research gap. First, the current study compares decoupling states between transportation CO_2 emissions and economic growth in Guangdong and Guangxi. Second, important technological factors (i.e., R&D efficiency and per capita R&D expenditure) are explored in accordance with the extended LMDI model. Lastly, this study compares the drivers of transportation CO_2 emissions and examines the differences in effects of various factors in the two areas. The result of this study is significant and provides new insights for sustainable transportation development in relatively developed and less developed areas.

Materials and Methods

Research Areas

Guangdong province is located in the southern coastal areas of China, which is one of the most developed provinces. The location of Guangdong is shown in Fig. 1. Adjacent to neighboring Hong Kong and Macau Special Administrative Region of China, Guangdong has been a pioneer in reform and opening-up, which breeds the three special economic zones of Zhuhai, Shenzhen and Shantou. Under the strong support of different policies, Guangdong has achieved rapid industrialization. Therefore, it has received considerable economic benefits. Guangxi Zhuang Autonomous Region is situated in the western part of South China (Fig. 1). The autonomous region borders Vietnam in the southwest, borders China's Yunnan, Guizhou, Hunan and Guangdong provinces and faces Hainan across the sea. Due to the Yunnan-Guizhou Plateau, hills and mountains account for 75% of the total land area of the region in Guangxi, which causes bad transportation. In 2016, Guangxi province's GDP ranked 18th among 31 provinces in China. Accordingly, Guangxi is regarded as a less developed province of China. Table 1 shows economic development between Guangdong and Guangxi. Clearly, economic growth in Guangdong is considerably higher than that in Guangxi in terms of GDP and GDP per capita. The study selects Guangdong and Guangxi to represent relatively developed and less developed areas, respectively, on the basis of economic development level. Given their unique geographical traits, promising transportation development has been observed in the research areas,

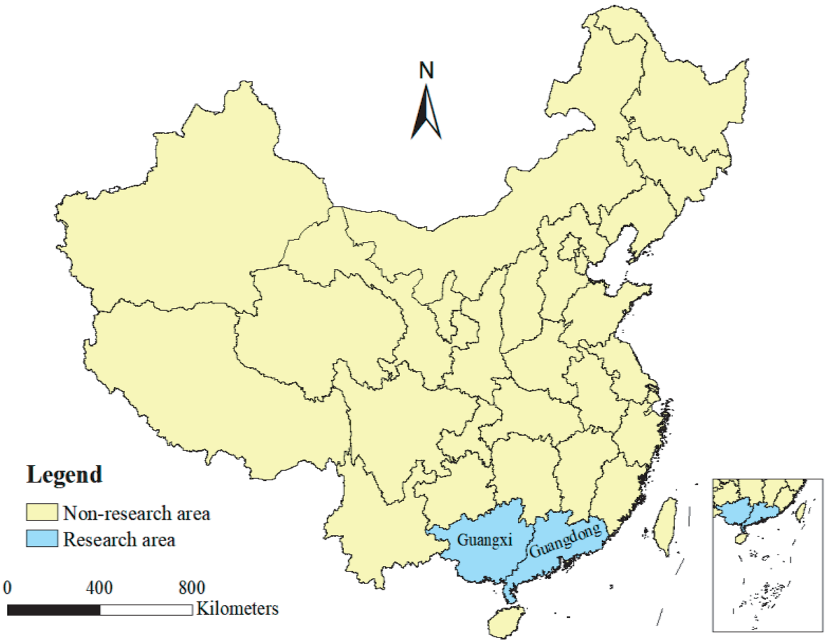

Fig. 1. Locations of the research areas in China.

increasing pressure on the environment. Transportation CO_2 emissions cannot be disregarded. In this context, identifying the drivers of transportation CO_2 emissions in relatively developed and less developed areas is necessary to meet the requirements for environmental protection.

Methods

Calculation of Transportation CO_2 Emissions

In accordance with the Intergovernmental Panel on Climate Change, calculation methods for transportation CO_2 emissions can be classified into two types: up-to-bottom and bottom-to-up methods. Specific factors should be considered in bottom-to-up methods. Moreover, data related to factors are not covered in China's current statistical yearbooks. An up-to-bottom method is used in the current study, and the total transportation CO_2 emissions are calculated as follows:

$$C = C_D + C_I \tag{1}$$

where C represents the total transportation CO_2 emissions (10^4 tons); and C_D and C_I indicate the direct and indirect transportation CO_2 emissions (10^4 tons), respectively. Direct transportation CO_2 emissions can be expressed as follows:

$$C_D = \sum_{j=1}\left(\frac{44}{12}\times E_j \times NCV_j \times CC_j \times O_j\right) \tag{2}$$

where E_j is the consumption of the fuel type j (10^4 tons), NCV_j represents the net calorific value for the jth fuel, CC_j refers to the carbon content for the jth fuel, and O_j denotes the carbon oxidation rate for the jth fuel. The parameter values of each fossil fuel are provided in Table 2.

Indirect transportation CO_2 emissions are calculated using Eq. (3), as follows:

$$C_I = E_{ele} \times EF_{ele} \tag{3}$$

where E_{ele} denotes the electricity consumption from the transportation sector (kW·h), and EF_{ele} represents the

Table 1. Comparison of economic development between Guangdong and Guangxi.

Province	2009		2013		2017	
	GDP (billion yuan)	GDP per capita (yuan)	GDP (billion yuan)	GDP per capita (yuan)	GDP (billion yuan)	GDP per capita (yuan)
Guangdong	3946.5	39418.0	6250.3	58860.0	9164.9	82685.6
Guangxi	778.5	16098.0	1451.2	30873.0	2039.6	41955.0

Source: Statistical yearbooks of the two provinces.

Table 2. Parameter values of major fossil fuels.

Types	Coal	Coke	Crude oil	Gasoline	Kerosene	Diesel fuel	Fuel oil	Liquefied petroleum gas	Natural gas
NCV (TJ/10^3ton)	20.91	28.44	41.82	43.07	43.07	42.65	41.82	50.18	38.93[a]
CC(ton/TJ)	26.37	29.50	20.10	18.90	19.50	20.20	21.10	17.20	15.30
O	0.94	0.93	0.98	0.98	0.98	0.98	0.98	0.98	0.99

[a] The unit is MJ/m^3.

Source: Guidelines to Provincial Lists of Greenhouse Gas Inventory

emission factor of electricity (kg/kW·h). The value of the emission factor for electricity in the current study is obtained from Wang et al. [8].

