



# Spatial heterogeneity of factors influencing transportation CO<sub>2</sub> emissions in Chinese cities: based on geographically weighted regression model

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## Abstract

Based on the 2015 transportation CO<sub>2</sub> emissions and economic and social data for the 286 cities in China, exploratory spatial data analysis (ESDA) method and a geographically weighted regression (GWR) model were used to analyze the spatial distribution characteristics of transportation CO<sub>2</sub> emissions and their influencing factors. The results showed that the CO<sub>2</sub> emissions from urban transportation in China featured significant spatial agglomeration. The high emission areas were mainly concentrated in Beijing, Shanghai, Chongqing, Chengdu, Nanjing, and other regional core cities, while the low emission areas were mainly concentrated in the cities of Gansu, Guizhou, Yunnan, and other underdeveloped provinces. Considering the overall evolution of the factors affecting transportation CO<sub>2</sub> emissions, private car ownership, technological innovation, and industrial structure correlated positively with transportation CO<sub>2</sub> emissions. Population density, urbanization rate, per capita urban road area, and transportation structure could significantly inhibit transportation CO<sub>2</sub> emissions. The impact of per capita GDP, public transportation, and environmental regulation on transportation CO<sub>2</sub> emissions was insignificant. From the perspective of spatial heterogeneity, there were significant regional differences in the impact of various factors on CO<sub>2</sub> emissions. Private car ownership, technological innovation capacity, and per capita GDP all had a positive impact on transportation CO<sub>2</sub> emissions. Urbanization rate, urban road area per capita, and transportation structure all had a negative impact on transportation CO<sub>2</sub> emissions. Population density, industrial structure, public transportation, and environmental regulation all had a two-way impact on transportation CO<sub>2</sub> emissions in different cities.

**Keywords** Transportation CO<sub>2</sub> emissions · Exploratory spatial data analysis · Geographically weighted regression · Spatial heterogeneity

## Introduction

Transportation is one of the main sources of carbon emissions. According to the International Energy Agency (IEA), in 2016, the carbon emissions of the transportation industry accounted for 24.3% of energy-related emissions worldwide and 30% of that for OECD countries (IEA 2018). In developing countries, CO<sub>2</sub> emissions from vehicles and traffic have become an important factor in the increase in global greenhouse gas emissions (ADB 2019). The transportation sector is expected to be

the largest emitter of greenhouse gases by 2050, accounting for 80% of global greenhouse gas emissions, with most of the growth expected to come from developing countries in Asia (ADB 2019). According to the National Bureau of Statistics, from 2000 to 2017, the energy consumption of the transportation industry in China has been on the rise, increasing by 3.3 times in 17 years. With the advancement of China's industrialization and urbanization process and the increasing demand for transportation, the oil consumption of the transportation industry ranks first among all industries in China. The increasing rate of transportation CO<sub>2</sub> emission also ranks first among the six major industries, and the transportation industry has become the second largest CO<sub>2</sub> emission sector after industry (Lu et al. 2017). Against a background of increasing greenhouse gas emissions and frequent smog, in 2015, the Chinese government proposed that China would reduce its carbon dioxide emissions per unit of GDP by 2030 to 60–65% lower than the level in 2005, and total emissions would have reached

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its peak (Feng et al. 2019). In the face of the arduous emission reduction target, as a key sector of emission reduction in China, the transportation sector should shoulder its share of the important responsibility of reducing carbon emissions, and reducing CO<sub>2</sub> emissions from transportation is the main way to achieve its climate change mitigation target. Because of the imbalanced urban development in China, there are significant differences in transportation CO<sub>2</sub> emissions between cities. Therefore, it is very important to study the spatial distribution and influencing factors of transportation CO<sub>2</sub> emissions in China to realize a low-carbon lifestyle and fulfill the promise of energy conservation and emission reduction.

