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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 CO₂ 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 CO₂ 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 CO₂ 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: CO₂ 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,

35 China has repeatedly stated its goal of reaching a peak in carbon emissions by 2030,
36 carbon neutral by 2060 (Li et al., 2021). The 2020 Central Economic Work Conference
37 (CEWC) also identified achieving peak carbon and carbon neutrality as one of the eight
38 key tasks of the 2021 (Liu et al., 2021).

39 Under the severe background of carbon emission reduction in China, the responsibility
40 of emission reduction should be divided into industries and regions. Transport is an
41 important sector for the emission reduction in China. According to the China
42 Automotive Industry Development Report (2020), from 2005 to 2017, CO₂ emissions
43 from China's transport sector maintained a steady growth trend, rising from 8% to 10%.
44 With the acceleration of emissions in China from 349.00 Mt in 2005 to 723.87 Mt in
45 2017, analyzing emissions from China's transport is necessary for reducing the total
46 emissions in China.

47 At present, the research methods of drivers of carbon emissions mainly focus on the
48 decomposition analysis and regression analysis. For example, Timilsina & Shrestha
49 (2009) found that energy intensity, per capita GDP, energy mix, population growth and
50 carbon efficiency were the main factors that affect transport carbon emissions in 20
51 countries in Asia and Latin America. V.Andreoni's analysis (2012) of the main
52 determinants of carbon emissions from European shipping and air transport in 2001-
53 2008 shows that economic growth was the most important driver. Li (2016) used the
54 LMDI to analyze the impact factors of carbon emissions in China's transport sector.
55 The results show that income was the leading factor of the increase in the emissions in
56 transport sector, and energy intensity was the main inhibiting factor of carbon emissions.
57 Using the STRIPATA model, Gao et al. (2014) calculated the elastic coefficients of the
58 driving factors such as population, GDP per capita, energy consumption per GDP,
59 transport investment and the number of private cars. Liang et al. (2018) analyzed
60 Beijing data from 1900 to 2016 by selecting seven driving factors, including passenger
61 mileage, freight mileage and total vehicle volume. Using STIRPAT model and ridge
62 regression method, Dong et al. (2017) analyzed the factors affecting the growth of
63 carbon emission from transport sector in Xinjiang and found that the carbon emissions
64 of transport sector in Xinjiang mainly came from the consumption of diesel and
65 gasoline, and the population density played a leading role in the growth of carbon
66 emissions.

67 However, in the study of transport sector carbon emissions, most of the literature
68 ignored the regional differences in development patterns. China has a vast territory.
69 There is a big gap in the development of various regions, and the level of development
70 of the transport industry is unbalanced. Therefore, studying the driving factors of

71 transport emissions from the perspective of regional development model is of great
72 significance to the implementation of emission reduction responsibilities in the
73 transport sector. In this case, through the regional analysis of carbon emissions in
74 China's transport sector from 1997 to 2017, the LMDI model is used to study the
75 regional differences in CO₂ emissions in order to fill these gaps.

76 **2. Literature Review**

77 Some scholars studied the CO₂ emissions from the transport sector from the national
78 perspective. Lakshmanan and Han (1997) analyzed energy consumption and CO₂
79 emissions in the U.S. transport sector from 1970 to 1991 and found that GDP,
80 population, and propensity to travel were the most important drivers of energy
81 consumption and emissions. Lopez et al. (2018) considered the availability and
82 limitations of data in developing countries, using population, transport activities, energy
83 intensity, fuel structure and emission intensity as driving factors. The results showed
84 that the most important emission reduction factor was transport activity. Saeed
85 Solaymani (2019) analyzed the carbon emissions of seven major transport-sector CO₂
86 emitting countries, showing that in most countries the main inhibiting contributor of
87 CO₂ emissions was carbon intensity, while the main drivers of the increase in CO₂
88 emissions were the electricity structure and economic output.

89 In addition, many researchers explored the drivers of CO₂ emissions from the China's
90 transport sector. Liang et al. (2017) quantitatively analyzed the effects of energy
91 structure, energy efficiency, transport patterns, transport development, economic
92 development and population size from 2001 to 2014. Li (2016) found that the income
93 led to the increase in carbon emissions, while the energy intensity effect caused the
94 decrease in carbon emissions. The changes of traffic mode, traffic intensity and
95 population had positive effects on the emissions of transport sector, but the effect was
96 relatively small. Feng et al. (2020) considered two new factors, namely spatial pattern
97 and age structure, and found that their effects were relatively small.

98 However, because of China's vast territory and different regional development, some
99 scholars have analyzed the factors that affect the carbon emissions in specific regions.
100 Dong et al. (2017) used the LMDI to identify driving factors of CO₂ emissions in
101 Xinjiang's transport sector from 1990 to 2014. The results show that economic growth,
102 population size, industrial structure, internal structure and energy structure can promote
103 the increase of CO₂ emission. Guo and Meng (2019) studied Beijing-Tianjin-Hebei as
104 representative of China's developed regions. The results show that transport energy
105 intensity and economic effect were the main factors for the increase of CO₂ emissions,
106 while energy structure, turnover of goods per unit of industrial output and

107 industrialization were the main factors for the reduction. Gu et al. (2019) used the
108 extended LMDI model and the system dynamics (SD) model to explore the
109 determinants of CO₂ emissions in Shanghai from 1995 to 2016. They considered new
110 factors such as car ownership, the structure of the city's tourism, and income levels and
111 concluded that GDP per capita was the main positive driver of the increase in CO₂
112 emissions.

113 Moreover, some scholars studied the regional differences in emissions in China. Zhang
114 and Nian (2013) used STIRPAT model and provincial panel data to study CO₂ emissions
115 from China's transport sector at the national and regional perspectives between 1995
116 and 2010. The results showed that passenger transport dominates CO₂ emissions from
117 transport sector, and its impact declines from west to east. Luo et al. (2016) analyzed
118 regional differences in CO₂ emissions from freight transport in China and used the Gini
119 coefficient to analyze inequality in regional economic development. The results show
120 that economic structure is the key driver of the change in emissions. Significant regional
121 differences and inequalities in freight transport emissions were revealed. Xu and Lin
122 (2016) used panel data model to analyze the regional differences and driving factors of
123 China's transport CO₂ emissions, and found that different investment and management
124 efficiencies led to different degree of emission reductions from energy efficiency
125 improvements in the eastern, central and western regions. Later, they used quantile
126 regression model (2018) to discuss the main drivers of CO₂ emission differences at high,
127 medium and low development levels. Liu et al. (2017) used a non-radial DEA model to
128 measure the CO₂ emission efficiency of land transport and found that eastern China has
129 the highest environmental efficiency, followed by central and western China. Yang and
130 Ma (2019) have decomposed and decoupled the CO₂ emissions model of China's
131 international maritime transport. They revealed that economic growth was the main
132 driving factor for the increase of CO₂ emissions, while the overall effect of energy
133 intensity and commodity structure played an important role in the reduction of CO₂
134 emissions.