Tapio Decoupling Model

The most commonly used method for decoupling analysis is the Tapio decoupling model [41]. The decoupling index φ is widely applied to measure the decoupling state between two variables. To determine the relationship between transportation CO_2 and economic development, the Tapio decoupling model is used in the current study. The decoupling index φ is described as follows:

$$\varphi = \frac{\left(C^t - C^0\right)/C^0}{\left(G^t - G^0\right)/G^0} = \frac{C\%}{G\%} \tag{4}$$

where C^0 and C^t denote transportation CO_2 emissions in the base year 0 and year t, respectively; G^0 and G^t represent regional economic output in the base year 0 and year t, respectively; and $C\%$ and $G\%$ signify the growth rate of transportation CO_2 emissions and regional economic output, respectively.

In accordance with the Tapio model, the decoupling index is classified into eight states. The decoupling states are provided in Table 3.

LMDI Decomposition Method

The LMDI method is a widely adopted method to identify the drivers of various variables. It is expressed smoothly with an extended Kaya identity. In the current study, the LMDI method is used to decompose factors of transportation CO_2 emissions in Guangdong and Guangxi. Transportation CO_2 emissions are decomposed as follows:

$$C = \frac{C}{E} \times \frac{E}{T} \times \frac{T}{G} \times \frac{G}{R} \times \frac{R}{P} \times P \tag{5}$$

where C denotes transportation CO_2 emissions (10^4 tons), E represents energy consumption in the transportation sector (10^4 tons of standard coal), T indicates freight turnover (100 million tons km), G is the regional economic output (100 million yuan), R indicates regional R&D expenditure (100 million yuan), and P denotes the resident population of the area (10^4 people).

In Eq. (5), C/E indicates transportation CO_2 emissions per unit of energy consumption. E/T denotes energy consumption per unit of freight turnover. T/G signifies freight turnover per unit of economic output. G/R indicates the economic output per unit of R&D expenditure, i.e., R&D efficiency. R/P represents per capita R&D expenditure. The aggregated transportation CO_2 emission changes can be decomposed into six driving factors: CO_2 emission intensity (*CE*), energy intensity (*EI*), freight transportation intensity (*TG*),

Table 3. Decoupling states based on the Tapio model.

States	Sub-states	ΔG	ΔC	φ
Decoupling	Strong decoupling (SD)	>0	<0	<0
	Weak decoupling (WD)	>0	>0	0-0.8
	Recessive decoupling (RD)	<0	<0	>1.2
Negative decoupling	Strong negative decoupling (SND)	<0	>0	<0
	Weak negative decoupling (WND)	<0	<0	0-0.8
	Expansive negative decoupling (END)	>0	>0	>1.2
Coupling	Expansive coupling (EC)	>0	>0	0.8-1.2
	Recessive coupling (RC)	<0	<0	0.8-1.2

R&D efficiency (GR), per capita R&D expenditure (RP), and population size (P). The aggregated CO_2 emission changes are shown in Eq. (6):

$$\Delta C = C^t - C^0 = \Delta CE + \Delta EI + \Delta TG + \Delta GR + \Delta RP + \Delta P \tag{6}$$

The specific formula for each effect is as follows:

$$\Delta CE = \frac{C^t - C^0}{lnC^t - lnC^0} \times ln\left(\frac{CE^t}{CE^0}\right) \tag{7}$$

$$\Delta EI = \frac{C^t - C^0}{lnC^t - lnC^0} \times ln\left(\frac{EI^t}{EI^0}\right) \tag{8}$$

$$\Delta TG = \frac{C^t - C^0}{lnC^t - lnC^0} \times ln\left(\frac{TG^t}{TG^0}\right) \tag{9}$$

$$\Delta GR = \frac{C^t - C^0}{lnC^t - lnC^0} \times ln\left(\frac{GR^t}{GR^0}\right) \tag{10}$$

$$\Delta RP = \frac{C^t - C^0}{lnC^t - lnC^0} \times ln\left(\frac{RP^t}{RP^0}\right) \tag{11}$$

$$\Delta P = \frac{C^t - C^0}{lnC^t - lnC^0} \times ln\left(\frac{P^t}{P^0}\right) \tag{12}$$

Data Sources

During the calculation, different types of energy consumption from transportation in Guangdong and Guangxi are obtained from the China Energy Statistical Yearbook (2001-2018). The GDP, population, freight turnover, and other data are from the Guangdong Statistical Yearbook (2001-2018) and Guangxi Statistical Yearbook (2001-2018). The R&D expenditure data for the two provinces are collected from the China Science and Technology Statistical Yearbook (2001-2018). To counteract the effect of inflation, GDP and R&D expenditure are converted into the 2000 constant price.

The freight turnover from the two provinces only considers rail, road, and waterway transport modes, whereas the freight turnover of aviation transport is not included because of two reasons. On the one hand, the statistical specifications of freight turnover for different transport modes are not uniform in the two provinces. No data for the freight turnover of aviation transport are found in the Guangxi Statistical Yearbook. On the other hand, the share of freight turnover from aviation transport among the four modes of transportation is extremely small. In Guangdong, the share of freight turnover by rail, road, and waterway transport modes is greater than 99.4% in 2000-2017. Guangxi as a less developed area, an inference can be made that its share of freight turnover from aviation transport is even smaller and can be disregarded.

Results and Discussion

All the models in this study were coded and calculated using R, an open source software. The results are presented in several sections. The first section shows characteristics of transportation CO_2 emissions in Guangdong and Guangxi. The second section reveals decoupling states during 2000-2017 in both provinces. Comparative analysis of factors related to CO_2 emissions in two provinces is presented in the third section. And it is followed by policy implications.

Characteristics of Transportation CO_2 Emissions in Guangdong and Guangxi

Trend Analysis of CO_2 Emissions

Fig. 2 shows the trends of transportation CO_2 emissions in Guangdong and Guangxi in 2000-2017. CO_2 emissions differ between the two regions. First, an upward trend is more highlighted in Guangdong, increasing from 20.03 million tons (Mt) in 2000 to 77.46 Mt in 2017, with an average annual growth rate of 8.44%. Meanwhile, CO_2 emissions increased from 4.90 Mt in 2000 to 23.00 Mt in 2017 in Guangxi. The average annual growth rate was 9.98%. Transportation CO_2 emissions in Guangdong were three times more than that in Guangxi in 2017. Regional disparities between CO_2 emissions reflect the technical differences and inadequate policies in two provinces. The apparent difference is attributed to the economy of Guangdong growing at a high rate for many years; given its impeccable transportation infrastructure and developed logistics industry, the income level and quality of life of Guangdong residents have been improving continuously. By contrast, economic development in Guangxi remains backward, and its industrialization and urbanization levels require further improvement. These factors inhibit transportation CO_2 emissions. Second, both provinces are in the growth phase of transportation CO_2 emissions during the periods of 2000-2012 and 2013-2017. Compared with that in Guangdong, the average annual growth rate was significant in Guangxi, with values of 12.02% and 11.35%, respectively, during these periods. A temporary decrease in CO_2 emissions was observed in 2012-2013 in both provinces. The decline in CO_2 emissions could be attributed to the formulation of various national policies in 2011, such as the 12th Five-Year National Environmental Protection Plan. They were implemented to reduce transportation CO_2 emissions effectively in Guangdong and Guangxi.