At present, scholarly research on transportation carbon emissions mainly focuses on the measurement of carbon emissions, its influencing factors, and so on. In terms of carbon emission measurements, Nocera et al. (2018a, b) used the TANINO model to estimate the carbon dioxide emissions along the ring road of Sevilla in Spain, and this model proved more accurate than the common estimation methods. Yang et al. (2020) calculated the traffic carbon emissions of Beijing, Xi'an, Wuhan, and Bangalore by constructing a carbon emission estimation model. Bai et al. (2020) calculated China's provincial transport carbon emissions from 2005 to 2015 by using a top-down method based on final energy consumption in the transport industry. The main factors affecting carbon emissions from transportation are economic growth, urbanization, transportation structure, energy efficiency, and so on. Some scholars have used the environmental Kuznets curve (EKC) or the decoupling model to analyze the nonlinear relationship between economic growth and transportation CO<sub>2</sub> emissions and argued that carbon emissions and per capita GDP had an inverted u-shaped relationship (Wang and Feng 2019; Lv et al. 2019). Compared with the EKC, the decoupling model was considered to have more advantages (Han et al. 2018; Liu and Feng 2020). Some scholars have explored the effect of urbanization on transportation carbon emissions (Huang et al. 2019; Yang et al. 2019). Cities are considered to be one of the important sources of factors leading to global climate change (Cai et al. 2018; Ahmed et al. 2019). Approximately 60–80% of energy consumption and 70% of global greenhouse gas emissions come from cities. Cities are population and transportation aggregation areas. Urbanization can result in the growth of the transportation industry, such as through an increase in cargo volume and air transportation volume, thereby increasing transportation CO<sub>2</sub> emissions (Lv et al. 2019). Some scholars have explored the influence of transportation structure on carbon emissions (Abdull et al. 2020). Among all transportation modes, road freight is considered to have the highest carbon emissions, and in the freight industry, it also has the fastest growth in carbon emissions (Lv et al. 2019). The use of railways, electric vehicles public transport, and alternative fuels has generally proven to be a reliable way to reduce carbon emissions (Liu

et al. 2015; Wu et al. 2018). If the growth of motor vehicle use is controlled below zero, the use of hybrid vehicles is encouraged, and a carbon quota allocation is implemented, we will probably achieve the carbon emission target by 2050; reducing the use of vehicles will bring carbon emissions 1.30–5.18% below the target by 2050 (Chang and Chung 2018). Some scholars suggest that the factors affecting transportation CO<sub>2</sub> emissions will change over time, that is, uncertainties exist, such as the vehicle scrap rate, annual growth rate in recent driving kilometers, total vehicle sales, technical uncertainty, economic uncertainty, and decision uncertainty. Therefore, to ensure the appropriateness of policy and investment decisions, decision-makers need to first understand the different types of uncertainties that exist and then find methods to solve them (Bastani et al. 2012; Nocera et al. 2018a, b). In addition, some scholars believed that energy efficiency, income, vehicle ownership, government investment, and per capita traffic expenditures had a significant impact on transportation CO<sub>2</sub> emissions (Wang et al. 2017; Wu and Xu 2019; Lv et al. 2019).

Considering 286 cities in China as samples, this paper uses the ESDA method to analyze the spatial distribution characteristics of transportation CO<sub>2</sub> emissions and adopts the GWR model to explore the spatial characteristics of the factors affecting transportation CO<sub>2</sub> emissions. The main contributions of this paper are as follows. First, the existing research largely studies transportation CO<sub>2</sub> emissions at the provincial or national levels, but the data at these levels cover up spatial differences at the city level. The city is the main body aggregating transportation CO<sub>2</sub> emissions, and the city scale is important for discussing the relationship between CO<sub>2</sub> emissions and social development. Therefore, this paper takes cities above the prefecture level as the research object, discusses the differences in transportation CO<sub>2</sub> emissions, and addresses the shortcomings of the existing research. Second, although China is a vast country, its cities are connected with each other in geographical space. However, most of the existing studies only focus on time series, ignoring the interdependence of the spatial effects between cities. This paper uses the ESDA method to reveal the spatial agglomeration characteristics of transportation CO<sub>2</sub> emissions. Finally, most of the existing literature studies the factors driving transportation CO<sub>2</sub> emissions using the common ordinary least squares (OLS) model, but the coefficients of this model will only reflect the average impact and not the spatial difference in the impact results. Therefore, the GWR model is introduced to obtain a more detailed understanding of the spatial scale of the socioeconomic factors driving transportation CO<sub>2</sub> emissions. Carbon emissions of emerging economies such as China, Brazil, India, Mexico, and South Africa are still on the rise, and there are imbalances in regional development and differences in carbon emissions within these countries. Therefore, investigating the spatial heterogeneity of the factors influencing

carbon emissions at the urban level will help each city formulate differentiated energy conservation and emission reduction policies, which will help them not only realize a green and low-carbon life within the city but also achieve the emission reduction objectives of the Paris Agreement. The research methods and conclusions of this paper also have important reference value for other emerging economies.