135 In summary, the available literature has discussed the drivers of China's CO₂ emissions
136 in detail, but limitations remain. Firstly, the impact of regional development patterns on
137 transport emissions have not been fully discussed. Secondly, the LMDI method has not
138 been used effectively to analyze the regional differences of specific driving factors.
139 Therefore, based on the LMDI, we decompose CO₂ emissions into 7 driving factors.
140 particularly we analyze the impact of regional development pattern on transport
141 emissions in China. Moreover, we focus the regional differences in the contributions of
142 7 driving factors in China, such that different emission reduction strategies are

143 formulated based on different driving mechanisms of carbon emissions in different
144 regions.

145 **3. Methods and data**

146 **3.1. LMDI**

147 In this paper, we use the extended Kaya equation to decompose the CO₂ emissions of
148 China's regional transport sector (C^t) as follows:

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

150 where, C_{ir} is the CO₂ emissions of the transport sector in province r by fuel type i ,
151 E_{ir} is the energy consumption of the transport sector in province r by fuel type i ,
152 CT_r is the transport turnover of province r , IV_r is the transport mileage of province
153 r , which represents investments in transport; Y_r stands for the increase in output of
154 r 's transport sector; and P is the total population.

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

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

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

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

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

164 (5) $TI = \frac{IV_r}{Y_r}$ is the transport intensity of province r , i.e. the ratio of mileage to the

165 added value of transport sector's output;

166 (6) $RS_r = \frac{Y_r}{Y}$ is the regional structure of province r , which represents the share of the

167 added value of transport sector in the country.

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

169 output of transport sector;

170 (8) P is the population.

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

$$173 \quad \begin{aligned} \Delta C^t &= C^t - C^{t-1} \\ &= \Delta C_{COE}^t + \Delta C_{ES}^t + \Delta C_{EI}^t + \Delta C_{CI}^t + \Delta C_{TI}^t + \Delta C_{RS}^t + \Delta C_{TA}^t + \Delta C_P^t \end{aligned} \quad (2)$$

174 where, ΔC_{COE}^t , ΔC_{ES}^t , ΔC_{EI}^t , ΔC_{CI}^t , ΔC_{TI}^t , ΔC_{TA}^t and ΔC_P^t denote respectively
175 the effects of carbon intensity, energy structure, energy intensity, turnover intensity,
176 traffic intensity, per capita traffic activity and population size. The effects can be
177 decomposed year by year as follows:

$$178 \quad \Delta C_{COE}^t = \sum \frac{C_{ir}^t - C_{ir}^{t-1}}{\ln(C_{ir}^t - C_{ir}^{t-1})} \times \ln\left(\frac{COE^t}{COE^{t-1}}\right) \quad (3)$$

$$179 \quad \Delta C_{ES}^t = \sum \frac{C_{ir}^t - C_{ir}^{t-1}}{\ln(C_{ir}^t - C_{ir}^{t-1})} \times \ln\left(\frac{ES^t}{ES^{t-1}}\right) \quad (4)$$

$$180 \quad \Delta C_{EI}^t = \sum \frac{C_{ir}^t - C_{ir}^{t-1}}{\ln(C_{ir}^t - C_{ir}^{t-1})} \times \ln\left(\frac{EI^t}{EI^{t-1}}\right) \quad (5)$$

$$181 \quad \Delta C_{CI}^t = \sum \frac{C_{ir}^t - C_{ir}^{t-1}}{\ln(C_{ir}^t - C_{ir}^{t-1})} \times \ln\left(\frac{CI^t}{CI^{t-1}}\right) \quad (6)$$

$$182 \quad \Delta C_{TI}^t = \sum \frac{C_{ir}^t - C_{ir}^{t-1}}{\ln(C_{ir}^t - C_{ir}^{t-1})} \times \ln\left(\frac{TI^t}{TI^{t-1}}\right) \quad (7)$$

183

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

184

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

185

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

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3.2. Data sources

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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).

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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.

207

4. Results

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4.1. Changes of CO₂ emissions from China's transport sector

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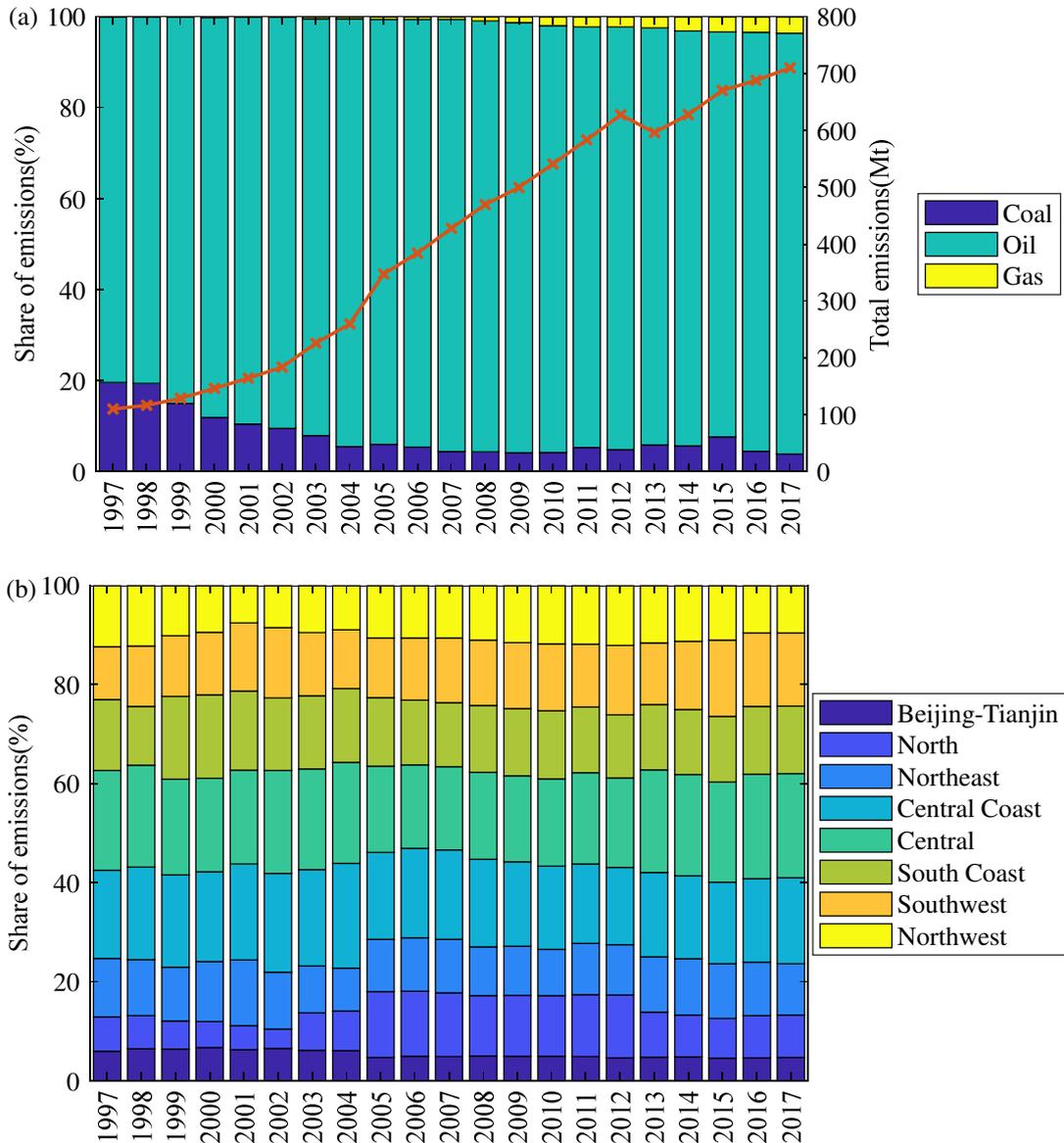
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In the 20 years from 1997 to 2017, China's CO₂ emissions in the transport sector rose 546%, from 107.2Mt to 705.38Mt (Fig.1). From 1997 to 2005, China's transport sector experienced a quick increase in total CO₂ emissions. Growth in emissions were, on

