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Spatiotemporal Patterns and Decomposition Analysis of CO_2 Emissions from Transportation in the Pearl River Delta

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Abstract: Controlling and mitigating CO_2 emissions is a challenge for the global environment. Furthermore, transportation is one of the major sources of energy consumption and air pollution emissions. For this reason, this paper estimated CO_2 emissions by the bottom-up method, and presented spatiotemporal patterns by spatial autocorrelation methods from transportation during the period 2006 to 2016. It further analyzed the impact factors of CO_2 emissions in the Pearl River Delta by the Logarithmic Mean Divisa Index (LMDI)decomposition method. The results indicated that from 2006 to 2016, total CO_2 emissions increased year by year. Guangzhou and Shenzhen were the major contributors to regional transportation CO_2 emissions. From the perspective of different transport modes, intercity passenger transport and freight transport have always been dominant in the past 11 years. The results indicated that aviation transport was the largest contributor, and that travel by road was the second one. The CO_2 emissions generated by rail and water transport were much lower than those from aviation. Private cars became the main source of urban passenger transport CO_2 emissions, and their advantages kept increasing. The results indicated that the spatial agglomeration trend feature was negatively correlated, and the further the distance, the more similar the attributes. The cumulative contribution values of population, economic development, transport intensity, energy intensity and energy structure were all positive values, while the cumulative contribution values of transport structure and emission factor were negative. The findings of this study offer help for the scientific understanding of those CO_2 emissions from transportation, and for adopting effective measures to reduce CO_2 emissions and for the development of green transportation.

Keywords: CO_2 emissions; transportation; LMDI Method; influencing factors; Pearl River Delta

1. Introduction

Greenhouse gases such as CO_2 will cause global warming and pose a serious issue to sustainable development. Transportation, as a key industry of energy consumption, contributes markedly to the sources of greenhouse gas and air pollution emissions [1]. Since the beginning of the 21st century, Asia has been the major source of CO_2 emissions from fuel combustion. In 2016, it reached 17.4 Gt CO_2 emissions, twice as much as the Americas, and three times as much as Europe [2]. In 2016, China accounted for 52% of emissions in Asia, followed by India, which accounted for 12%.

In 2016, transport-generated CO_2 emissions reached 7.87 Gt, with a share of 27%, which is 71% higher than the 1990 levels [2]. The International Energy Agency predicts that global carbon emissions from transportation will increase by 140% in 2050, compared with 2000 [3]. The continuous increase of CO_2 emissions from transportation has increased the difficulty of carbon emission reduction in transportation, and seriously affected the efficiency of social and economic development as well as the quality of travel of residents. Thus, the study of CO_2 emissions from transportation has important implications for effectively reducing carbon emissions, achieving energy conservation and the development of green transportation.

Many studies mainly focuses on the estimation of CO_2 emissions from transportation, the relationship between energy consumption, CO_2 emissions and industry development, energy efficiency and any influencing factors of carbon emissions [4–6]. In general, most CO_2 emissions are caused by transportation, and from the German Socio-Economic Panel (GSOEP), it can be seen that nearly 50% of all carbon emissions are caused by private transportation [4]. Many factors affect CO_2 emissions from transportation, for instance, transport scales [5], the growth of population and the increase of economic levels [6]. Lu et al. tested a comparative study on the carbon emissions data of highway vehicles, and proposed that economic growth, vehicle fuel intensity and vehicle emission efficiency are the main factors affecting the carbon emission of highway vehicles [7]. Andreoni and Galmarini argued that carbon emissions from air and water transport in Europe from 2001 to 2008 have increased, indicating that economic increase is the main driver of rising CO_2 emissions [8]. Carbon emissions from passenger or freight transport have also been extensively studied [9,10].

Many studies have explored the factors influencing CO_2 emissions from transportation, such as economic growth [6,11,12], CO_2 intensity [8,13,14], energy intensity [15,16], and transport intensity [17,18]. On the one hand, scholars have analyzed CO_2 emissions from transportation in many countries. The main drivers for the Latin America region are the activity and the population effects, followed by the fossil fuel and the carbonization effects, while the intensity effect is revealed as the only inhibitor [19]. Schipper et al. analyzed the relative contribution of transportation in 10 industrial countries, and found that freight energy consumption and CO_2 emissions increased significantly [16]. Timilsina and Shrestha studied the potential impacts of CO_2 emissions growth in 12 Asian countries, and found that per capita Gross Domestic Product (GDP), population growth, and transportation energy intensity were the main drivers [14]. On the other hand, some scholars have focused the CO_2 emissions from transportation in a specific country. Lakshmanan and Han analyzed the energy consumption and CO_2 emissions of American transportation, pointing out that GDP, population and population travel propensity are the most important factors [6]. Wang et al. explored the factors affecting transportation CO_2 emissions in China, and found that per capita economic activities and transport mode conversion are important factors for the increase of CO_2 emissions, while transport energy intensity and transport service share are important factors for the reduction of CO_2 emission [17]. Yang et al. concluded that social and economic development and income are the main factor forces for per capita transportation carbon emissions [20].

Previous studies have explored transportation carbon emissions from different perspectives, but overall, most of research on CO_2 emissions from transportation concentrated at the national level [18,21,22], and therefore lacking research on the regional level. Moreover, in the study of CO_2 emissions from transportation, compared with passenger transport, freight transport is rarely studied [23]. Hence, this study selected the Pearl River Delta region, and classified the transportation system into four modes: Road, railway, water and aviation, including freight and passenger transportation. The bottom-up and spatial autocorrelation methods were used to quantitatively analyze the change trend and characteristics of CO_2 emissions during 2006 to 2016, from the perspective of time series and spatial distribution. On this basis, the decomposition model of the factors affecting CO_2 emissions is constructed, in order to provide a basis for formulating policies for mitigating CO_2 emission from the comprehensive transportation system, and the alleviation of global warming.

2. Methodology and Data Source

2.1. Calculation the CO_2 Emission from Transportation

According to Figure 1, the three major transport systems of any region are freight transport, intercity passenger transport and urban passenger transport. Freight transport and intercity passenger transport cover rail, road, water, and aviation transport. Nevertheless, in the transport sector, in China, few studies considered urban passenger transport when calculating CO_2 emissions because of the limitation of statistics scale, that urban passenger transport is not included in the statistics of passenger transport volume, and is usually neglected [24]. Therefore, this research aimed to calculate urban passenger transport by various vehicle types [25].

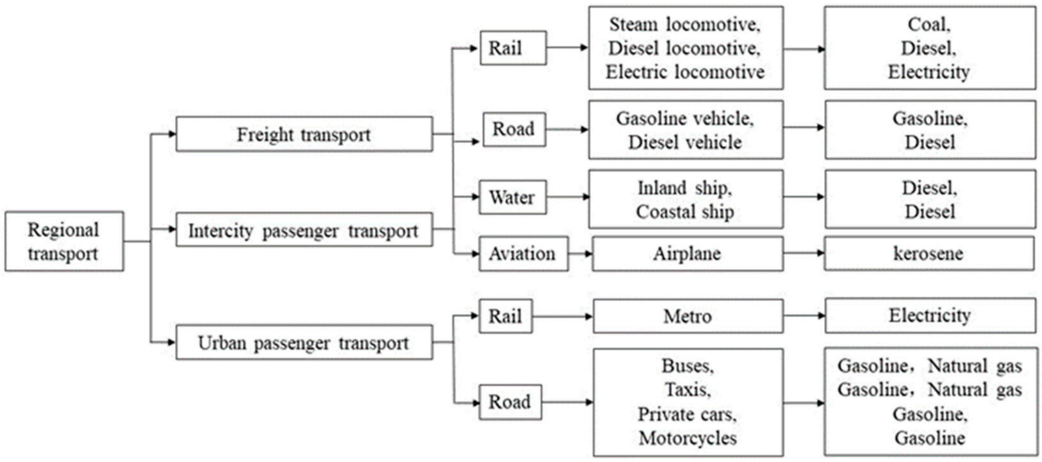


Figure 1. Architecture of calculation of CO_2 emission from transportation.