Energy Structure of CO_2 Emissions

Fig. 3 depicts the energy structure of transportation CO_2 emissions in Guangdong and Guangxi in 2000-2017. The energy structure of the two provinces

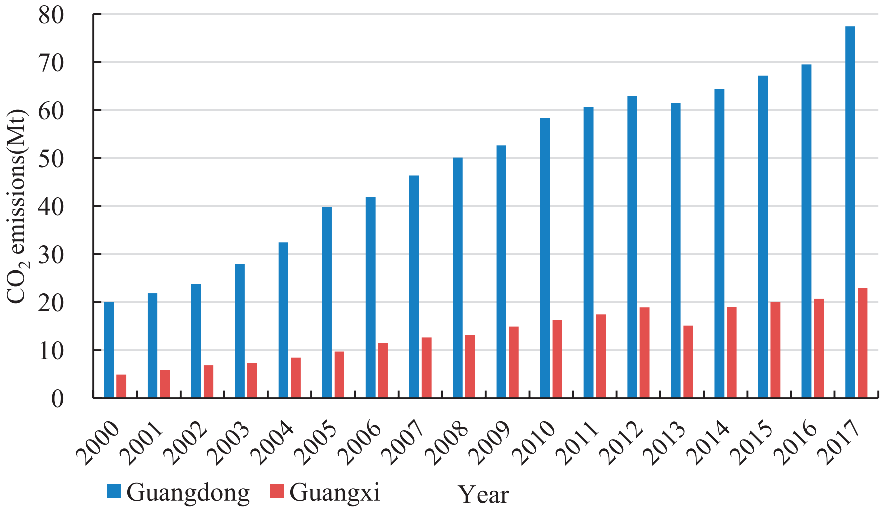

Fig. 2. Transportation CO_2 emissions in the two provinces.

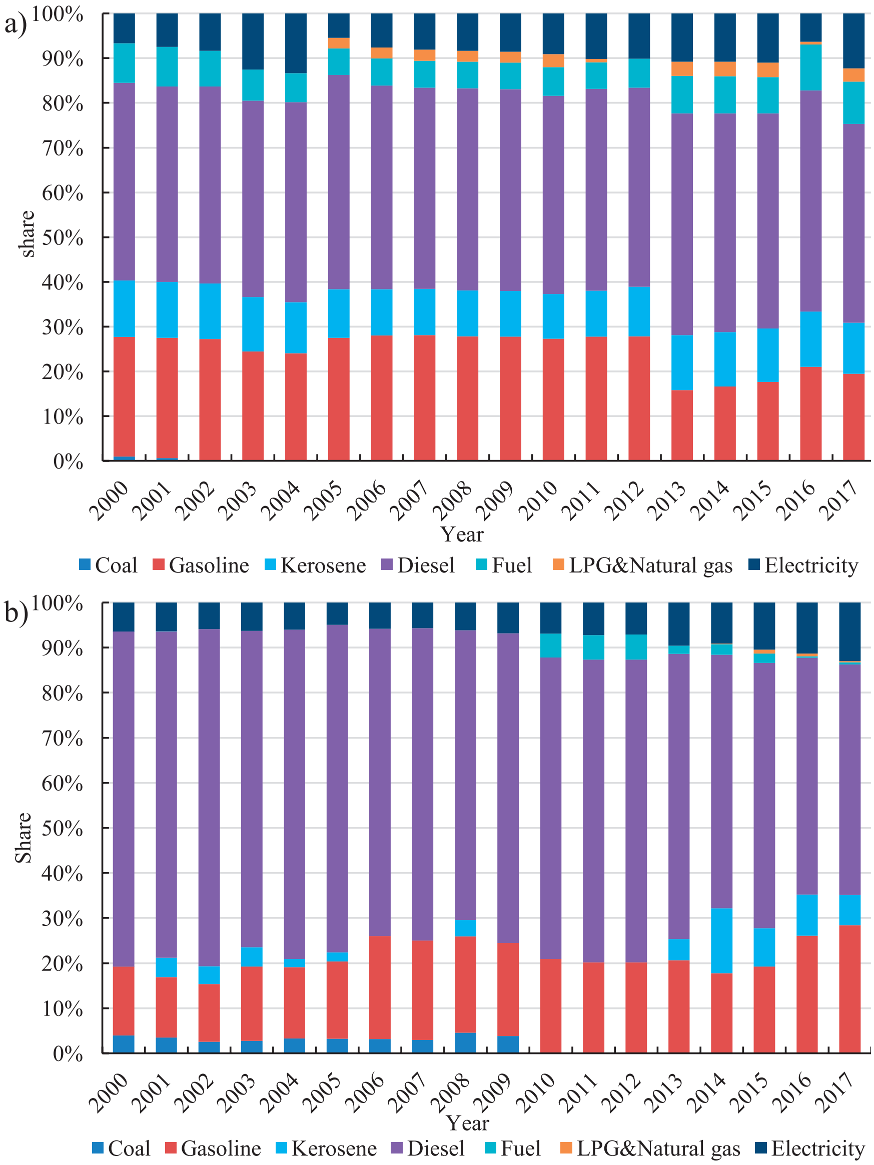

Fig. 3. Energy structure of CO_2 emissions in two areas: a) Guangdong, b) Guangxi.

exhibits similarities and differences. The energy structure of Guangdong is significantly improved relative to that of Guangxi. The similarity between the two is that gasoline and diesel are the primary sources of transportation energy in both provinces, while the contribution of electricity is gradually increasing. The proportion of diesel among these energy sources is more evident, particularly in Guangxi. The CO_2 generated by diesel accounted for 74.32% in 2000, and then decreased to 51.18% in 2017, clearly signifying the continuous optimization of the energy structure in the transportation sector in Guangxi. The share of diesel in Guangdong is relatively stable, with an annual average of 45.73%. Simultaneously, the CO_2 produced by coal gradually decreased with time for the two provinces. The energy structure differs in two aspects in the two regions. First, the CO_2 generated by fuel oil accounts for a small proportion in Guangxi but is more stable in Guangdong, with an annual average share of 7.36%. Second, the proportions of liquefied natural gas and natural gas are inadequate in Guangxi compared with those in Guangdong. The central cause for this phenomenon is the gradual increase in the role of technological advancements in the transportation sector in Guangdong, promoting energy efficiency. It is worth learning in Guangxi.