212 average, 15.49% per year during 1997-2005, decreasing 8.80% per year between 2005
213 and 2012. These trends mirror the evolution of the Chinese transport sector during this
214 time period: growth of the Chinese GDP from transport sector accelerated, reaching an
215 average GDP growth of over 10.16% per year between 1997 and 2005 (NBS, 2006).
216 The high growth rate of Chinese GDP from transport sector led to a rise in CO₂
217 emissions as fast transport development increased investment in building transport
218 networks, driving the energy consumption from the transport sector. Although the CO₂
219 emissions from the transport sector declined in 2013, they showed a strong rebound
220 from 596.08 Mt in 2013 to 709.97 Mt in 2017, with an average annual growth rate of
221 4.47%. Thus, during the whole period 1997-2017, China's CO₂ emissions can be
222 divided into four stages: high growth period (1997-2005), slow growth period (2005-
223 2012), recession period (2012-2013), and stable growth period (2013-2017).

224 Fig.1 shows the significant changes over 1997-2017 in the emission shares of fossil
225 fuels and regions in the total emissions from Chinese transport sector. The oil was a key
226 source of the total CO₂ emissions through all years, peaking at 95.03% of emissions in
227 2007 (Fig.1a). The CO₂ emissions from coal decreased quickly from 1997 to 2005,
228 decreasing from 19.57% in 1997 steadily to 5.98% of all emissions by 2005. During
229 2005-2012, the CO₂ emissions from coal showed a stable proportion over time,
230 accounting for less than 5.98% of emissions. The CO₂ emissions from natural gas
231 developed rapidly during 2005-2017, growing from 0.60% in 2005 to 3.64% by 2017.
232 Between 1997 and 2017, the central and central coast regions had the largest share,
233 accounting for 21.03% and 17.38% of the total in 2017 (Fig.1b). During 1997-2004,
234 the emission share of Beijing-Tianjin region increased from 5.95% to 6.07%, and
235 during 2005-2012 it is stable at more than 4.63% of the total emissions, increasing to
236 4.67% by 2017. The southwest's share grew steadily from 10.68% in 1997 to 14.80%
237 in 2017, exceeding the south coast (13.62%) and northeast regions (10.35%).