Estimate the CO_2 emission based on transport activity by means of a consideration of the travel mode, modal share, emission factor, and energy intensity [26] (IPCC, 2006). Thus, the CO_2 emissions of the total regional transport turnover volume can be expressed as:

$$G_t = \sum{}_{i,j} TV_{i,j,t} \times EI_{i,j,t} \times EF_{i,j,t} \quad (1)$$

where G_t represents the CO_2 emissions from transportation. The i, j and t indicate the transport mode, vehicle type and year, respectively, while $TV_{i,j,t}$ means the total regional transport turnover volume, and $EI_{i,j,t}$ implies the energy consumption per ton-km. $EF_{i,j,t}$ denotes the CO_2 emissions factor.

To better analyze the CO_2 emission of urban passenger transport, this paper selects buses, taxis, private cars and motorcycles as the main vehicles (Liu et al., 2013). The formula is

$$G_{t,up} = \sum{}_{i,j} VP_{i,j,t} \times VKT_{i,j,t} \times FE_{i,j,t} \times EF_{i,j,t} \quad (2)$$

where $G_{t,up}$ indicates CO_2 emissions from urban passenger transport.$VP_{i,j,t}$ means the vehicle population; $VKT_{i,j,t}$ represents the vehicle kilometer traveled each year; $FE_{i,j,t}$ implies the fuel consumption rate, and $EF_{i,j,t}$ indicates the CO_2 emissions factor.

2.2. Spatial Autocorrelation

Spatial autocorrelation is a global measure of whether a certain property of a space has obvious clustering or discrete features in its geographic location. Moran's I coefficient is the most frequently used method for spatial autocorrelation [27]. In this paper, the spatial correction of CO_2 emissions from transportation was calculated using the Moran's I index, and ArcGIS software, which in general is calculated as Equation (3):

$$Moran's\ \mathrm{I} = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}(x_i - \overline{x})(x_j - \overline{x})}{\sum_{i=1}^{n}(x_i - \overline{x})^2\left(\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}\right)} \quad (3)$$

where n represents the quantity of cities, x_i and x_j stands for the CO_2 emission from transportation within cities i and j, respectively; W_{ij} is the spatial weight matrix of cities i and j, and $\overline{x}$ indicates the average CO_2 emission. The importance of the Moran's I can be tested using the Z (I), which can be computed with the formula (4):

$$Z(I) = \frac{[I - E(I)]}{\sqrt{Var(I)}} \quad (4)$$

where E(I) represents the mathematical expectation of Moran's I, and Var(I) refers to the variance in this Moran's I. If the value of Moran's I is greater than 0, this will indicate positive spatial correlation, in that the CO_2 emission from transportation has spatial clustering characteristics, which means that, if the geographical location is close, the CO_2 emission value will show the same trend. Inversely, when Moran's I is less than 0, this implies a negative spatial correlation that has discrete features. If Moran's I is near 0, this will indicate the spatially random distribution of the pattern. The closer the absolute value is to 1, the more significant the clustering or discrete features.

2.3. The Logarithmic Mean Divisia Index (LMDI) Decomposition Model

Currently, the decomposition model is frequently adopted to measure the influencing factors upon CO_2 emission from transportation [28]. There are two major models of decomposition analysis, namely, index decomposition analysis (IDA) and structural decomposition analysis (SDA) [29]. The SDA approach utilizes an input-output table based upon a matrix of consumption coefficients, which constrains its application [30]. Therefore, the IDA approach is relatively superior. The LMDI has more obvious advantages than the IDA approach. First, the LMDI has a strong theoretical foundation, better adaptability, good interpretation results and ease of use [31]. Second, it solves the residual and negative value problems [32]. Thus, this study adopts the LMDI approach to investigate the influential drivers of regional CO_2 emissions from transportation. Based on the Kaya identity [33], the CO_2 emissions can be expressed as:

$$G = \sum_{i,k} P \times \frac{D}{P} \times \frac{T}{D} \times \frac{T_i}{T} \times \frac{E_i}{T_i} \times \frac{E_{i,k}}{E_i} \times \frac{G_{i,k}}{E_{i,k}} \quad (5)$$

where i means the transport mode, including rail, road, water, aviation; k refers to the energy type; P stands for the population, D indicates the GDP, T denotes the transport turnover volume, E means the energy consumption, and G stands for the CO_2 emission. The Formula (5) can be further described as:

$$\mathrm{G} = \sum_{i,k} P \times ED \times TI \times TS_i \times EI_i \times ES_{i,k} \times EF_{i,k} \quad (6)$$

As shown in Equation (6), there are seven factors influencing total CO_2 emissions (G). Taking the population, economic development, transport structure, transport structure, energy intensity, energy structure and emission factor constituted the seven drivers of CO_2 emissions [34].

Based on the decomposition method proposed by Ang, the aggregate CO_2 emission change can be further expressed in Equations (7) and (8), respectively [35].

$$D_{\mathrm{tot}} = \frac{G^t}{G^0} = D_p D_{ED} D_{TI} D_{TS} D_{EI} D_{ES} D_{EF} \quad (7)$$

$$\Delta G_{tot} = \mathrm{G}^{\mathrm{t}} - \mathrm{G}^0 = \Delta G_P + \Delta G_{ED} + \Delta G_{TI} + \Delta G_{TS} + \Delta G_{EI} + \Delta G_{ES} + \Delta G_{EF} \quad (8)$$

where G^t and G^0 refer to the CO_2 emissions in a base year 0 and a target year t, respectively; *tot* denotes the whole change of CO_2 emission. The P, ED, TI, TS, EI, ES, and EF, represent population, economic development, transport year, transport structure, energy intensity, energy structure and emission factor, respectively. ΔG_{tot} indicates the total variation in CO_2 emissions. Variables ΔG_P, ΔG_{ED}, ΔG_{TI}, ΔG_{TS}, ΔG_{EI}, ΔG_{ES}, and ΔG_{EF} imply the CO_2 emission caused by carbon coefficient changes, population, economic development, transport intensity, transport structure, energy intensity, energy structure, and emission factor, respectively. D_P, D_{ED}, D_{TI}, D_{TS}, D_{EI}, D_{ES}, and D_{EF} indicate the contribution rate of drivers to the variety of CO_2 emissions from transportation, respectively. The calculation for the decomposing changes results of the effects according to the LMDI decomposition analysis are as follows [35]:

$$D_P = \exp\left(\sum_{i,k} \frac{\left(G_{i,k}^t - G_{i,k}^0\right)/\left(InG_{i,k}^t - InG_{i,k}^0\right)}{\left(G^t - G^0\right)/\left(InG^t - InG^0\right)} In\left(\frac{P^t}{P^0}\right)\right) \tag{9}$$

$$\Delta G_P = \sum_{i,k} \frac{G_{i,k}^t - G_{i,k}^0}{InG_{i,k}^t - InG_{i,k}^0} In\left(\frac{P^t}{P^0}\right) \tag{10}$$

$$D_{ED} = \exp\left(\sum_{i,k} \frac{\left(G_{i,k}^t - G_{i,k}^0\right)/\left(InG_{i,k}^t - InG_{i,k}^0\right)}{\left(G^t - G^0\right)/\left(InG^t - InG^0\right)} In\left(\frac{ED^t}{ED^0}\right)\right) \tag{11}$$

$$\Delta G_{ED} = \sum_{i,k} \frac{G_{i,k}^t - G_{i,k}^0}{InG_{i,k}^t - InG_{i,k}^0} In\left(\frac{ED^t}{ED^0}\right) \tag{12}$$

$$D_{TI} = \exp\left(\sum_{i,k} \frac{\left(G_{i,k}^t - G_{i,k}^0\right)/\left(InG_{i,k}^t - InG_{i,k}^0\right)}{\left(G^t - G^0\right)/\left(InG^t - InG^0\right)} In\left(\frac{TI^t}{TI^0}\right)\right) \tag{13}$$

$$\Delta G_{TI} = \sum_{i,k} \frac{G_{i,k}^t - G_{i,k}^0}{InG_{i,k}^t - InG_{i,k}^0} In\left(\frac{TI^t}{TI^0}\right) \tag{14}$$

$$D_{TS} = \exp\left(\sum_{i,k} \frac{\left(G_{i,k}^t - G_{i,k}^0\right)/\left(InG_{i,k}^t - InG_{i,k}^0\right)}{\left(G^t - G^0\right)/\left(InG^t - InG^0\right)} In\left(\frac{TS_i{}^t}{TS_i{}^0}\right)\right) \tag{15}$$

$$\Delta G_{TS} = \sum_{i,k} \frac{G_{i,k}^t - G_{i,k}^0}{InG_{i,k}^t - InG_{i,k}^0} In\left(\frac{TS_i{}^t}{TS_i{}^0}\right) \tag{16}$$

$$D_{EI} = \exp\left(\sum_{i,k} \frac{\left(G_{i,k}^t - G_{i,k}^0\right)/\left(InG_{i,k}^t - InG_{i,k}^0\right)}{\left(G^t - G^0\right)/\left(InG^t - InG^0\right)} In\left(\frac{EI_i{}^t}{EI_i{}^0}\right)\right) \tag{17}$$

$$\Delta G_{EI} = \sum_{i,k} \frac{G_{i,k}^t - G_{i,k}^0}{InG_{i,k}^t - InG_{i,k}^0} In\left(\frac{EI_i{}^t}{EI_i{}^0}\right) \tag{18}$$

$$D_{ES} = \exp\left(\sum_{i,k} \frac{\left(G_{i,k}^t - G_{i,k}^0\right)/\left(InG_{i,k}^t - InG_{i,k}^0\right)}{\left(G^t - G^0\right)/\left(InG^t - InG^0\right)} In\left(\frac{ES_{i,k}^t}{ES_{i,k}^0}\right)\right) \tag{19}$$

$$\Delta G_{ES} = \sum_{i,k} \frac{G_{i,k}^t - G_{i,k}^0}{InG_{i,k}^t - InG_{i,k}^0} In\left(\frac{ES_{i,k}^t}{ES_{i,k}^0}\right) \tag{20}$$

$$D_{EF} = \exp\left(\sum_{i,k} \frac{\left(G_{i,k}^t - G_{i,k}^0\right)/\left(InG_{i,k}^t - InG_{i,k}^0\right)}{\left(G^t - G^0\right)/\left(InG^t - InG^0\right)} In\left(\frac{EF_{i,k}^t}{EF_{i,k}^0}\right)\right) \tag{21}$$

$$\Delta G_{EF} = \sum_{i,k} \frac{G_{i,k}^{t} - G_{i,k}^{0}}{InG_{i,k}^{t} - InG_{i,k}^{0}} In\left(\frac{EF_{i,k}^{t}}{EF_{i,k}^{0}}\right) \tag{22}$$

2.4. Data Sources

The Pearl River Delta is located in southeastern China (114°47–114°53 E, 21°50–23°53 N), which spatial distribution is shown in Figure 2. The data of turnover volume and the energy consumption per ton-kilometer are all from the China Statistical Yearbook [36]. The related CO_2 emission factors come from the Intergovernmental Panel on Climate Change [25,37]. The vehicle populations are from the Guangdong Statistical Yearbook [38]. The numbers of road vehicles are shown in Figure 3. The VKT for different vehicle types from 2006–2016 are taken from the literature [39–46]. The fuel consumption rates are collected from a research report [33].

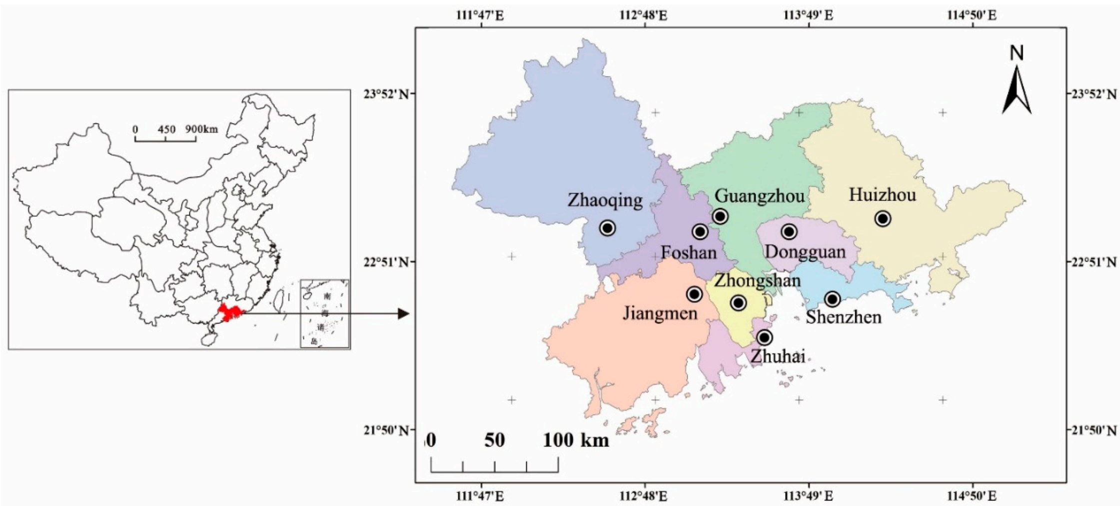


Figure 2. Location of the Pearl River Delta.