## Materials and methods

### Models

#### Global spatial autocorrelation

Spatial autocorrelation analysis can well explain the spatial distribution characteristics of transportation CO<sub>2</sub> emissions in various cities and reflect the spatial agglomeration throughout China. Global spatial autocorrelation is a global index that measures whether a certain spatial attribute has obvious clustering in a given geographical location. The global Moran's *I* index is used for evaluation, and the *z*-score is calculated to test the significance of the measurement results. In this paper, the index is used to measure the global correlation in China's urban transportation CO<sub>2</sub> emissions, and the formula is outlined as follows.

$$I = \frac{n \sum_i \sum_{j \neq i} w_{ij} (x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^n (x_i - \bar{x})^2 \sum_{i=1}^n \sum_{j \neq i} w_{ij}} \quad (1)$$

where *n* is the number of cities, *w<sub>ij</sub>* is the spatial weight matrix, *X<sub>i</sub>* and *X<sub>j</sub>* are the transportation CO<sub>2</sub> emissions of cities *i* and *j*, respectively, and  $\bar{x}$  is the average transportation CO<sub>2</sub> emissions of each city. *I* > 0 represents positive spatial correlation, *I* < 0 represents negative spatial correlation, and the smaller the value of *I* is, the greater the spatial difference is. Otherwise, *I* = 0 represents no spatial correlation.

#### Local spatial autocorrelation

The global Moran's *I* index only reflects the difference in spatial mean value and may ignore the atypical characteristics of the transportation CO<sub>2</sub> emissions of some cities in local areas (Elhorst 2012). The local Moran's *I* index mainly verifies the distribution pattern of each element in the heterogeneous elements and can measure the local spatial correlation between each region and its surrounding regions. The index can explore the change pattern of transportation CO<sub>2</sub> emissions in different cities. The formula is as follows.

$$I_i = \frac{n(x_i - \bar{x})}{\sum_{j=1}^n (x_j - \bar{x})} \sum_{j=1}^n W_{ij} (x_j - \bar{x}) \quad (2)$$

where *I<sub>i</sub>* is the local Moran's *I* index, and the other indicators have the same meaning as in Formula 1. *I<sub>i</sub>* > 0 indicates that transportation CO<sub>2</sub> shows high-high or low-low agglomeration, while *I<sub>i</sub>* < 0 indicates that transportation CO<sub>2</sub> emissions show high-low or low-high agglomeration. The local Moran's *I* clusters can help to identify regions with high CO<sub>2</sub> emissions.

#### GWR model

The GWR model is an improved spatial linear regression model that overcomes the defects of the OLS method, ignoring spatial effects and presupposing homogeneity between variables (Qin et al. 2019). In the analysis of influencing factors, the GWR model fully considers the role of spatial effects, embeds geographic information into the original regression equation, and uses the local weighted least squares method to estimate the parameters of each research region, thereby better reflecting the spatial dependence and spatial differences among economic variables. The formula is as follows.

$$Y_i = c(u_i, v_i) + \sum_j^m b_j(u_i, v_i) x_{ij} + \varepsilon_i \quad (3)$$

where *Y<sub>i</sub>* represents the transportation CO<sub>2</sub> emissions of city *i*, (*u<sub>i</sub>*, *v<sub>i</sub>*) is the longitude and latitude coordinate of city *i*, *c(u<sub>i</sub>*, *v<sub>i</sub>*) is the constant term, *b<sub>j</sub>(u<sub>i</sub>*, *v<sub>i</sub>*) is the regression coefficient of the influencing factor *J* in city *i*, and  $\varepsilon_i$  is the residual term. The nonstationarity of spatial relations can be intuitively detected by how the regression coefficient changes with the geographical location.