Analysis of Decoupling State in Guangdong and Guangxi

Fig. 4 presents the decoupling results between energy-related CO_2 and regional economic output in Guangdong

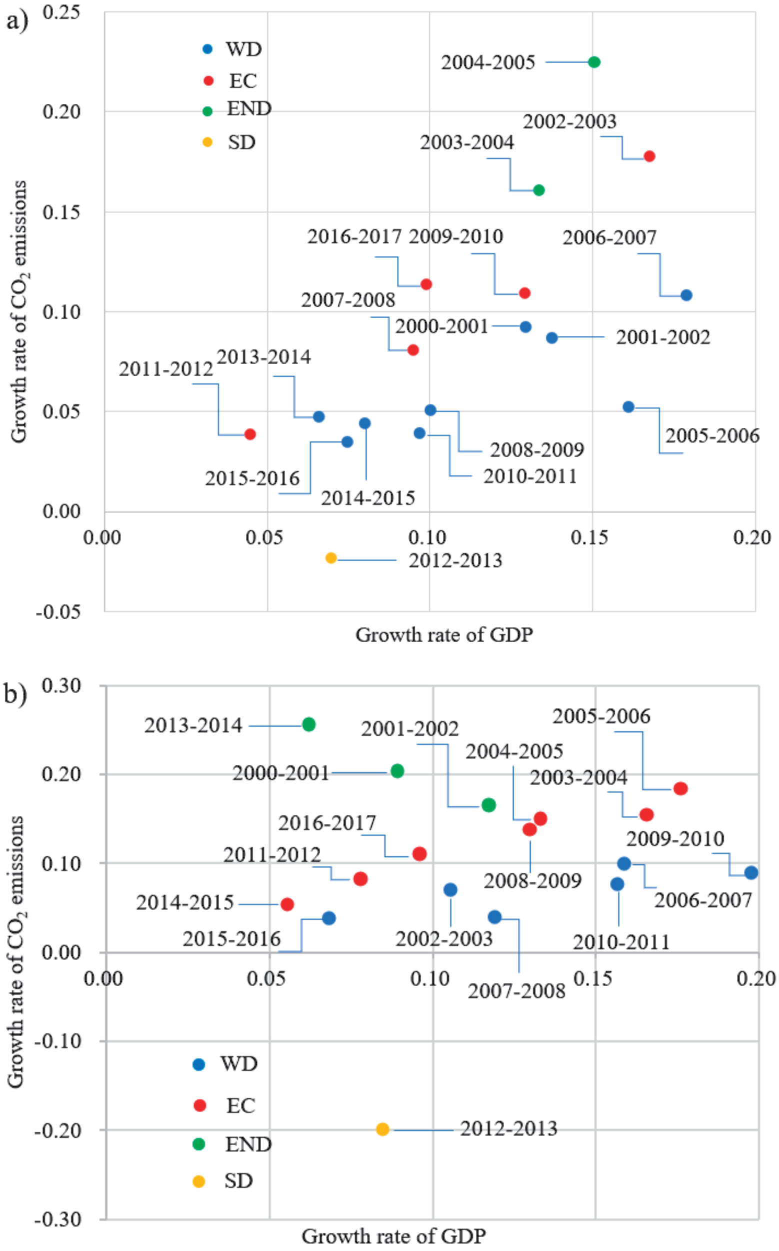

Fig. 4. Decoupling results of transportation CO_2 emissions in two areas: a) Guangdong, b) Guangxi.

and Guangxi. As shown in the figures, four decoupling states occurred in both provinces during the study period: weak decoupling (WD), expansive coupling (EC), expansive negative decoupling (END), and strong decoupling (SD).

The WD state was observed in Guangdong in 2000-2002, 2005-2007, 2008-2009, 2010-2011, and 2013-2016 and in Guangxi in 2002-2003, 2006-2008, 2009-2011, and 2015-2016. These results agree with the findings of Chen et al. [38]. WD is a good state, indicating that although CO_2 emissions increase with transportation, the growth rate is lower relative to that of economic development. The 9-year WD state in Guangdong and the 6-year WD state in Guangxi denote strategies related to energy saving and emission reduction have clearly emerged.

The EC state occurred in Guangdong in 2002-2003, 2007-2008, 2009-2010, 2011-2012, and 2016-2017. This finding is inconsistent with the result of Chen et al. [38], which reported a WD state in 2007-2008 and 2011-2012. The EC state emerged in Guangxi in 2003-2006, 2008-2009, 2011-2012, 2014-2015, and 2016-2017. In this state, transportation CO_2 emissions exhibit a homologous evolution trend with regional economic growth, reflecting a gradual increase in transportation energy consumption. Compared with that in Guangdong, the EC state lasted for 7 years in Guangxi, indicating relatively low energy efficiency.

Guangdong entered an END state in 2003-2005, which concurs with the finding of Wang et al. [8]. This state occurred in Guangxi in 2000-2002 and 2013-2014. In the END state, the CO_2 growth rate is higher than economic growth, signifying an inefficient and expansive development pattern. Excessive CO_2 emissions occur at the cost of high environmental pressure and energy consumption. In such case, energy conservation and environmental protection should be urgently considered while developing transportation for both provinces. The two provinces entered an SD state in 2012-2013. The state in Guangxi differed from that in Li et al. [35] probably due to disregarding CO_2 emissions from electricity. Although this decoupling state is ideal, it is unstable. Maintaining an SD state is an effective approach for achieving low-carbon transportation. That is, this state is the goal of transportation development in both provinces.

Regarding the comparison between decoupling states of Guangdong and Guangxi, the similarity is that the decoupling state of the whole research interval was concentrated on WD and EC states. And the SD state was observed in 2012-2013 for two provinces. The difference is that the WD state was dominating in Guangdong while the EC state was main in Guangxi during 2000-2017. It shows that the governance ability of the environment has been more strengthened in Guangdong than that of Guangxi. And Guangdong was further decoupled from economy and energy consumption.