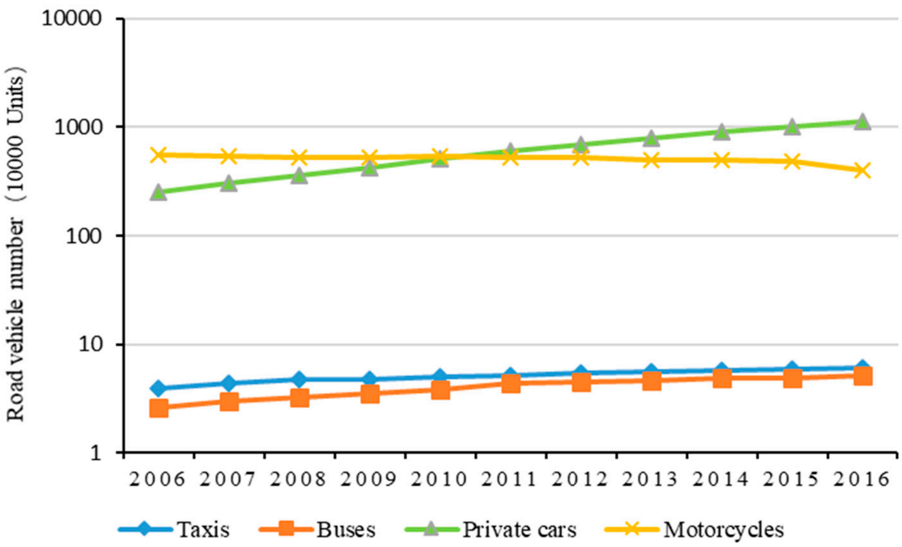


Figure 3. Road vehicle numbers in the Pearl River Delta, 2006-2016.

3. Results and Discussions

3.1. Estimation of CO_2 Emissions

3.1.1. CO_2 Emissions Trends

Figure 4 portrays the variation trends of CO_2 emissions from transportation of the Pearl River Delta from 2006 to 2016.The total CO_2 emissions maintained a remarkable growth from 43.98 million tons in 2006 to 117.16 million tons in 2016. In terms of Figure 4, the CO_2 emissions of transport in Guangzhou and Shenzhen were both continuously increasing. Specifically, Guangzhou increased more, while Shenzhen had a higher growth rate. In 2016, the contribution rate of CO_2 emission in Guangzhou was the highest, reaching 64.10%, while that in Shenzhen and Foshan were 24.99% and 2.33%, respectively. Compared with 2006, the contribution rate of Guangzhou increased by 5.89%, Shenzhen increased by 8.85%, Zhuhai increased by 1.32%, and Foshan decreased by 4.74%. However, the contribution rate of Huizhou, Dongguan, Zhongshan, Jiangmen and Zhaoqing all decreased. Thus, after nearly 11 years of development, the internal structure of transport CO_2 emissions has not changed greatly. Guangzhou and Shenzhen are still the main contributors to regional transport CO_2 emissions. The proportion of the two cities was 89.10% in 2016, and the contribution rate of Shenzhen showed the fastest growth.

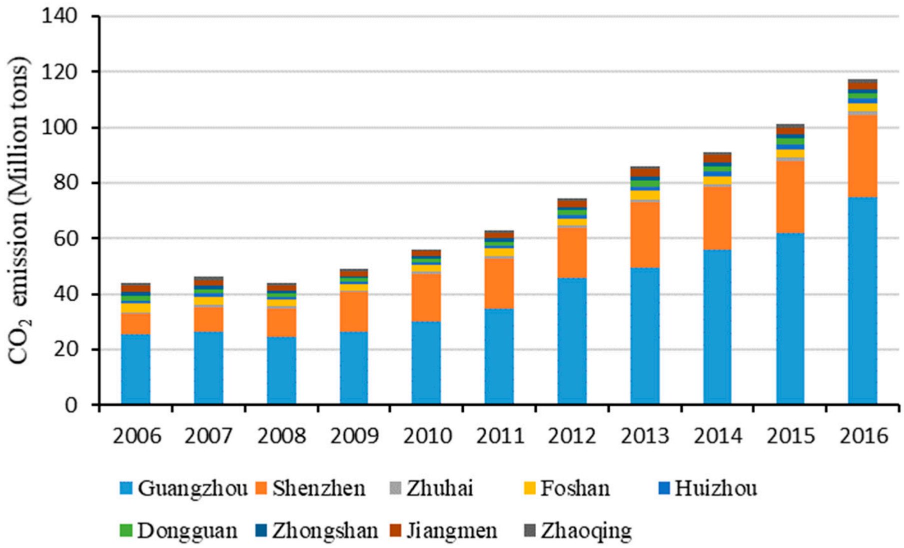


Figure 4. The CO_2 emissions from transportation of the Pearl River Delta, 2006–2016.

3.1.2. Contribution of Different Transport Modes

As indicated in Figure 5, intercity passenger transport and freight transport have always been dominant in the past 11 years. In 2016, the contribution rate of intercity passenger carbon emissions reached 49.43%, freight carbon emissions accounted for 42.74%, and urban passenger carbon emissions contributed 7.83% (Figure 5). Aviation transport was the largest contributor to CO_2 emissions in the Pearl River Delta, the share of which increased from 48.85% in 2006 to 69.98% in 2016 (Figure 6). Road transport was the second contributor, but the proportion decreased from 42.98% in 2006 to 14.14% in 2016. In contrast, rail transport and water transport maintained the lower emissions. The railway increased from 1.04% in 2006 to 11.57% in 2016, while water transportation decreased from 7.53% in 2006 to 4.30% in 2016. During the study period, the number of private car ownerships in the Pearl River Delta region increased from 2,500,000 in 2006 to 11,366,000 in 2016, and the total quadrupled, with an average annual increase of 886,700 (Figure 3). Private cars became the main source of urban passenger transport CO_2 emission in the Pearl River Delta, and their advantages kept increasing. By contrast, the number of motorcycles continued to decrease, with a reduction of 1,595,000 vehicles in

11 years; motorcycles had a low fuel consumption per unit kilometer and a short average mileage, resulting in a continuous reduction in total CO_2 emissions. During the periods, the number of buses increased by 24,900, and the number of taxis has increased by 20,700. There was a relatively small absolute amount and little increase, so the total CO_2 emissions remained stable (Figure 7).

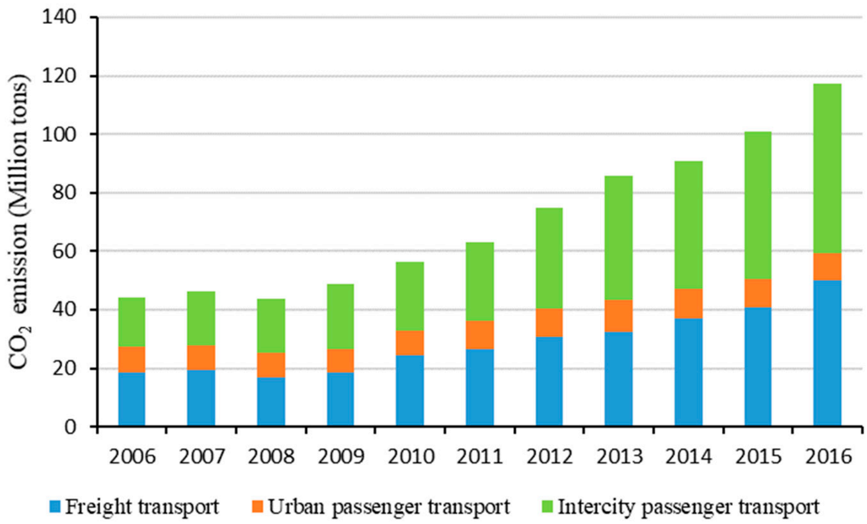


Figure 5. CO_2 emissions from passenger and freight transport of the Pearl River Delta, 2006–2016.