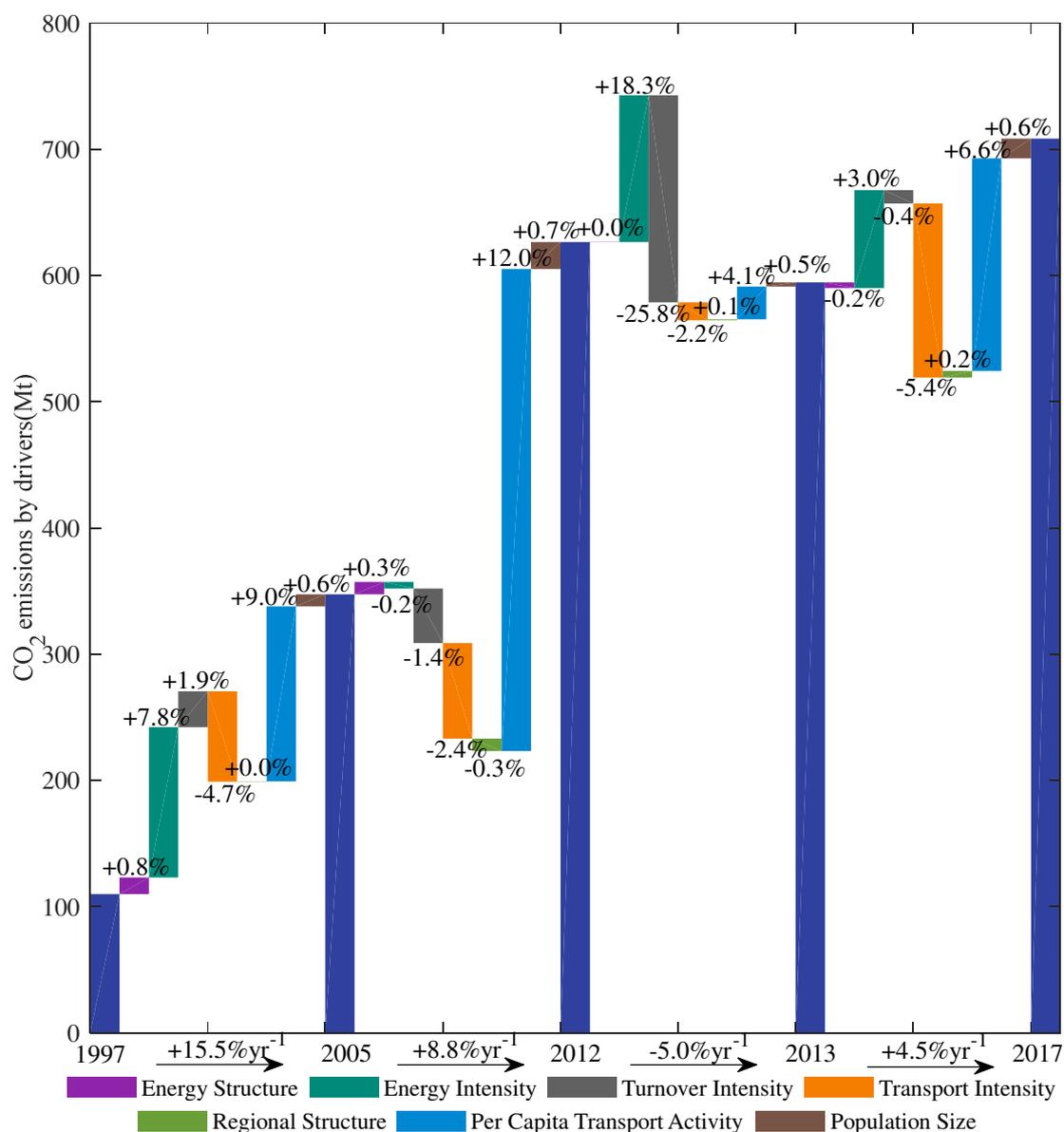
238

239 **Fig. 1.** Changes of CO₂ emissions in China's transport sector. (a) Total CO₂ emissions
 240 in China's transport sector from 1997 to 2017 and shares of CO₂ emissions from three
 241 fossil fuels; (b) Shares of CO₂ emissions from eight regions.

242 **4.2 Driving factors of CO₂ emissions from China's transport sector**

243 Fig. 2 presents the decomposition of total emissions into energy structure, energy
 244 intensity, turnover intensity, transport intensity, regional structure, per capita transport
 245 activity, population size and carbon intensity. Overall, the total emissions from transport
 246 sector grew at an average rate of 15.49% yr⁻¹ between 1997 and 2005 (Fig.3), more than
 247 three times over the period. Per capita transport activity and energy intensity
 248 contributed 9.0% yr⁻¹ and 7.8% yr⁻¹ of this growth, respectively. Conversely, transport
 249 intensity resulted in an average -4.7% yr⁻¹ decrease in emissions. During 2005-2012,
 250 China saw the strongest per capita transport activity, which contributed to emission

251 increases of 12.0% yr⁻¹. Transport intensity drove the largest emissions decrease (-2.4%
 252 yr⁻¹), but policies to decreasing transport intensity seem unlikely to cancel the positive
 253 emission impact of per capita transport activity. Although energy intensity had a large
 254 positive impact on the total emissions during 2012-2013, driving a 18.3% yr⁻¹ increase
 255 in emissions, the total CO₂ emissions declined at -5.0% yr⁻¹. This was mainly because
 256 that per capita transport activity growth in the China slowed down, resulting in an
 257 increase in emissions of “only” +4.1% yr⁻¹, and was offset by the emission contribution
 258 of turnover intensity (-25.8% yr⁻¹) over this period. During 2013-2017, the total
 259 emissions continued to increase, at +4.5% yr⁻¹, which was mainly driven by the fast per
 260 capita transport activity and energy intensity increase, driving increasing emissions of
 261 6.6% yr⁻¹ and 3.0% yr⁻¹, respectively. Moreover, we find a steeper reduction due to
 262 further reduction in transport intensity (-5.4% yr⁻¹) during this period.



263

264 **Fig. 2.** Contributions of seven drivers to the change in CO₂ emissions. The selected
265 periods include 1997-2005,2005-2012,2012-2013 and 2013-2017, and the lengths of
266 the bars reflect the contributions of factors during each period.