Comparison of Factors Related to CO_2 Emissions in Guangdong and Guangxi

In accordance with Eq. (6), Fig. 5 depicts the changes in aggregated transportation CO_2 emissions in Guangdong and Guangxi in 2000-2017. Aggregated changes in transportation CO_2 emissions differed between the two provinces. On the one hand, CO_2 emissions increased by 57.43 Mt in Guangdong and 18.10 Mt in Guangxi throughout the study period. Moreover, they decreased by 1.49 Mt in Guangdong

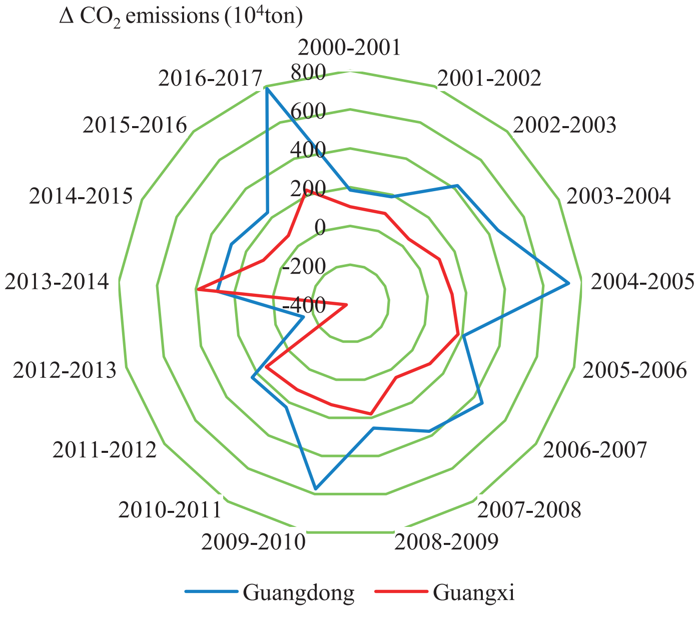

Fig. 5. Aggregate CO_2 emission changes in the two provinces.

and 3.78 Mt in Guangxi in 2012-2013. On the other hand, the annual CO_2 increase in Guangdong was more than that in Guangxi, except in 2012-2013, fully reflecting the regional difference in transportation CO_2 emissions between Guangdong and Guangxi. Simultaneously, the result also indicates that pressure on the environment from transportation CO_2 emissions in Guangdong has increased significantly. Thus, reducing CO_2 emissions should be given sufficient attention in Guangdong.

To study the effects of different factors related to transportation CO_2 emissions, the factors are divided into CO_2 emission intensity, energy intensity, freight transportation intensity, R&D efficiency, per capita R&D expenditure, and population size. The effects of the six factors are comparatively analyzed in the next section. In the current study, a positive value of each effect indicates an increase in CO_2 emissions, whereas a negative value shows a decrease in CO_2 emissions.

CO_2 Emission Intensity

As a commonly adopted indicator, CO_2 emission intensity is the ratio of transportation CO_2 emissions to energy consumption in a certain sector. It reflects the effect of the energy structure. Fig. 6 illustrates the effect of CO_2 emission intensity on CO_2 emissions in Guangdong and Guangxi. From a global perspective, no observable changes occurred in the CO_2 emission intensity of the two provinces in 2000-2017; this result is in line with other research findings [33, 42]. Moreover, evident fluctuations occurred in Guangdong in 2012-2014 and 2015-2017 compared with that in Guangxi. The most significant decrease in CO_2 emissions in Guangdong was 10.05 Mt in 2012-2013 and the most evident increase was 9.79 Mt in 2013-2014. The possible reason for these phenomena is the profound effect of the implementation of the 12th Five-Year Plan of Guangdong, which is a critical period for accelerating the transformation of economic development in Guangdong. During this period, Guangdong actively implemented strategies related to energy conservation and emission reduction while simultaneously optimizing its energy structure, such as eliminating highly polluting and energy-consuming enterprises. These measures led to temporary changes in CO_2 emissions.

Energy Intensity

Energy intensity is energy consumption per unit of freight turnover; it reflects the efficiency of energy utilization and freight transportation. Fig. 7 shows the effect of energy intensity on CO_2 emissions in Guangdong and Guangxi in 2000-2017. Energy intensity plays a positive role in reducing CO_2 emissions in the two areas, although this effect is small in Guangxi. This result is consistent with the findings of other studies [17, 19]. From a microscopic point of view, energy intensity increased CO_2 emissions in Guangdong in 2000-2008 (except in 2005-2006), but significantly reduced such emissions in 2008-2017 (except in 2014-2015). This result shows that the energy structure in Guangdong was effectively improved from the 11th Five-Year Plan to the 12th Five-Year Plan. Meanwhile, energy intensity significantly decreased CO_2 emissions by 8.82 Mt in Guangxi in 2009-2013. From a macro perspective, the aggregate influence of energy intensity decreased CO_2 emissions by 74.33 Mt in Guangdong and 5.12 Mt in Guangxi in 2000-2017, although the decrease is not too evident in the latter. The primary reason for such phenomenon may be the slow industrial development that leads to the low demand for freight transportation in Guangxi. Moreover, industrial development strategies have not been effectively transformed. The gross industrial output value increased to 10628.27 billion yuan in Guangdong and 1854.39 billion yuan (at 2000 constant price) in Guangxi in 2017, indicating the significant difference in total industrial output between the two provinces. The poor industrial development pattern

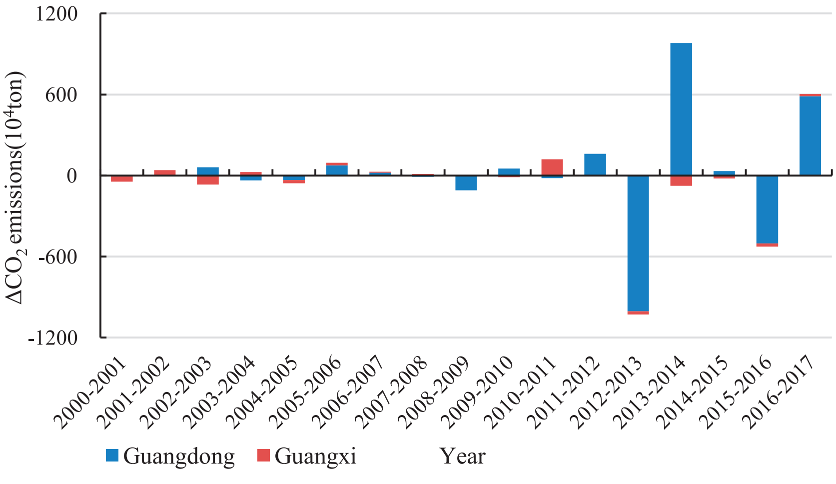

Fig. 6. Effect of CO_2 emission intensity on CO_2 emissions between Guangdong and Guangxi.