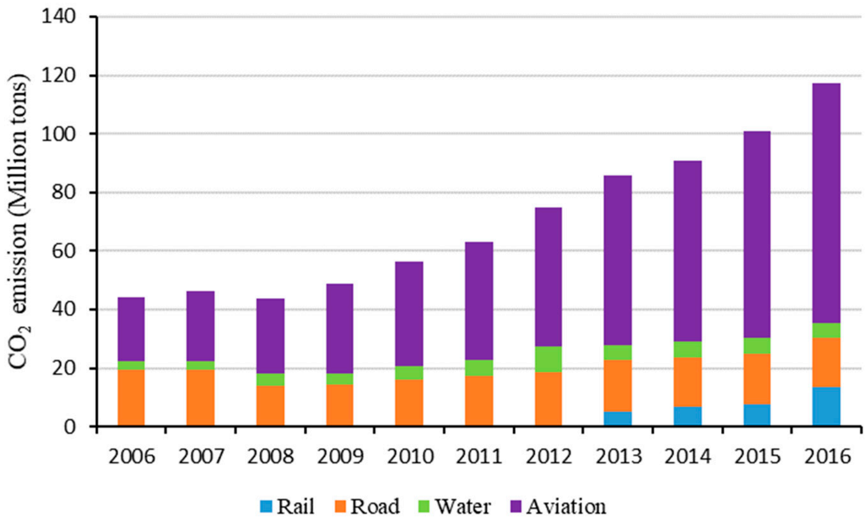


Figure 6. The modal structure of CO_2 emissions from transportation of the Pearl River Delta, 2006–2016.

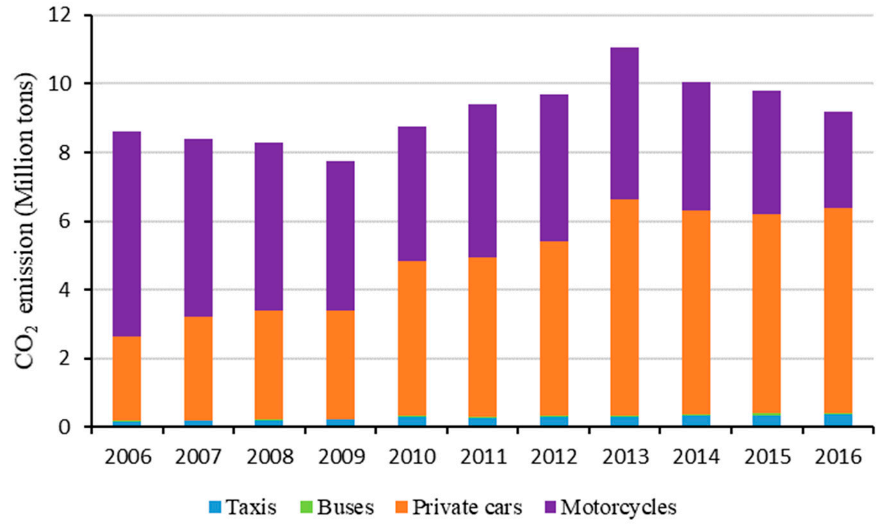


Figure 7. The CO_2 emissions of various vehicles of the Pearl River Delta, 2006–2016.

3.1.3. Trends of per Capita CO_2 Emissions and Emissions Intensities

The per capita CO_2 emission is calculated by the human unit, which directly reflects and illustrates the population occupancy of limited emission space in different regions [39]. Figure 8 visualized that the per capita CO_2 emissions are on the rise, from 928.68kg/person in 2006 to 1952.21kg/person in 2016, increasing by two times. The emission intensity represents the CO_2 emissions generated by each unit of GDP growth, which was mainly adopted to estimate the relationship between the economic level and CO_2 emissions. The emission intensity of the Pearl River Delta was fluctuating, showing a trend, first of decline, then of stabilizing, and then of rising again. According to the trend of emission intensity, this can be classified into three stages: 2006–2008, 2008–2011 and 2011–2016. From 2006 to 2008, the emission intensity of transportation decreased, that is, the CO_2 emissions from the unit GDP decreased, which indicated that any development of transport-ation tended to be a low-carbon mode. From 2008 to 2011, the emission intensity of transport developed steadily. From 2011 to 2016, the emission intensity of transport increased, which may be due to the acceleration of industrialization and urbanization, and the rapid development of motorization, resulting in a higher growth rate of CO_2 emissions than GDP.

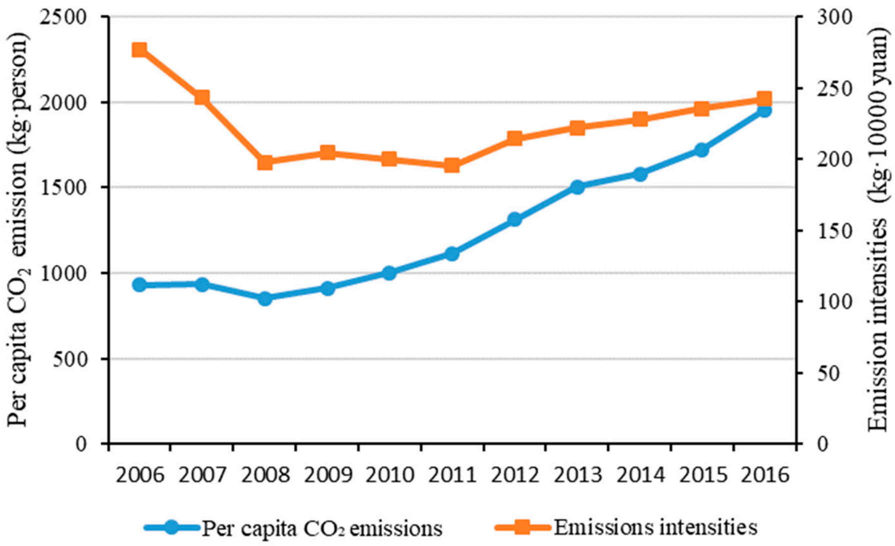


Figure 8. The per capita CO_2 emissions and emissions intensities of the Pearl River Delta, 2006–2016.

3.2. Spatiotemporal Patterns of CO_2 Emissions

In this study, the spatiotemporal evolution characteristics of CO_2 emissions from transportation were analyzed by CV and Moran's I (Figure 9). The CV value increased continuously from 2007 to 2012, hitting its highest point in 2012, after which it reduced in 2013, and then rose steadily. It revealed that that there is a big gap overall between the cities, and that it requires measures to reduce regional differences. As shown in Figure 9, compared to the CV index, Moran's I index variation trend was approximately similar to it. Moreover, Moran's I was less than 0, indicating that the spatial agglomeration trend feature was negatively correlated, and the further the distance, the more similar the attributes. Based on the estimated CO_2 emissions from 2006 to 2016, ArcGIS software was used to study the variations characteristics of each urban spatial pattern. The CO_2 emissions from transportation were calculated, and the chart of the spatiotemporal patterns of urban CO_2 emissions during 2006 to 2016 (Figure 10) was made. It shows that the urban CO_2 emissions from transportation had a significant overall upward trend. From the perspective of high emission cities, Guangzhou and Shenzhen were the two cities with the highest emissions, and their CO_2 emissions kept rising and were always ranked in the top two.