267 **4.3 Changes in emissions from regional structure**

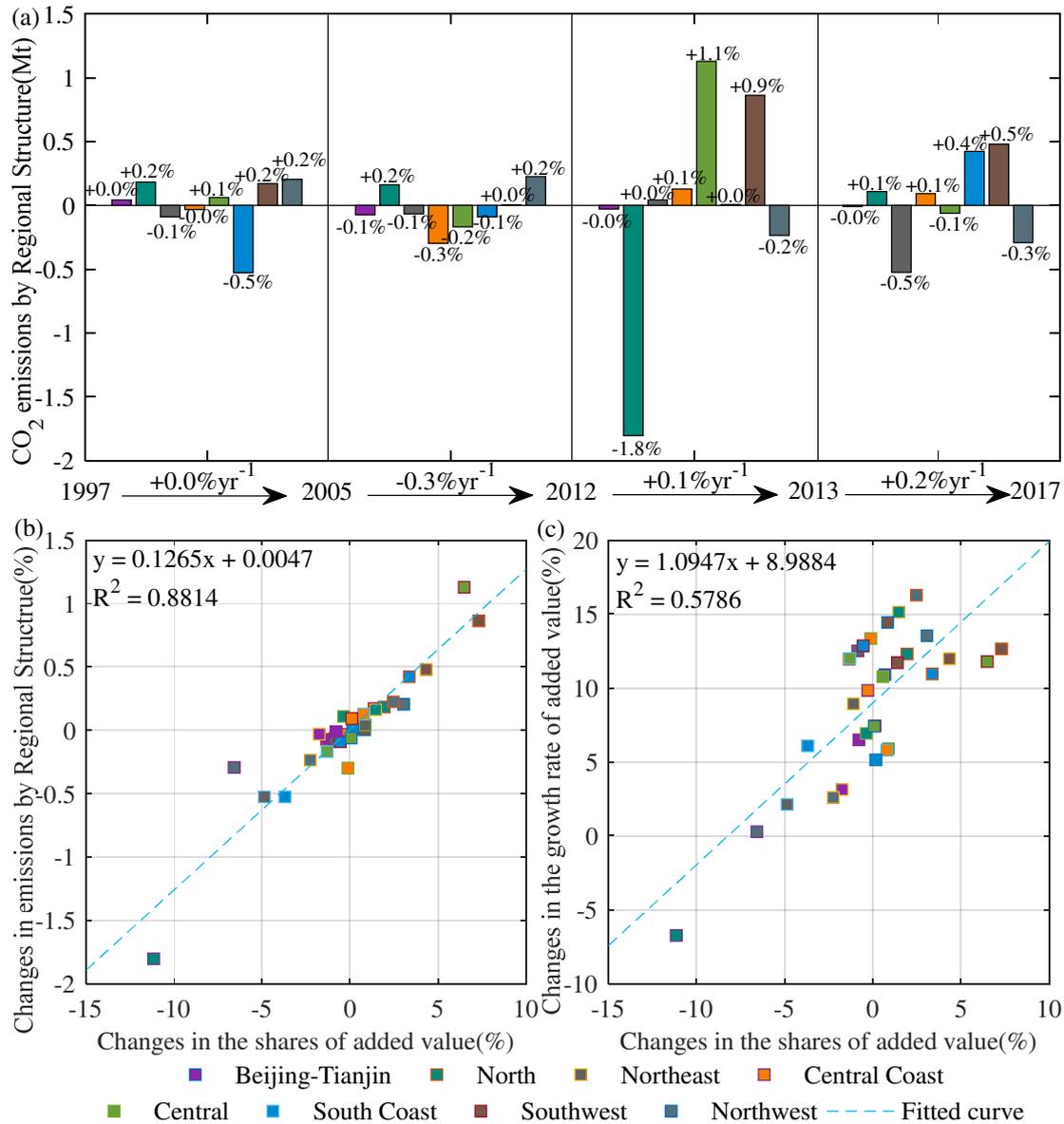
268 Although regional structure, measured by shares of regional transport output is a small
269 driving factor on the emissions from transport sector, its driving impact on emissions is
270 increasing. The regional structure drove emissions at 0.21% yr⁻¹ during 2013-2017.
271 Thus, we further investigate the emission contribution of regional structure for different
272 regions. Between 1997 and 2005, as the Northwest, North and Southwest regions
273 experienced the development of transportation, regional structural in these regions
274 contributed CO₂ emissions increases, all at around 0.20% yr⁻¹. Among them, the
275 contribution of Southwest was mainly driven by Guizhou province (see Table S1), in
276 which the average annual emission contribution of regional structure was 0.18% yr⁻¹.
277 The decrease in the transport value added of South Coast region led to a CO₂ emission
278 reduction of -0.53% yr⁻¹, with large reduction from Fujian (-0.10% yr⁻¹), Guangdong (-
279 0.41% yr⁻¹) and Hainan (-0.02% yr⁻¹) provinces. Between 2005 and 2012, the emissions
280 impact of regional structure only for Northwest (+0.22% yr⁻¹), North (+0.16% yr⁻¹) and
281 Southwest (+0.00% yr⁻¹) regions remained positive. The largest contribution of regional
282 structure to emission reduction was in Central Coast region, which decreased from -
283 0.03% yr⁻¹ during 1997-2005 to -0.30% yr⁻¹ during 2005-2012. The inhibitory effect of
284 South Coast region decreased to -0.09% yr⁻¹, and compared with that in 1997-2005, the
285 decreasing extent of its share of transport value added was reduced. The contribution
286 of regional structure to CO₂ emissions in Beijing-Tianjin region changed from positive
287 (+0.04%) during 1997-2005 to negative (-0.07%) during 2005 to 2012 due to Beijing's
288 negative inhibiting impact at -0.08% yr⁻¹.

289 Between 2012 and 2013, regional structure started to increase CO₂ emissions by 0.10%
290 yr⁻¹. This is mainly because continuing transport development drives emissions at 1.13%
291 yr⁻¹ in Central region, of which 0.72% yr⁻¹ in Henan and 0.43% yr⁻¹ in Hubei. Moreover,
292 we find steeper increase due to further transport development in Southwest (+0.86% yr⁻¹).
293 However, since transport development in North and Northwest regions was
294 relatively weak during this period, the emission reductions resulting from regional
295 structure in these two regions were relatively high, at -1.80% yr⁻¹ and -0.24% yr⁻¹
296 respectively. Between 2013 and 2017, we saw a larger emission increase due to regional
297 structure (at 0.21% yr⁻¹). This is mainly from the emissions increases caused by the
298 regional structure impacts in Southwest and South Coast regions, which contributed to
299 emission changes of +0.48% yr⁻¹ and +0.42% yr⁻¹, respectively. At the same time,

300 Northeast ($-0.53\% \text{ yr}^{-1}$) and Northwest ($-0.29\% \text{ yr}^{-1}$) regions were the regions with the
301 largest inhibiting emissions effects of regional structure.

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

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



323

324 **Fig.3.** Changes in CO₂ emissions caused by regional structure. (a) Contribution of
 325 emissions by regional structure; (b) Relationship between the change of emissions by
 326 regional structure and the changes in the regional share of transport value added (c)
 327 Relationship between the change in the regional growth rate of transport value added
 328 and the change in the regional share of transport value added

329 4.4 Regional emission changes by drivers

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

332 Among them, the per capita transport activity's promotion function was the most
 333 obvious. Emissions increased in all four stages except for North region, where
 334 emissions decreased by $-1.36\% \text{ yr}^{-1}$ during 2012 to 2013 (Fig.4a). The decline in North

335 region was mainly due to Shandong province ($-1.50\% \text{ yr}^{-1}$) (Table S2), where a
336 reduction in the value added of transport output led to a reduction in emissions. In the
337 first three phases, Central region contributed the most, with more than $1.90\% \text{ yr}^{-1}$.
338 During 2013 to 2017, the emission contribution rate of Southwest region was the
339 highest, reaching $1.37\% \text{ yr}^{-1}$, mainly driven by Sichuan province ($0.58\% \text{ yr}^{-1}$). In recent
340 years, the rapid increase in transport activity in Southwest region promoted the increase
341 of emissions. The Central region, second only to Southwest, also contributed $1.32\% \text{ yr}^{-1}$
342 growth, with stable growth in value added of transport output leading to a steady rise
343 in emissions.