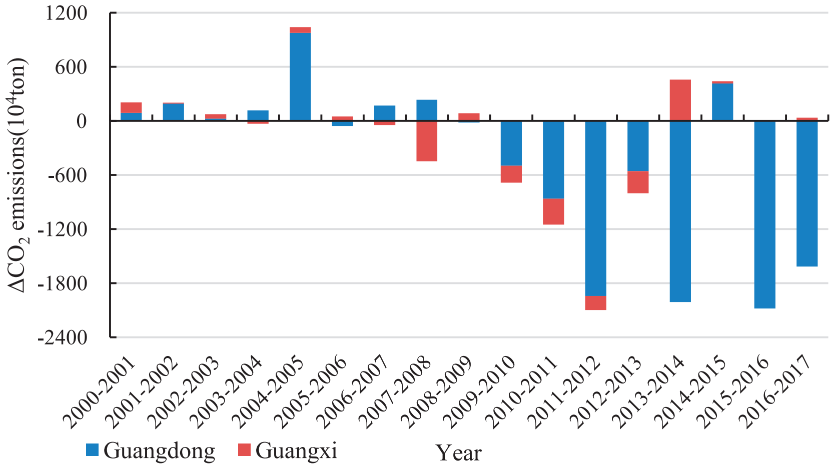

Fig. 7. Effect of energy intensity on CO_2 emissions between Guangdong and Guangxi.

in Guangxi is unfavorable for freight transportation in the long run. To achieve the maximum potential of industrial development, the structure of industrial development must be transformed further in Guangxi.

Freight Transportation Intensity

Freight transportation intensity indicates the amount of freight turnover per unit of economic output. Fig. 8 presents the effect of freight transportation intensity on CO_2 emissions in the two areas in 2000-2017. This effect differs between the two provinces. The aggregate effect of freight transportation intensity increased CO_2 emissions by 48.27 Mt in Guangdong in 2000-2017. This result disagrees with the findings of other studies [30, 43]. This phenomenon is attributed to the existing booming economy, frequent foreign direct investments, and high urbanization rate in Guangdong, facilitating a large proportion of passenger and freight transport. In this case, the increase in CO_2 emissions is expected. The accumulated effect decreased CO_2 emissions by 0.65 Mt in Guangxi in 2000-2017. The effect of freight transportation intensity is not evident. This phenomenon is largely related to the inadequate transportation infrastructure in Guangxi. From 2013 to 2017, the length of the expressway in Guangxi increased from 3305 km to 5259 km, while that in Guangdong increased from 5703 km to 8347 km. This indicates the slow development of Guangxi's transportation infrastructure. The inadequate transportation infrastructure constrains the freight transportation development in Guangxi. Therefore, enhancing transportation infrastructure construction is the priority goal of transportation development in Guangxi. Simultaneously, waterway freight in Guangxi exhibits promising development potential. It should fully utilize its advantages to promote waterway transport for Guangxi, which cannot only save energy effectively, but can also reduce CO_2 emissions.

R&D Efficiency

The effect of R&D efficiency on transportation CO_2 emissions was not discussed in previous studies.

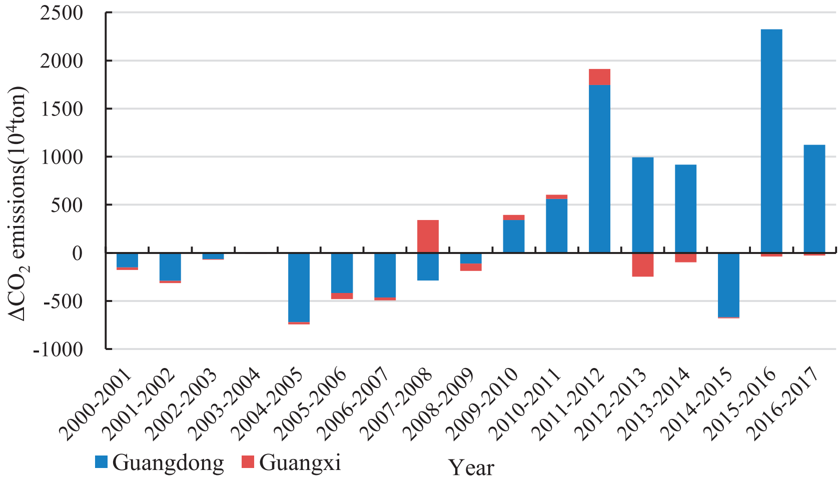

Fig. 8. Effect of freight transport intensity on CO_2 emissions between Guangdong and Guangxi.

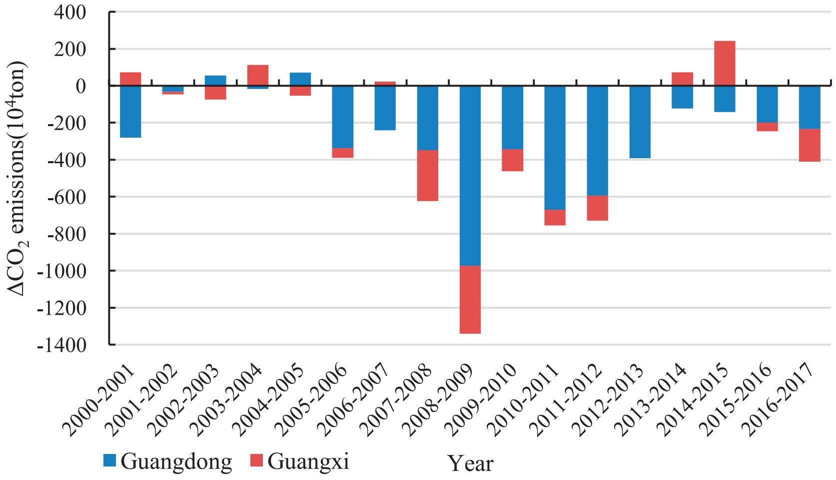

Fig. 9. Effect of R&D efficiency on CO_2 emissions between Guangdong and Guangxi.