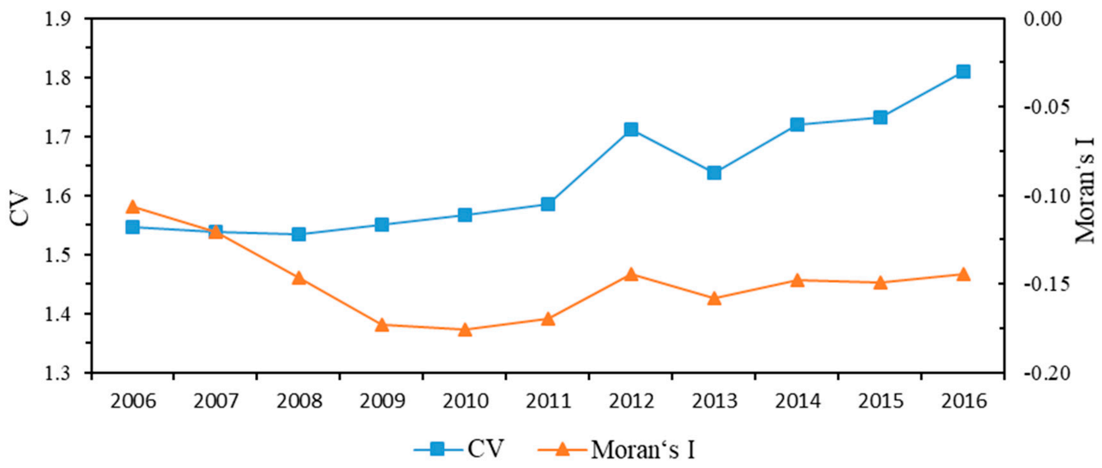


Figure 9. CV and Global Moran's I of the CO_2 emission in the Pearl River Delta, 2006–2016.

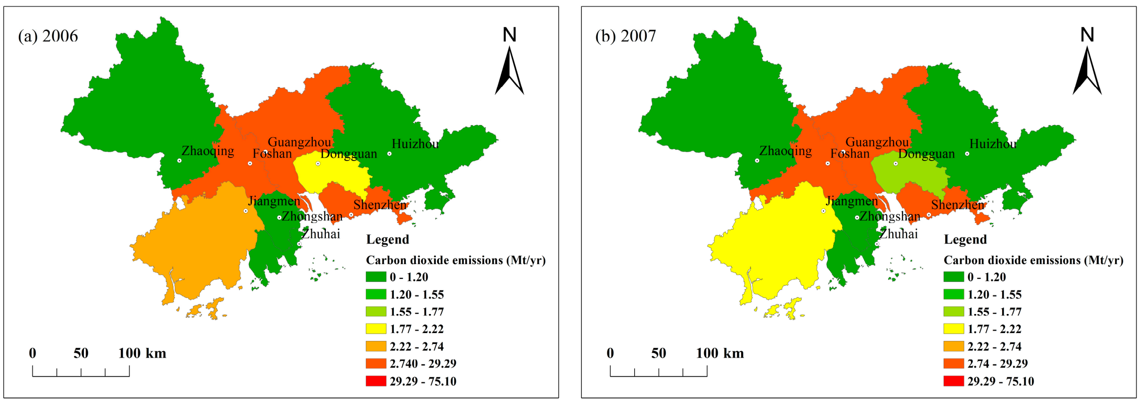
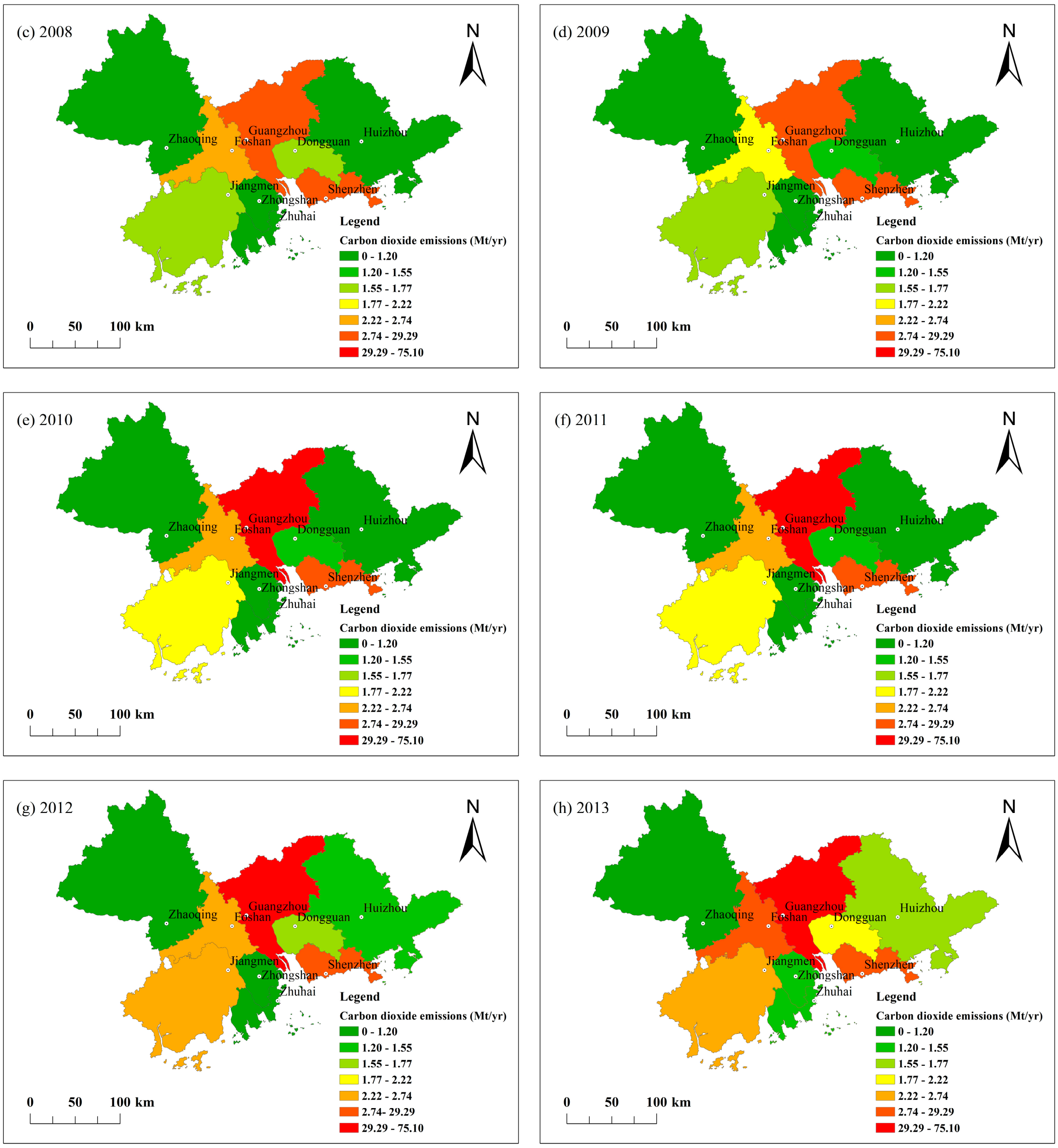