344 For the whole development process, energy intensity also played a certain role in
345 promoting regional emissions. But it helped to reduce emissions from 2005 to 2012
346 (Fig.4b). During 1997 to 2005, the contribution rate of North region was the highest,
347 reaching $1.25\% \text{ yr}^{-1}$, mainly driven by Shandong province ($1.26\% \text{ yr}^{-1}$) (Table S3),
348 whose contribution rate was the highest in the country. During 2005-2012, energy
349 intensity had an inhibiting impact on the total emissions. Energy intensity improved in
350 the Beijing-Tianjin, South Coast, North and Central regions, with emissions of $-0.33\% \text{ yr}^{-1}$,
351 $-0.28\% \text{ yr}^{-1}$, $-0.26\% \text{ yr}^{-1}$ and $-0.01\% \text{ yr}^{-1}$, respectively. Beijing ($-0.18\% \text{ yr}^{-1}$),
352 Tianjin ($-0.15\% \text{ yr}^{-1}$) and Shandong ($-0.29\% \text{ yr}^{-1}$), which are close to the capital, were
353 the base areas with high energy consumption and became the primary task of
354 environmental control. Therefore, these provinces should vigorously promote
355 technological innovation and improve energy intensity to reduce carbon emissions.
356 Moreover, the region with the largest contribution to CO_2 emissions was Northwest
357 region, at just $0.29\% \text{ yr}^{-1}$. However, between 2012 and 2013, there was a relatively large
358 increase in the contribution of each region and the impact of energy intensity in all
359 regions all turned positive. Central region contributed an increase of $5.20\% \text{ yr}^{-1}$ in
360 emissions by energy intensity. This was mainly because the contribution of Henan and
361 Anhui were $1.39\% \text{ yr}^{-1}$ and $1.19\% \text{ yr}^{-1}$ respectively, ranking the highest all the provinces.
362 The annual contribution Southern Coast region also reached $4.69\% \text{ yr}^{-1}$. Only in North
363 and Northwest regions, the contribution was low ($0.38\% \text{ yr}^{-1}$), mainly because the
364 contribution of Shandong ($-0.12\% \text{ yr}^{-1}$) and Inner Mongolia ($-0.57\% \text{ yr}^{-1}$) provinces
365 were negative. From 2013 to 2017, the contribution of each region tended to level off.
366 The region with the largest annual contribution was Southwest region ($0.91\% \text{ yr}^{-1}$),
367 because of Sichuan's $0.64\% \text{ yr}^{-1}$ contribution ranked first in the country.

368 In addition, population and energy structure factors also played a role in the growth of
369 emissions. The contribution rate of population was relatively stable, except for the
370 emission reduction of $-0.02\% \text{ yr}^{-1}$ in Northeast region during 2013 to 2017, the emission

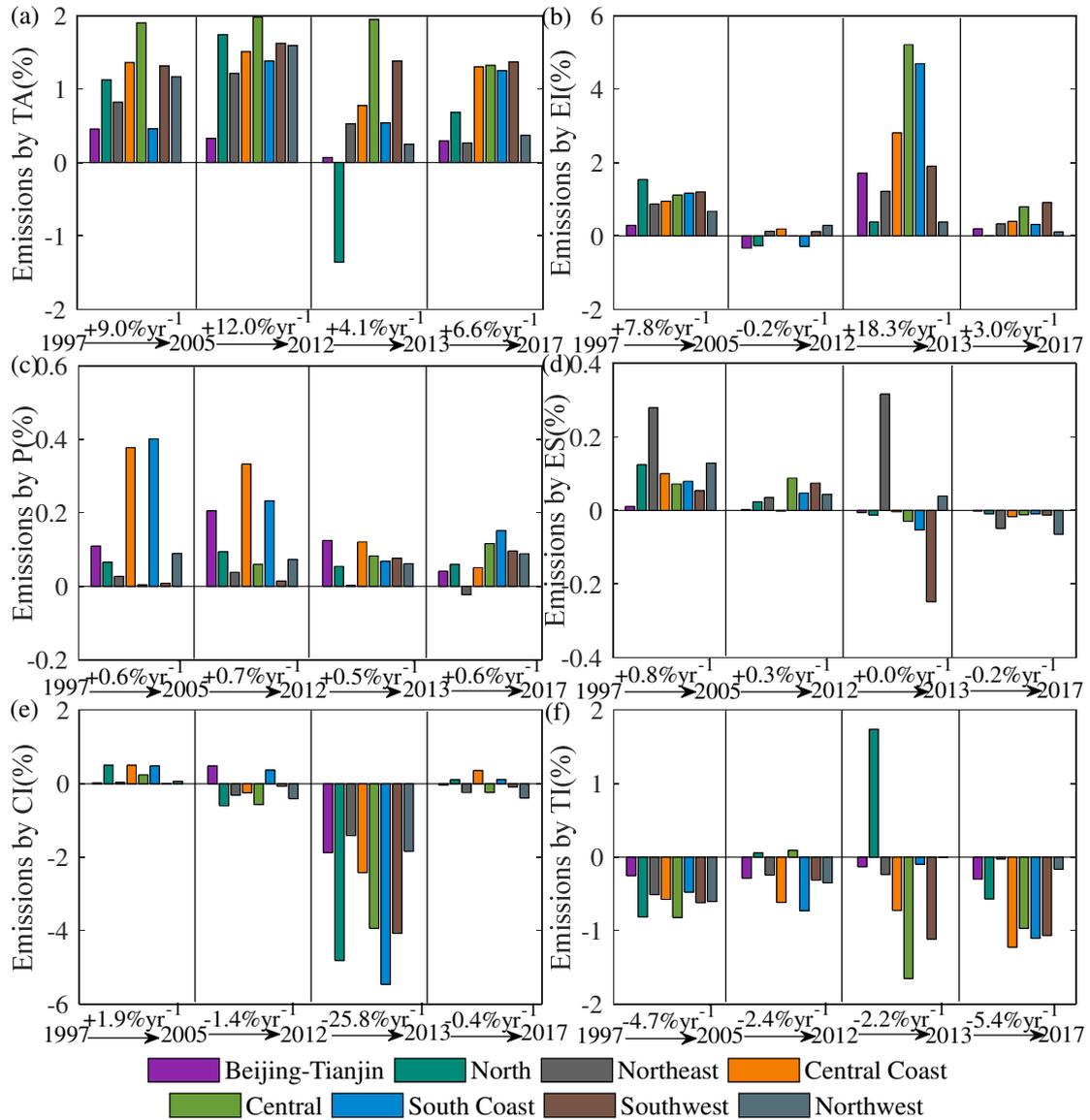
371 increased in the other stages and regions (Fig.4c). The reduction in emissions in
372 Northeast region was driven by all provinces in Northeast, contributed $-0.01\% \text{ yr}^{-1}$
373 respectively. The reduction in population size led to a reduction in carbon emissions
374 from the transport sector. In the first two periods, Central Coast and South Coast regions
375 had the largest emissions, mainly influenced by Shanghai and Guangdong (Table S4).
376 After entering the recession period, the two regions that contributed the most to CO₂
377 emissions became the Central Coast and Beijing-Tianjin regions ($0.12\% \text{ yr}^{-1}$). During
378 2013 to 2017, the influence of Central region ($0.12\% \text{ yr}^{-1}$) increased significantly, and
379 it had become a high-contribution region second only to South Coast ($0.15\% \text{ yr}^{-1}$). This
380 shows that developed regions have higher population growth rates, leading to more
381 contribution to CO₂ emissions. In addition, China's economic development and
382 population are gradually expanding from the coastal areas to inland regions such as
383 Beijing-Tianjin and Central regions.