### Variable description

#### Explained variables: TCE

Since there are no data on transportation CO<sub>2</sub> emissions at the city level in the existing database, this paper will calculate these data indirectly, including the three areas of road, railway, and air transportation CO<sub>2</sub> emissions. For road transportation CO<sub>2</sub> emissions, first, carbon emissions are calculated according to the energy consumption of road traffic in each province; the specific calculation method can be found in Cai et al. (2012). Second, China's road network (GIS) data are divided into freeway and first-class, second-class, third-class, and fourth-class highways. With the designed daily traffic volume of different road levels as the weight, provincial traffic carbon emissions are allocated to each road segment in every 1-km spatial grid. Finally, the transportation CO<sub>2</sub> emissions of each

urban road are summarized based on the GIS spatial boundary of China's cities. For railway transportation CO<sub>2</sub> emissions, first, the carbon emissions of railways in each province are calculated based on railway turnover and energy consumption data. Second, according to the railway network data of each province (GIS data), the railway emissions from each province are allocated to each section of the railway in each 1-km spatial grid. Finally, the railway transportation CO<sub>2</sub> emissions of each city are summarized and formed based on the GIS spatial boundaries of Chinese cities. For transportation CO<sub>2</sub> emissions, first, the CO<sub>2</sub> emissions of each airport are calculated based on oil consumption. Second, the oil consumption of the transportation, storage, and postal industries in each province is used to verify the sum of the airport fuel consumption without considering international aviation.

### Explanatory variables

This paper chooses 10 indicators—private car ownership (CAR), technological innovation (TI), population density (PD), urbanization rate (UR), per capita urban road area (UA), transportation structure (TS), industrial structure (IS), per capita GDP (RGDP), public transport (BUS), and the level of environmental regulation (ER)—as the factors influencing transportation CO<sub>2</sub> emissions in the GWR model. These indicators and their impacts on transportation CO<sub>2</sub> emissions can be simply described as follows. CAR is measured by the number of private cars per 10,000 people, which reflects the saturation of a city with private cars. Cars are an important source of transportation CO<sub>2</sub> emissions. TI is measured by the number of patent authorizations per 10,000 people and is considered to be one of the important ways to solve the carbon emission problem. However, technological progress can also have a rebound effect, which can result in an increase in CO<sub>2</sub> emissions. PD is measured by the number of people per square kilometer and is generally considered to be positively related to transportation carbon emissions. UR is expressed as the proportion of the urban population. UR is an important factor affecting transportation CO<sub>2</sub> emissions, as generally, the higher the urbanization degree is, the more developed the transportation industry is, and the higher the corresponding carbon emissions are. However, higher urbanization can also mean more intensive energy utilization and, thus, reduced carbon emissions. UA reflects urban road construction. Generally, the better the road construction is, the less likely it is that there will be traffic jams, and therefore, the lower carbon emissions will be. TS is the ratio of railway transport turnover to total comprehensive transport turnover. Generally, a higher proportion of railway transport turnover means a lower promotion of transportation CO<sub>2</sub> emissions. IS is expressed by the proportion of secondary industry, as a higher proportion of secondary industry generally leads to greater carbon emissions. RGDP reflects the quality of economic

growth. The EKC shows that economic growth can both increase and reduce transportation CO<sub>2</sub> emissions depending on the starting economic level. BUS is measured by the number of buses per 10,000 people, as buses are regarded as a powerful measure for reducing transportation CO<sub>2</sub> emissions. ER is calculated by the entropy weight method and reflects the government's administrative intervention in environmental governance.

### Data description

Due to the lack of data for some cities, this paper selected 286 cities above the prefecture level in China as the research objects in 2015. The data are mainly from the China City Statistical Yearbook, the Yearbook of China Transportation & Communications, and the provincial Statistical Yearbooks. Descriptive statistics of the variables are shown in Table 1.