Figure 10. *Cont.*



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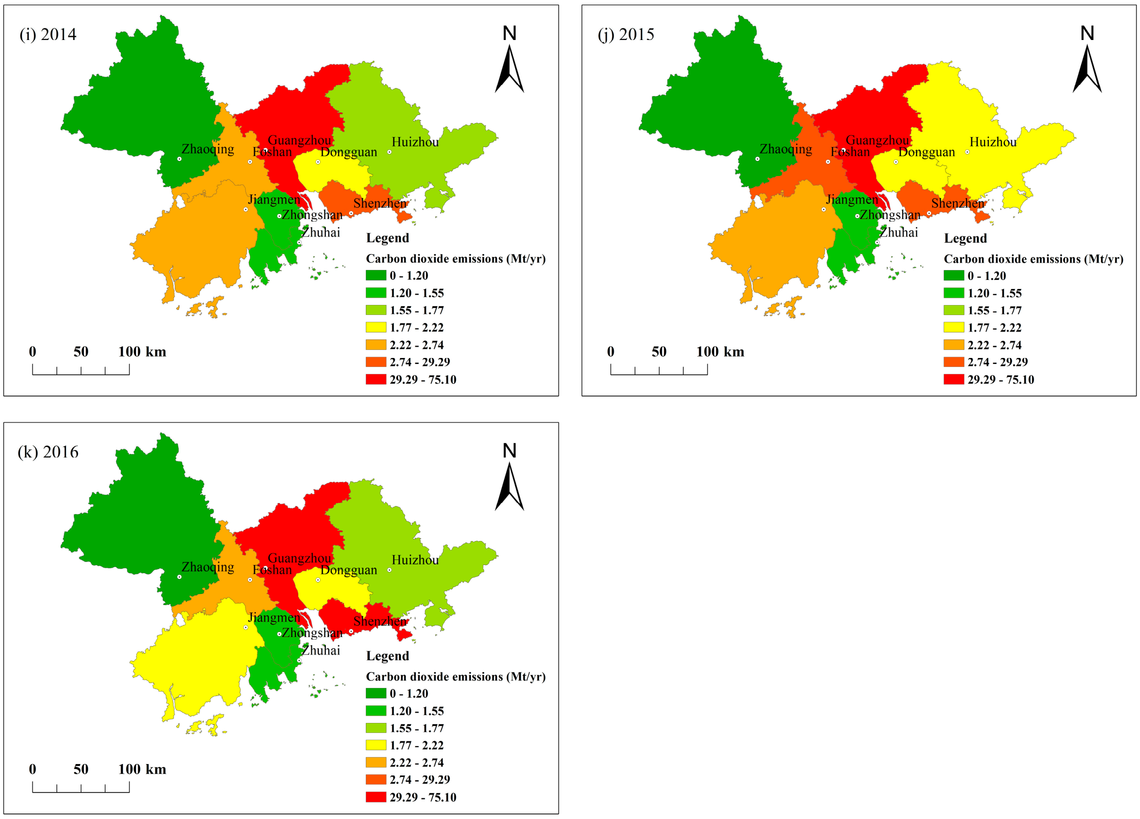

Figure 10. Spatiotemporal patterns of CO_2 emission of the Pearl River Delta, 2006–2016.

In Guangzhou, CO_2 emissions in 2016 increased about threefold compared with 2006. In Shenzhen, CO_2 emissions increased about fourfold compared with 2006. In terms of low emission cities, four cities had a CO_2 emission of less than 1.2 million tons in 2006, and it decreased to one city in 2013. The CO_2 emissions of the other seven cities were all behind Guangzhou and Shenzhen, but there were also four levels. Foshan was the third high-emission city in addition to Guangzhou and Shenzhen. In 2010, it was in the second level. In 2012, Jiangmen entered the ranks of high-emission cities. Dongguan entered the fourth level in 2014, and the CO_2 emissions of the three cities of Zhongshan, Zhuhai and Zhaoqing were at the lowest level, but their own emissions were rising. The total CO_2 emissions of Guangzhou and Shenzhen were in the first level in the region, and with the growth of CO_2 emissions in the whole region, the proportion of emissions in Guangzhou and Shenzhen showed an upward trend, from 74.35% in 2006 to 89.10% in 2016.

3.3. Decomposition Analysis of Factors Influencing CO_2 Emission

In this section, LMDI decomposition method results demonstrate different influencing factors. From 2006 to 2016, the CO_2 emissions of the region increased by 73.18 million tons. According to formulas (3) to (22), the trends of all seven factors are shown in Table 1, Table 2 and Figure 11. It can be seen that the contribution value and contribution rate of population factors and economic development factors to the growth of CO_2 emission were relatively stable and always played a facilitating role. Other factors have different roles in different years, changing alternatively. Some were positive for several years, and some were negative for a few years. As Figure 11 shows, the cumulative contribution values of population, economic development, transport intensity, energy intensity and energy structure are all positive values, while the cumulative contribution values of transport structure and emission factor are negative.

Table 1. The contribution value of seven factors to the growth of CO_2 emissions of the Pearl River Delta.

Years	The contribution value (Million tons)							
	ΔG	ΔG_p	ΔG_{ED}	ΔG_{TI}	ΔG_{TS}	ΔG_{EI}	ΔG_{ES}	ΔG_{EF}
2006–2007	2.13	1.10	3.92	−5.10	5.76	−2.21	−0.11	−1.22
2007–2008	−2.30	0.71	2.03	−2.02	2.25	−0.95	0.12	−4.44
2008–2009	5.11	0.72	0.60	−4.96	10.98	−2.82	0.12	0.46
2009–2010	7.24	2.17	5.46	−1.76	2.71	−2.15	1.02	−0.22
2010–2011	6.83	0.35	9.10	1.01	0.01	−4.93	−0.72	2.01
2011–2012	11.65	0.30	3.62	20.06	−12.05	−1.57	−0.25	1.55
2012–2013	11.32	0.24	4.22	6.24	−14.01	15.69	0.73	−1.79
2013–2014	5.06	0.71	1.89	15.91	−11.74	0.45	1.85	−4.01
2014–2015	10.03	2.02	5.65	−1.79	0.24	2.84	2.82	−1.76
2015–2016	16.12	1.50	27.25	7.35	−22.02	−0.64	2.65	0.03
2006–2016	73.19	9.80	63.74	34.94	−37.87	3.73	8.23	−9.39

Table 2. The contribution rate of seven factors to the growth of CO_2 emission of the Pearl River Delta.