This indicator represents economic output per unit of R&D expenditure, and it reflects the efficiency of R&D expenditure. Fig. 9 illustrates the effect of R&D efficiency on transportation CO_2 emissions in Guangdong and Guangxi. The magnitude of this effect differs between the two areas. R&D efficiency reduced CO_2 emissions by 48.02 Mt in Guangdong throughout the study period, particularly in 2008-2009 when it decreased by 9.73 Mt. This result is consistent with the finding of another study [44]. The related reason is that Guangdong has upgraded its industrial structure. R&D expenditure increased to 168.10 billion yuan (at 2000 constant price) in 2017, with an average annual growth rate of 17.77%. The innovation-driven development strategy has been implemented in Guangdong. R&D, as a key driver of economic growth, is increasingly valued. The inhibitory effect of R&D efficiency is relatively weak in Guangxi, and it decreased CO_2 emissions by 8.78 Mt in 2000-2017. Evidently, R&D expenditure in Guangxi is not yet significant primarily due to its slow economic development relative to Guangdong. Total economic output improved from 208.00 billion yuan in 2000 to 1355.99 billion yuan in 2017 in Guangxi, while it increased from 1081.02 billion yuan to 6573.81 billion yuan (at 2000 constant price) in Guangdong. This finding effectively illustrates the effect of economic development on R&D expenditure. For Guangxi, seizing the opportunity to accelerate economic development is urgent. Unleashing the development potential of Guangxi by deepening reforms is imperative. An example is accelerating the transformation of the industrial development pattern and improving the quality of the tourism industry. Simultaneously, an innovation-driven development strategy can be implemented to promote high-quality economic development in Guangxi.

Per Capita R&D Expenditure

Per capita R&D expenditure is a technological indicator that complements previous studies in transportation. Fig. 10 illustrates the effect of per capita R&D expenditure on CO_2 emissions in the two

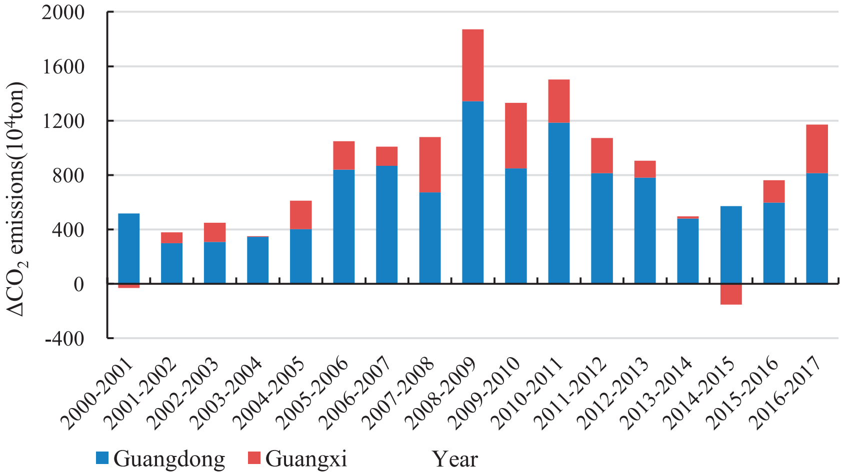

Fig. 10. Effect of per capita R&D expenditure on CO_2 emissions between Guangdong and Guangxi.

provinces in 2000-2017. Per capita R&D expenditure plays a decisive role in increasing CO_2 emissions in Guangdong and Guangxi, although this effect is relatively small in Guangxi. Such result is in line with the finding of Li et al. [45]. The effect of per capita R&D expenditure increased CO_2 emissions by 116.86 Mt in Guangdong, while it cumulatively added 32.59 Mt in Guangxi throughout the study period. The effect is relatively small in Guangxi compared with that in Guangdong, which may be ascribed to the inadequate R&D expenditure in Guangxi. R&D expenditure in Guangdong and Guangxi increased to 168.10 billion yuan and 9.45 billion yuan (at 2000 constant price), respectively, in 2017. Another reason is probably the smaller population size in Guangxi than in Guangdong every year. In addition, the increase in CO_2 emissions of 13.43 Mt and 5.28 Mt was significant in Guangdong and Guangxi, respectively, in 2008-2009. This phenomenon may be attributed to the economic crisis in 2008. To stabilize the domestic economy during this period, the government accelerated the construction of transportation infrastructure, increasing transportation CO_2 emissions.

Population Size

With regard to the effect of population size on transportation CO_2 emissions, many studies [27, 28, 37] have shown that population size is an important factor to increases CO_2 emissions. Fig. 11 depicts the positive relationship between population size and CO_2 emissions in Guangdong and Guangxi in 2000-2017; such relationship is consistent with those in other studies [17, 19, 28]. However, a difference in the role of population size is evident between the two areas. Cumulative CO_2 emissions in Guangdong increased by 12.27 Mt during the study period, with the most significant increase of 1.68 Mt occurring in 2009-2010. This finding indicates that the excessive population size in Guangdong tends to exert major pressure on its transportation system. The aggregate effect increased CO_2 emissions by 0.54 Mt in Guangxi in 2000-2017. This effect fully reflects the difference in the role of population size between Guangdong and Guangxi. This phenomenon is attributed to the population size in the two provinces. Resident population size increased from 47.51 million in 2000 to 48.85 million in 2017 in Guangxi and from 86.50 million to 111.69 million in Guangdong. Another reason that cannot be disregarded is that the labor force from Guangxi moves to developed regions, further decreasing population size in Guangxi. In the long run, population size in Guangdong should be appropriately controlled. Meanwhile, the local government should properly increase population size to promote sustainable development in Guangxi. In addition, the role of population size in Guangxi unexpectedly reduced CO_2 emissions in 2004-2005 and 2009–2010 due to a decrease in population of 4.68% and 5.07% in 2005 and 2010, respectively.

Policy Implications

Transportation CO_2 emissions and their influencing factors differ in Guangdong and Guangxi. From the preceding results, the following policy recommendations are presented to decrease transportation CO_2 emissions in relatively developed and less developed areas.