## Results and discussion

### Spatial distribution pattern of TCE

The distribution of total transportation CO<sub>2</sub> emissions in China is shown in Fig. 1. Chongqing, Shanghai, and Beijing are the three cities with the highest CO<sub>2</sub> emissions. Most cities with high CO<sub>2</sub> emissions are regional core cities, such as Tianjin, Chengdu, Wuhan, Dalian, Shenyang, Guangzhou, and Suzhou. Cities with low transportation CO<sub>2</sub> emissions are mostly concentrated in underdeveloped areas, such as the northwest, northeast, and southwest of China. Thus, the spatial distribution characteristics of transportation CO<sub>2</sub> emissions are closely connected with the level of regional economic development. Coastal areas have good geographical advantages, rapid urban economic development, and high CO<sub>2</sub> emissions. Northeast China is mainly an old industrial base and is facing a serious problem with population loss. In recent years, the decline has been obvious, and even negative growth has been observed. Compared with the eastern and central regions, the development of the vast western regions of China is relatively slow. Although it accounts for 72% of the total area of the country, the total population is only approximately 29% of the country. Approximately 48% of the land resources are the Gobi Desert and alpine areas with an altitude of more than 3000 m. All of these factors will have important impacts on transportation CO<sub>2</sub> emissions.

### Global and local correlation

According to Formula 1, the Moran's *I* index is 0.098796, the *p* value is 0.000, and the *z*-score is 4.422. The results show that the Moran's *I* index is greater than 0, the *p* value is less than 0.01, and the *z*-score is greater than 1.96, which indicates that

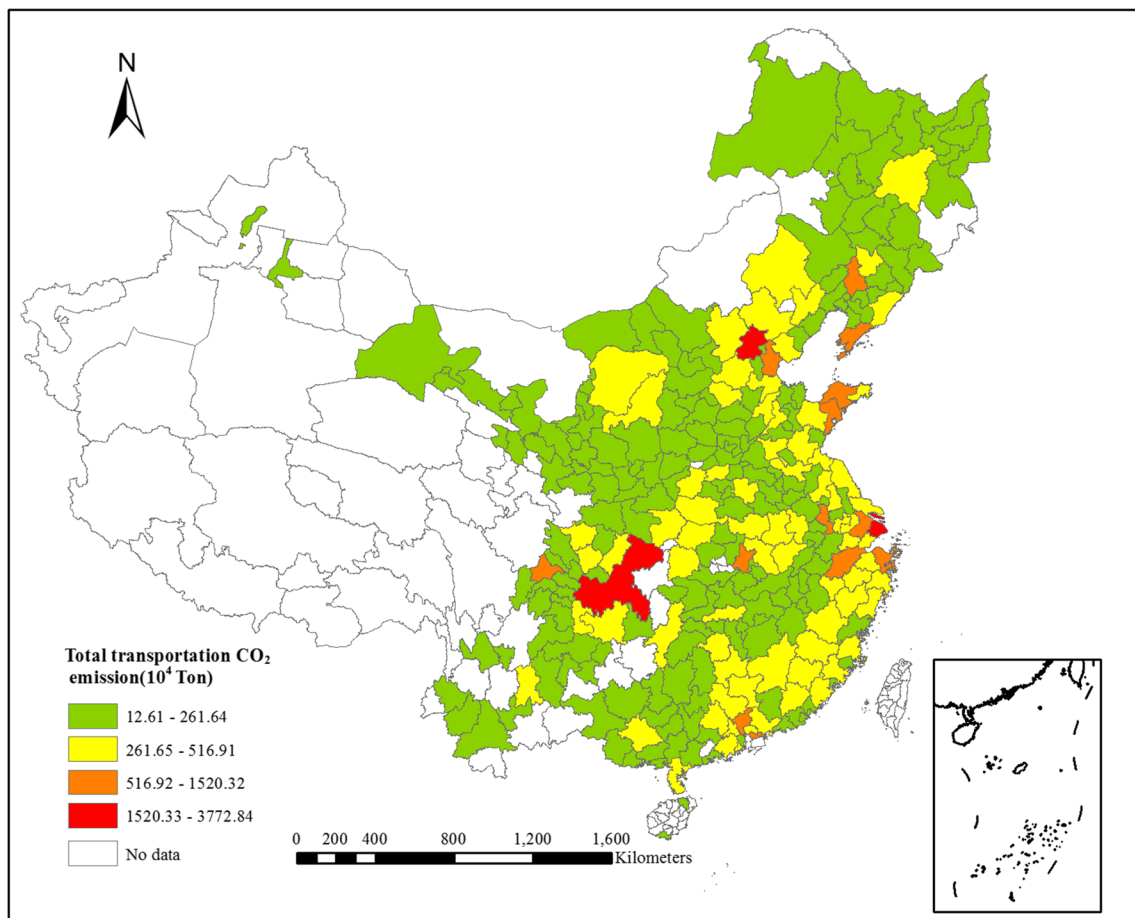
**Table 1** Statistical description of variables