Years	D_p	D_{ED}	D_{TI}	D_{TS}	D_{EI}	D_{ES}	D_{EF}
2006–2007	1.01	1.05	0.94	1.07	0.97	1.00	0.99
2007–2008	1.01	1.04	0.96	1.04	0.98	1.00	0.92
2008–2009	1.01	1.01	0.93	1.18	0.96	1.00	1.01
2009–2010	1.01	1.03	0.99	1.01	0.99	1.01	1.00
2010–2011	1.00	1.03	1.00	1.00	0.98	1.00	1.01
2011–2012	1.00	1.02	1.10	0.94	0.99	1.00	1.01
2012–2013	1.00	1.02	1.04	0.93	1.09	1.00	0.99
2013–2014	1.00	1.00	1.04	0.97	1.00	1.00	0.99
2014–2015	1.00	1.01	1.00	1.00	1.01	1.01	1.00
2015–2016	1.00	1.02	1.08	0.94	1.00	1.01	1.00
2006–2016	1.23	2.93	1.25	0.75	0.90	1.04	0.81

The cumulative value of CO_2 emissions caused by economic development was continuously rising, indicating that economic growth led to a growth of CO_2 emissions during this period. From 2006 to 2016, the cumulative contribution of CO_2 emissions was 63.74 million tons, and the contribution rate reached 2.93, which was the first incremental factor for CO_2 emissions. The transport intensity was the ratio of the passenger and goods conversion turnover completed by transport within a certain period to the gross national product of the same period, and measures the degree of connection with the transport and the national economy. From the perspective of time series, transport intensity had both a promoting effect and a restraining effect on the increase of CO_2 emissions. It had a general role in boosting the cumulative contribution of CO_2 emissions during the period of 34.94 million tons, contributing 1.25 to the Pearl River Delta, which was the second incremental factor of CO_2 emissions.

With the increase in population and urbanization rate, the growth of transport demand and the change of transport mode, the annual contribution of population to the growth of CO_2 emissions remained stable. The cumulative contribution CO_2 emissions in 2006–2016 were 9.80 million tons, with a contribution rate of 1.23, which was the third incremental factor. In the structure of transport energy consumption, the proportion of high emission energy such as kerosene and gasoline was continuously decreasing. However, with the continuous improvement of peoples' living standards, the aviation transport industry developed rapidly, and the use ratio of kerosene increased from 10.03% to 14.64%. The CO_2 emission contribution values of 2007, 2011 and 2012 decreased during 2006–2016, but overall, the adjustment of energy structure had no obvious effect on CO_2 emission reduction, and accumulated a contribution of 8.23 million tons, the contributing rate was 1.04, which was the fourth incremental factor. The energy intensity was rooted in the energy consumption of the unit transport turnover to characterize the energy input and output characteristics of the transport mode, reflecting the overall utilization efficiency of transport energy. It showed inhibition in multiple years, but overall showed a promoting effect.

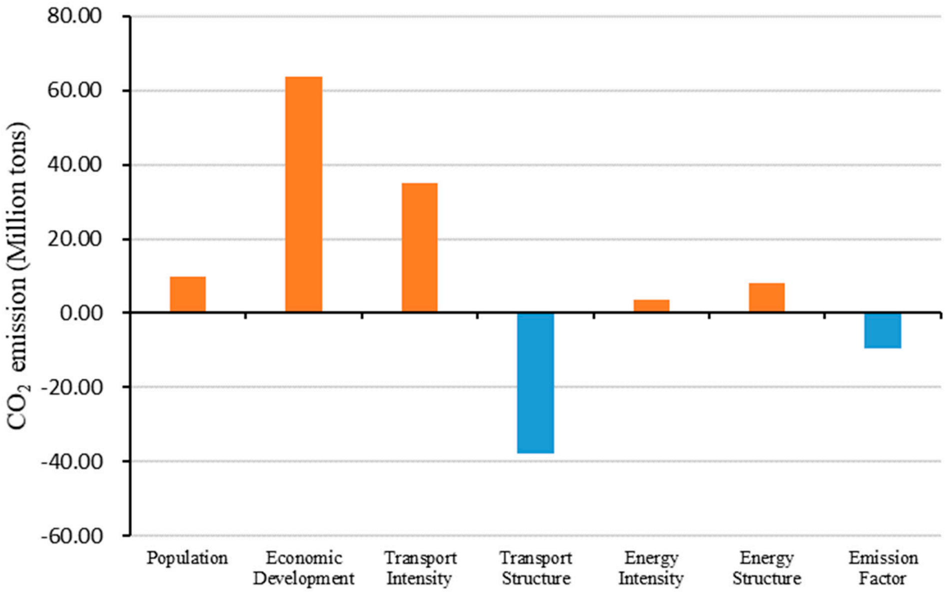

Figure 11. The cumulative contribution values of seven factors to the growth of CO_2 emissions within the Pearl River Delta.

The transport structure had an important inhibitory effect on the increasing emissions from transportation. The contribution value in 2007–2009 exceeded the economic development of the increasing emissions, but it played a depressing effect in the following years. In 2006–2016, the CO_2 emissions decreased by 37.87 million tons, with a contribution rate of 0.75, which was the first reduction factor. The CO_2 emission factor reflects the changes in the structure of transport energy, and characterizes the changes in the overall level of CO_2 emission reduction technology. Among the major energy sources for transport, the CO_2 emission coefficient of gasoline was the highest, while that of the natural remained the smallest. In 2006–2016, the CO_2 emission decreased by 9.39 million tons, with the contribution rate of 0.81, which was the second reduction factor.

4. Conclusions

Transportation is the leading and basic industry of national economic and social development. While promoting economic and social development, with the increase of transportation volume, the scale of energy consumption and CO_2 emission has also increased year by year, resulting in higher social costs and great pressure on environmental resources. As such, this paper estimated the CO_2 emissions, and presented spatiotemporal patterns from transportation. It further analyzed the impact factors of CO_2 emissions by the LMDI decomposition method.

From 2006 to 2016, the total CO_2 emissions of the Pearl River Delta region increased year by year. Guangzhou and Shenzhen were the major contributors to regional transportation CO_2 emissions, and the emissions of these two cities accounted for 89.10% in 2016. The CO_2 emissions of transport in Guangzhou and Shenzhen have been increasing since 2006. Specifically, Guangzhou increased more, while Shenzhen had a higher growth rate. From the perspective of different transport modes, intercity passenger transport and freight transport have always been dominant in the past 11 years. The results indicate that aviation transport was the largest contributor, and the road were the second one. The CO_2 emissions generated by rail and water transport were much lower than aviation. Private cars became the main source of urban passenger transport CO_2 emission, and their advantages kept increasing. By contrast, the number of motorcycles continued to decrease. In the past 11 years, the absolute amount of buses and taxis was relatively small, and the increase was not much, so that total carbon emissions remained stable.

The results indicated that the spatial agglomeration trend feature was negatively correlated, and the further the distance, the more similar the attributes. We found that per capita CO_2 emissions were continuously increasing, from 928.68kg/person in 2006 to 1952.21kg/person in 2016, thus increasing by two times. According to the trend of CO_2 emission intensity, it can be classified into three stages: The development of low carbon mode from 2006 to 2008, the steady development during 2008 and 2011, and the upward trend in 2011–2016.

From the perspective of high emission cities, Guangzhou and Shenzhen were always the two highest emission cities, and their values continued to rise and consistently ranked among the top two. Foshan and Jiangmen were in the second and third levels. Dongguan entered the fourth level in 2014, and the CO_2 emissions of the three cities of Zhongshan, Zhuhai and Zhaoqing were in the lowest level. The contribution value and contribution rate of population factors and economic development factors to the growth of emissions are relatively stable, and always play a facilitating role. The cumulative contribution values of population, economic development, transport intensity, energy intensity and energy structure were all positive values, while the cumulative contribution values of transport structure and emission factor were negative.

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