384 Overall, the energy structure played a positive role in CO₂ emissions between 1997 and
385 2012 (Fig.4d). But between 2012-2013, the disincentive effect of the energy structure
386 on CO₂ emissions began to emerge. This is because in the recession period, emission
387 reductions were achieved by optimizing the energy structure in all regions except for
388 Northeast ($0.32\% \text{ yr}^{-1}$) and Southwest ($0.04\% \text{ yr}^{-1}$) regions. Jilin ($0.31\% \text{ yr}^{-1}$) in
389 Northeast region contributed the most to the increase in CO₂ emissions (Table S5). The
390 largest contributor to CO₂ reduction was Southwest region ($-0.25\% \text{ yr}^{-1}$). All the
391 provinces in the Southwest region, except for Chongqing, have promoted emission
392 reduction, especially Sichuan province, with a contribution rate of $-0.21\% \text{ yr}^{-1}$, which
393 ranked first among all provinces. From 2013 to 2017, the changes in the energy
394 structure in all the regions helped reduce emissions. With the wide use of natural gas
395 gradually replaced the use of coal and oil in transport sector, the emission reduction due
396 to energy structure in Northwest region was the largest, which reached -0.07 yr^{-1} .

397 However, turnover intensity and transport intensity mainly played a negative role in
398 affecting emissions. From 1997 to 2005, the turnover intensity led to a small increase
399 in emissions. All regions had positive contribution rates (Fig.4e), with Central Coast
400 and North regions having the highest contribution rates ($0.50\% \text{ yr}^{-1}$). In the early stages
401 of economic development, emissions increased as a result of increased turnover per
402 mile in all regions. With the continuous development of transport, only Beijing-Tianjin
403 ($0.49\% \text{ yr}^{-1}$) and South Coast ($0.37\% \text{ yr}^{-1}$) regions increased their emissions between
404 2005 and 2012, whose urban traffic pressure was significant, while other regions
405 reduced their emissions to varying degrees. The highest contribution rate to CO₂
406 reduction was $-0.60\% \text{ yr}^{-1}$ in North region, which was mainly due to Shandong

407 province's contribution rate of $-0.41\% \text{ yr}^{-1}$ (Table S6). During 2012 to 2013, emissions
408 were reduced in all regions. South Coast region ($-5.46\% \text{ yr}^{-1}$) had the highest
409 contribution rate to reduction. Guangdong ranked first among provinces, with a
410 reduction rate of $-4.81\% \text{ yr}^{-1}$. The continuous development of the transport industry
411 improved the transport efficiency and alleviates the turnover density of the unit mileage.
412 For 2013-2017, the negative impact of turnover intensity decreased in all regions, and
413 the negative impact in Northwest region was relatively large, reaching $-3.89\% \text{ yr}^{-1}$.
414 Central Coast ($0.36\% \text{ yr}^{-1}$), North ($0.11\% \text{ yr}^{-1}$) and South Coast ($0.11\% \text{ yr}^{-1}$) regions
415 showed smaller increases in emissions. Visible in recent years, the development of
416 traffic volume intensity has gradually entered the bottleneck.

417 In terms of transport intensity, emissions decreased in most regions between 1997 and
418 2017 (Fig.4f). In the first phase (1997-2005), the contribution of each region to CO₂
419 emissions was negative. The largest contribution rate of emission reduction was in
420 Central ($-0.82\% \text{ yr}^{-1}$) and North ($-0.81\% \text{ yr}^{-1}$) regions. By 2005, the rate of emission
421 reduction slowed down and the contribution rate of Central ($0.09\% \text{ yr}^{-1}$) and North ($0.06\% \text{ yr}^{-1}$)
422 regions were positive. South Coast region saw the biggest drop in CO₂ emissions
423 ($-0.73\% \text{ yr}^{-1}$). This reflects the increasing role of government investment in the region
424 in promoting the output of transportation industry. Between 2012 and 2013, Central ($-$
425 $1.65\% \text{ yr}^{-1}$) and Southwest ($-1.11\% \text{ yr}^{-1}$) regions contributed significantly more to
426 emission reductions. The North region was the region that contributed most to the
427 increase in carbon dioxide emissions ($1.74\% \text{ yr}^{-1}$). Shandong ($1.71\% \text{ yr}^{-1}$) had the
428 highest contribution rate of transport intensity adjustment (Table S7). Since 2013,
429 transport intensity had improved, and CO₂ emissions had decreased in all regions. The
430 highest contribution rate of emission reduction was in Central Coast ($-1.22\% \text{ yr}^{-1}$) and
431 South Coast ($-1.10\% \text{ yr}^{-1}$) regions. This is mainly because the contribution rates of
432 Guangdong and Sichuan provinces reached $-0.73\% \text{ yr}^{-1}$ and $-0.53\% \text{ yr}^{-1}$ respectively,
433 ranking the highest among all provinces. The lowest rate of reduction was in Northeast
434 ($-0.02\% \text{ yr}^{-1}$) region. This is mainly because the reductions elsewhere were partly offset
435 by the 0.29% contribution from Gansu. This also reflects the government investment to
436 the transport industry output promotion function tends to smooth.



437

438 **Fig.4.** Changes in CO₂ emissions in China's transport sector caused by drivers at the
 439 regional level. (a) Region-specific contributions of energy structure to changes in
 440 national CO₂ emissions; (b) Region-specific contributions of energy intensity to
 441 changes in national CO₂ emissions; (c) Region-specific contributions of turnover
 442 intensity to changes in national CO₂ emissions; (d) Region-specific contributions of
 443 transport intensity to changes in national CO₂ emissions. The compound annual rate of
 444 total emissions (r) is related to the total rate (R) across n years as $r = \sqrt[n]{1 + R} - 1$, and
 445 compound annual contribution of a given factor (k) is $r \times S_k$ where S_k is the share
 446 of the contribution of the factor during the whole period.

447 5. Discussion

448 Many scholars have discussed the driving factors of CO₂ emissions in the transport
 449 sector, but the differences in emission reduction effects due to the differences in the

450 development models of various regions have not been discussed in detail. In this study,
451 the regional structure was added to the division of impact factors. The impact of
452 regional structure on the CO₂ emission of the national transport sector and the
453 differences between the CO₂ emission factors of various regions are discussed.