	Description	Max	Min	Mean	Std. Dev.
TCE	Transportation CO <sub>2</sub> emissions (10 <sup>4</sup> ton)	3772.84	267.24	12.61	342.74
CAR	Private car ownership (unit)	5,350,000.00	593,475.00	41,999.00	693,057.90
TI	Number of patent authorization per 10 <sup>4</sup> people (unit)	118,225.00	6204.47	73.00	13,576.61
PD	Population density (people/km <sup>2</sup> )	2501.14	436.64	5.77	338.21
UR	Urbanization rate (%)	1.00	0.56	0.29	0.14
UA	Per capita urban road area (m <sup>2</sup> )	105.02	13.23	1.78	9.31
TS	Transportation structure (%)	1.00	0.89	0.26	0.17
IS	Proportion of secondary industry (%)	0.71	0.47	0.15	0.09
RGDP	Per capita GDP (Yuan)	207,163.00	51,125.54	10,987.00	29,543.82
BUS	Number of buses per 10 <sup>4</sup> people (unit)	225.50	9.61	1.04	14.97
ER	Environmental regulation level	0.95	0.76	0.39	0.11

the transportation CO<sub>2</sub> emissions in China's cities have significant spatial clustering characteristics and positive spatial autocorrelation.

The distribution of the local indicators of spatial association (LISA) of transportation CO<sub>2</sub> emissions, which can be used to explore the local characteristics, is shown in Fig. 2. There are

four main forms of spatial agglomeration: high-high, high-low, low-high, and low-low. Among them, the transportation CO<sub>2</sub> emissions of high-high agglomeration cities and their neighboring cities are relatively high and are mainly concentrated in developed provinces, such as Beijing, Tianjin, Shanghai, Jiaying, Hangzhou, and Guangzhou. The possible