(1) Reducing energy intensity is an effective method for decoupling CO_2 emissions and GDP. From the above analysis, energy intensity can reduce transportation CO_2 emissions; however, the inhibitory effect is relatively weak in Guangxi, indicating considerable potential to enhance this effect. The following measures can be taken to reduce energy intensity in different areas. 1) Restricting or banning high-emission trucks. Due to the significant pressure exerted on the environment by high-emission trucks, taking measures for managing trucks is necessary. 2) Increasing technological innovations to improve energy efficiency. R&D

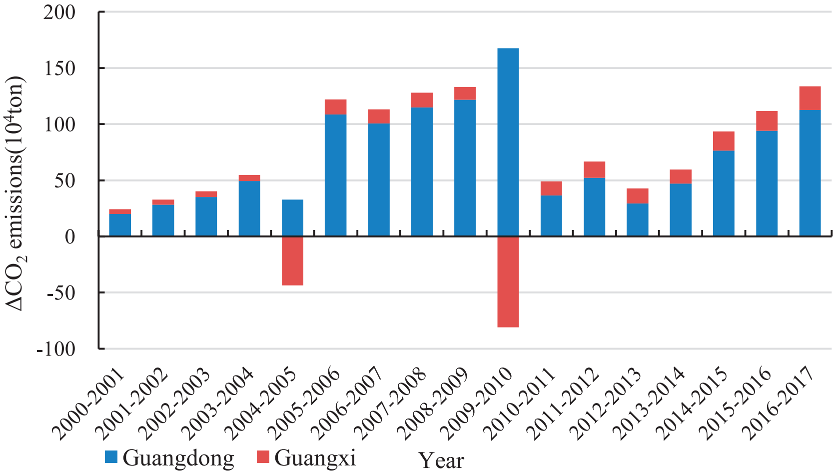

Fig. 11. Effect of population size on CO_2 emissions between Guangdong and Guangxi.

expenditure should be increased further to promote the quality of oil products.

(2) Optimizing the energy structure can reduce transportation CO_2 emissions from a long-term perspective. It is also the goal of transportation energy development in different areas. The government should take relevant measures to decrease the proportions of diesel and gasoline in transportation. An active adoption of clean energy sources will effectively cut down CO_2 emissions. The proportions of liquefied petroleum gas, natural gas, and electricity in transportation should be improved further in different areas. Moreover, R&D expenditure is planned properly in the transportation sector for different regions in accordance with the actual situation. Appropriately increasing R&D expenditure could facilitate to develop energy-saving technologies. Simultaneously, the use of energy-saving technologies should be actively promoted in transportation in different areas.

(3) The layout of the transport networks in different areas is supposed to be optimized further. Guangxi is an underdeveloped area with an inadequate transportation infrastructure. It should prioritize investing in transportation infrastructure development to improve accessibility and connectivity of rails and roads, facilitating the movement of people and freight. In the beginning of the 14th Five-Year Plan, the layout of the transport network urgently needs a scientific planning for Guangxi. Taking advantage of its geographical location, it is strongly supported to establish a comprehensive high-quality transportation network in Guangdong and achieves easy and fast connections between different modes of transportation in the context of low-carbon transportation.

(4) Accelerating modal shift to public and active transport is largely indispensable for transport towards carbon neutrality. The explosive growth of private cars has generated a large amount of CO_2, especially in developed areas, which has aroused widespread concern. In order to effectively alleviate this problem, local authorities should actively carry out the project of a transformed bus industry and a green bus revolution for different provinces. Moreover, local government would continue to support demand for zero emission vehicles through a series of financial and non-financial incentives. And publishing specific guidance for local authorities on support for shared car ownership and shared occupancy schemes and services is highly encouraging. People will use their cars differently and less often.

(5) Less developed areas should learn from the experiences of developed areas. Advanced management and technical experiences exist in some fields in developed areas, such as Guangdong. However, many detrimental development issues exist in less developed areas, providing an opportunity to enhance association between regions. Guangxi, as a less developed area, should learn valuable experiences from Guangdong with respect to industrial development, environmental management, R&D expenditure, and freight transportation. It should facilitate the promotion of economic growth and decrease transportation CO_2 emissions.

The five measures for reducing transportation CO_2 emissions are introduced from the perspective of carbon neutrality. However, reducing CO_2 emissions is not only limited to these aspects, such as the development of multimodal transport in different provinces. Nevertheless, these measures exert a positive effect for carbon neutrality in the long run. Decreasing transportation CO_2 emissions is a common way to achieve carbon neutrality for a country or region, however, it is not the final goal in the long run. Achieving sustainable development and carbon neutrality in transportation is the ultimate goal [46]. Realizing this target brings many benefits to human healthy life [47]. It may take a long time to achieve this goal for different areas in China. However, we firmly believe that it can be realized with the progress of technology and economic development.

Conclusions

On the basis of related data in the transportation sector, the Tapio decoupling model and the LMDI model are used to explore the relationship between energy-related CO_2 emissions and economic development for the period of 2000-2017. Moreover, this study extends the LMDI model by introducing R&D efficiency and per capita R&D expenditure. It verifies the differences in drivers related to CO_2 emissions between Guangdong and Guangxi. The key findings of this research are as follows.

(1) Only four decoupling states were observed in Guangdong and Guangxi in 2000–2017. WD and EC were the major decoupling states in the two areas while SD and END occurred less frequently.

(2) Per capita R&D expenditure in both provinces was the primary contributor to increasing CO_2 emissions in 2000–2017, followed by population size. The increases were 116.86 Mt and 12.27 Mt in Guangdong, respectively. Relative to those in Guangdong, the roles played by per capita R&D expenditure and population size in increasing CO_2 emissions were smaller in Guangxi, increasing by 32.59 Mt and 0.54 Mt, respectively.

(3) Energy intensity was the decisive inhibitory factor for reducing CO_2 emissions, followed by R&D efficiency in 2000–2017 in Guangdong. The reductions were 74.33 Mt and 48.02 Mt, respectively. Meanwhile, the two effects were smaller in Guangxi compared with those in Guangdong. Energy intensity and R&D efficiency reduced CO_2 emissions by 5.12 Mt and 8.78 Mt, respectively.

(4) Interestingly, freight transportation intensity increased CO_2 emissions by 48.27 Mt in Guangdong. By contrast, it reduced CO_2 emissions by 0.65 Mt in

Guangxi throughout the study period, demonstrating a weak inhibitory effect.

In the paper, some limitations need to be considered. First, six factors were investigated and other factors were not considered, such as economic structure and transport mode. Second, it does not explore the spatial role of the factors related transportation CO_2 emissions. Our future research includes the following directions:1) Other factors need further validate to reflect regional disparities. 2) A spatial econometric model is employed to uncover spatial characteristics of factors in Guangdong and Guangxi. Besides, the two provinces are only representatives of relatively developed and less developed areas, respectively. Other developed and less developed areas can be selected in future studies.

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Conflicts of Interest

The authors declare that they have no conflict of interest.

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