454 The results show that the regional structure does not have a significant impact on the
455 CO₂ emission of the national transport sector. However, at the regional level, driving
456 factors under different regional development models have different contributions to
457 CO₂ emission. From the comparison of the regional structure contribution rates of
458 various regions in 2013-2017, the contribution rates of Southwest, South Coast, Central
459 Coast and North regions were positive. The reason is that the growth rate of the output
460 value of the transportation sector in these areas were relatively high. In Southwest
461 region, due to the continued prosperity of tourism in recent years, transport
462 consumption has increased. Chengdu and Chongqing also jumped into new first-tier
463 cities. With the introduction of the concept of Chengdu-Chongqing Economic Circle,
464 Southwest region has become increasingly connected. The continuous improvement of
465 its internal transport network and the communication network with the outside world
466 has resulted in the highest growth rate of the output value added of its transport sector
467 in recent years. In addition, since the South Coast, Central Coast and North regions
468 were more developed and had higher total consumption capacity, it is not surprising
469 that the added value of the transport sector maintained a steady growth.

470 Different regional development models lead to great differences in the contribution of
471 each region in per capita transport activity, energy intensity, population, energy
472 structure, turnover intensity and transport intensity factors. In 2013-2017, the first three
473 factors led to an increase in CO₂ emission in all regions. Energy structure and traffic
474 intensity led to CO₂ emission reductions in all regions. However, in terms of turnover
475 intensity, some regions promoted CO₂ emissions and some regions suppressed it. The
476 regional difference in turnover intensity was consistent with that in regional structure.
477 Only the Central Coast, South Coast and North regions promoted CO₂ emissions. It can
478 be speculated that the contribution of turnover intensity was related to the level of
479 economic development. The transport construction in developed regions was at the
480 leading level in the country, but due to the increase in population, transport pressure
481 was still relatively high. But at the same time, South Coast and Central Coast regions
482 optimized transport intensity and contributed the most to reducing CO₂ emission. It can
483 be seen that the transport in developed areas was more complete. Therefore, taking into
484 account the different characteristics and different resources of each region, regions
485 should strive to discover different factors that make emission reduction more efficient,

486 and use its own advantages to achieve emission reduction. At the same time, all regions
487 should strengthen cooperation to achieve complementary advantages and further
488 promote the reduction of national CO₂ emissions.

489 By comparing the impact of regional development models on national total CO₂
490 emission (J. Zheng et al., 2019), the total average annual growth rate of CO₂ emissions
491 from 2012 to 2016 was 1.7% yr⁻¹, but we found that the average annual growth rate of
492 CO₂ emission from the transport sector reached 4.5% yr⁻¹ in 2013-2017. It can be seen
493 that in recent years, CO₂ emissions from the transport sector have become a major factor
494 in the increase in China's total CO₂ emissions. The main factors leading to the increase
495 of the total CO₂ emission of the country were economy and population. Consistent with
496 this, we found that per capita transportation activities and population factors also
497 contributed to the growth of CO₂ emission from the transport sector. The difference is
498 that, energy efficiency contributed to emission reductions in terms of total CO₂
499 emission, but the energy intensity of the transport sector still promoted to emissions.
500 This indicates that the energy efficiency of the transport sector needs to be improved.
501 In addition, regional structure had a greater impact on total emissions and was the
502 second most important factor. However, in terms of total emission, the positive
503 correlation between the growth rate of output value and emission was still valid.

504 At the regional level, improvements in energy efficiency in all regions contributed to
505 overall emission reduction in 2012-2016. However, energy intensity in all regions in
506 2013-2017 led to an increase in CO₂ emission from the transport sector. The North
507 region contributed the largest to the reduction of total CO₂ emission, which was
508 consistent with the least contribution of it to the increase of CO₂ emission in the
509 transport sector. It can be seen that the energy efficiency improvement in the North
510 region was at the leading level in the country. The Central and Southwest regions were
511 also at the top of the list of contributors to total emission reduction, but contributed the
512 largest to the emission increase in transport sector. It is clear that their energy efficiency
513 improvement was concentrated in other sectors. In terms of the energy structure, each
514 region contributed to reducing emission from the transport sector, but the South Coast,
515 Northwest, Central Coast and North regions contributed to the increase in total emission.
516 It can be seen that the energy restructuring of the transport sector was developing more
517 rapidly than that of other sectors. The two emission reduction contribution rates of the
518 Northwest region were both the highest, which indicates that the energy structure
519 improvement of the northwest region was in a leading position of the country. However,
520 the Northeast and Central Coasts, which were the second and third largest contributors
521 to CO₂ reduction in the transport sector, accounted for the second and third largest

522 increase in total CO₂ emission. The Beijing-Tianjin region contributed the second most
523 to total CO₂ reduction in the country, but the least to the emission reduction in transport
524 sector. These regions did not penetrated energy structure adjustments into various
525 industries, which led to this imbalance.

526 **6. Conclusion**

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

540 From regional perspective, in all stages, the regional structural adjustment in Southwest
541 region resulted in a continuous increase in CO₂ emissions, with the largest contribution
542 rate among all provinces. The regional structural adjustment in Northwest region led to
543 an increase in CO₂ emissions in the first two stages, but resulted in the largest decrease
544 in CO₂ emissions in the second two stages. Moreover, we found that the change in the
545 rate of output growth of the regional transport sector is positively correlated with the
546 change in the share of output value added, while the change in emissions by regional
547 structure is positively correlated with the change in the share of output value added of
548 the regional transport sector. As a result, the higher the rate of growth of output and the
549 larger the share, the greater the increase in CO₂ emissions from the transport sector.

550 As far as the influencing factors of regional CO₂ emission change are concerned, the
551 promoting effect of energy intensity is relatively continuous, but its contribution rate is
552 relatively stable in recent years. The effect of energy structure gradually changed from
553 promoting emissions in the first two stages to restraining emissions. The change of
554 traffic intensity and turnover intensity can obviously restrain the regional emissions. In
555 particular, transport intensity has maintained a high contribution rate to emission
556 reduction in recent years, but the contribution rate of turnover intensity to emission
557 reduction is slowly weakening.

558 **Declarations**

559 **Ethics approval and consent to participate**

560 Not applicable.

561 **Consent for publication**

562 Not applicable.

563 **Availability of data and materials**

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

566 **Competing interests**

567 The authors declare that they have no competing interests.

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571 **Authors' contributions**

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

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