**Fig. 1** Spatial distribution of transportation CO<sub>2</sub> emissions



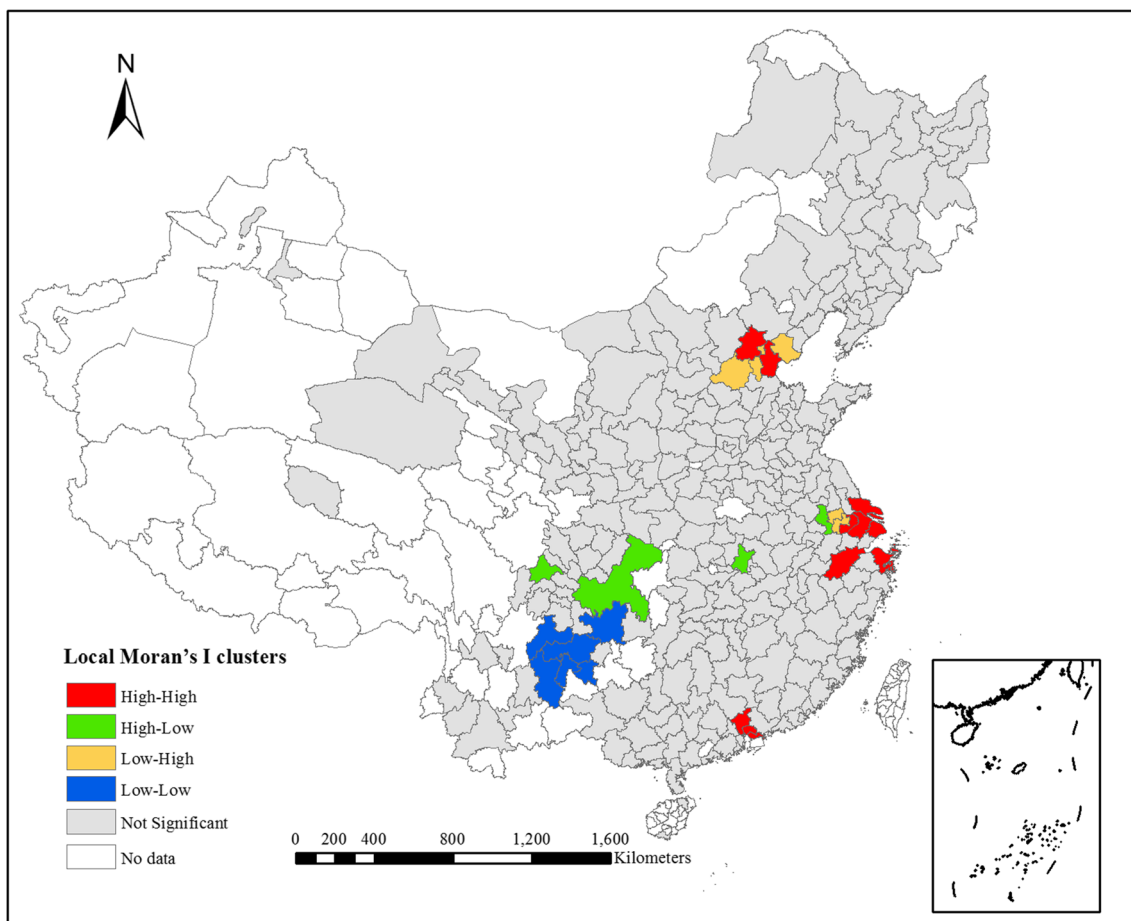


Fig. 2 Local Moran's *I* clusters of transportation CO<sub>2</sub> emissions in China

reasons for the high emissions include urban agglomeration, large economic capacity, and intensive human activities. The transportation CO<sub>2</sub> emissions of high-low agglomeration cities are high, while those of surrounding cities are low, and these are mainly represented by Nanjing, Chengdu, Chongqing, and other regional core cities. The transportation CO<sub>2</sub> emissions of low-high agglomeration cities are low, while those of surrounding cities are high; these include cities such as Zhenjiang, Changzhou of Jiangsu Province, and the peripheral cities of Beijing. The transportation CO<sub>2</sub> emissions of low-low agglomeration cities and the surrounding cities are relatively low and mainly concentrated in Guizhou and Yunnan, where the economy is underdeveloped and human activities are relatively scattered; thus, the carbon emissions are low.

**Spatial heterogeneity characteristics of the influencing factors**

**OLS regression results**

The OLS model is used to estimate parameters before using the GWR model, and the results are shown in Table 2. The

ANOVA *F* test shows that the model has strong significance, and the VIF values of all variables are far less than 10, indicating that there is no serious collinearity problem in the model. The coefficients show that most of the explanatory variables have a significant correlation with transportation CO<sub>2</sub> emissions. The three factors of private car ownership,

Table 2 OLS regression results

	Coefficient	Std. Error	<i>t</i> value	<i>p</i> value	VIF
Constant	-0.698	1.049	-0.67	0.506	
CAR	0.385	0.051	7.49	0.000	2.42
TI	0.260	0.038	6.75	0.000	3.73
PD	-0.221	0.049	-4.55	0.000	2.18
UR	-1.053	0.339	-3.11	0.002	2.49
UA	-0.230	0.072	-3.19	0.002	1.74
TS	-0.361	0.193	-1.87	0.063	1.24
IS	0.115	0.071	1.61	0.097	1.06
RGDP	0.146	0.102	1.43	0.155	3.14
BUS	0.042	0.055	0.77	0.443	1.78
ER	0.126	0.326	0.39	0.699	1.45

technological innovation, and industrial structure have significant positive effects on transportation CO<sub>2</sub> emissions, and every 1% increase in these three factors can lead to an increase of 0.39%, 0.26%, and 0.12% in transportation CO<sub>2</sub> emissions, respectively. The rapid growth in the number of private cars and low fuel efficiency are considered the main factors leading to transportation CO<sub>2</sub> emissions. In some developed cities, such as Beijing, the CO<sub>2</sub> emissions of private cars can account for as much as 88% of traffic CO<sub>2</sub> emissions. The influence coefficient of technological innovation found here is not consistent with the conclusions of Pei et al. (2019) and other scholars. The possible reason for this difference is that this paper uses the number of patent authorizations rather than automobile technology as a measure of technological innovation. In practice in China, a large number of patents come from universities and research institutes, and these cannot be converted into technical applications and thus cannot reduce CO<sub>2</sub> emissions. In addition, most enterprises apply for patents to develop new products and expand production, which will promote energy consumption and increase CO<sub>2</sub> emissions. In 2019, the proportion of secondary industry in China was as high as 39.0%, which is far higher than that of developed countries. The demand for raw materials and product transportation in secondary industry is still huge, and this inevitably leads to an increase in transportation CO<sub>2</sub> emissions. Population density, urbanization rate, per capita urban road area, and transportation structure can significantly inhibit transportation CO<sub>2</sub> emissions, and every 1% increase in these four factors reduces the corresponding transportation CO<sub>2</sub> emissions by 0.22%, 1.05%, 0.23%, and 0.35%, respectively. The lower the population density, the lower the number of cars, lessening traffic and lowering the corresponding CO<sub>2</sub> emissions. A large amount of transportation CO<sub>2</sub> emissions comes from the production and life of rural residents. With urbanization, energy is intensively used, and utilization efficiency is greatly improved, correspondingly reducing CO<sub>2</sub> emissions. Under the high degree of urban construction and land utilization, land resources are scarcer, which will encourage local governments to replace traditional energy with more environmentally friendly energy to reduce transportation CO<sub>2</sub> emissions (Liu et al. 2016). Compared with highway transportation, railway transportation is a lower carbon mode. The impact of per capita GDP, public transport, and environmental regulation on transportation CO<sub>2</sub> emissions is insignificant. Due to the large regional economic development gap in China, some cities with high per capita GDP have high CO<sub>2</sub> emissions, but some resource-based cities with low per capita GDP also have high CO<sub>2</sub> emissions. It may be that these contrasting situations result in per capita GDP not being significant in this paper. China began developing public transport relatively late, especially in the central and western cities, and the corresponding level of public transport development is far lower than that of developed countries, making it difficult to

curb transportation CO<sub>2</sub> emissions. Due to China's special decentralized fiscal system, local governments tend to relax environmental regulation standards and collude with polluting enterprises to pursue GDP and expand fiscal revenue, rendering environmental regulation policies ineffective (Shen et al. 2017).

### GWR regression results

Since the OLS model cannot explain the local heterogeneity in the impacts of the 10 variables on transportation CO<sub>2</sub> emissions, this paper will use the GWR model for further analysis, and the local  $R^2$  value of the spatial distribution is shown in Fig. 3. The  $R^2$  value varies between 0.4788 and 0.7973, and the degree of fit for different regions varies. The  $R^2$  value gradually decreased from Northeast China and North China to Central and Northwest China. The area best fitting the GWR model is Northeast China, and the areas with the worst fit are Central China, South China, and Northwest China. This result shows that in Northeast China, the relationship between driving factors and transportation CO<sub>2</sub> emissions is better reflected in the regression model. Across all cities, the local  $R^2$  value of Hulunbuir City in Inner Mongolia is the highest and that of Jiuquan City in Gansu Province is the lowest.

The statistical description of the influencing coefficient of each variable in the GWR model on transportation CO<sub>2</sub> emissions is shown in Table 3. The standard deviation of the estimated coefficient varies widely, with a minimum value (TS) of 0.027 and a maximum value (IS) of 0.108. The larger the range of each coefficient is, the greater the spatial variation in the influence degree of each factor, and the more appropriate the GWR model will be in local estimation. Table 3 also shows the proportion of cities with significant estimated coefficients ( $p < 0.10$ ), and the proportion of cities with positive and negative estimated coefficients. To explore the spatial heterogeneity of the relationship between various influencing factors and transportation CO<sub>2</sub> emissions, this paper describes the spatial distribution characteristics of the estimation coefficients, as shown in Fig. 4.

The impact of private car ownership on transportation CO<sub>2</sub> emissions is positive, and it is significant in 99.3% of the cities, which is basically consistent with the estimates of the OLS model. In the cities of Shandong, Liaoning, Jiangsu, Anhui, Zhejiang, Fujian, and other eastern provinces, private cars have the highest impact on transportation CO<sub>2</sub> emissions, while the impact is lower in western cities. The possible reason is that there are many more private cars in developed coastal cities than that in other regions, and the rapid growth in the number of private cars and low fuel efficiency are considered the main factors leading to transportation CO<sub>2</sub> emissions. Therefore, the impact of private cars is higher in coastal regions than in other regions.

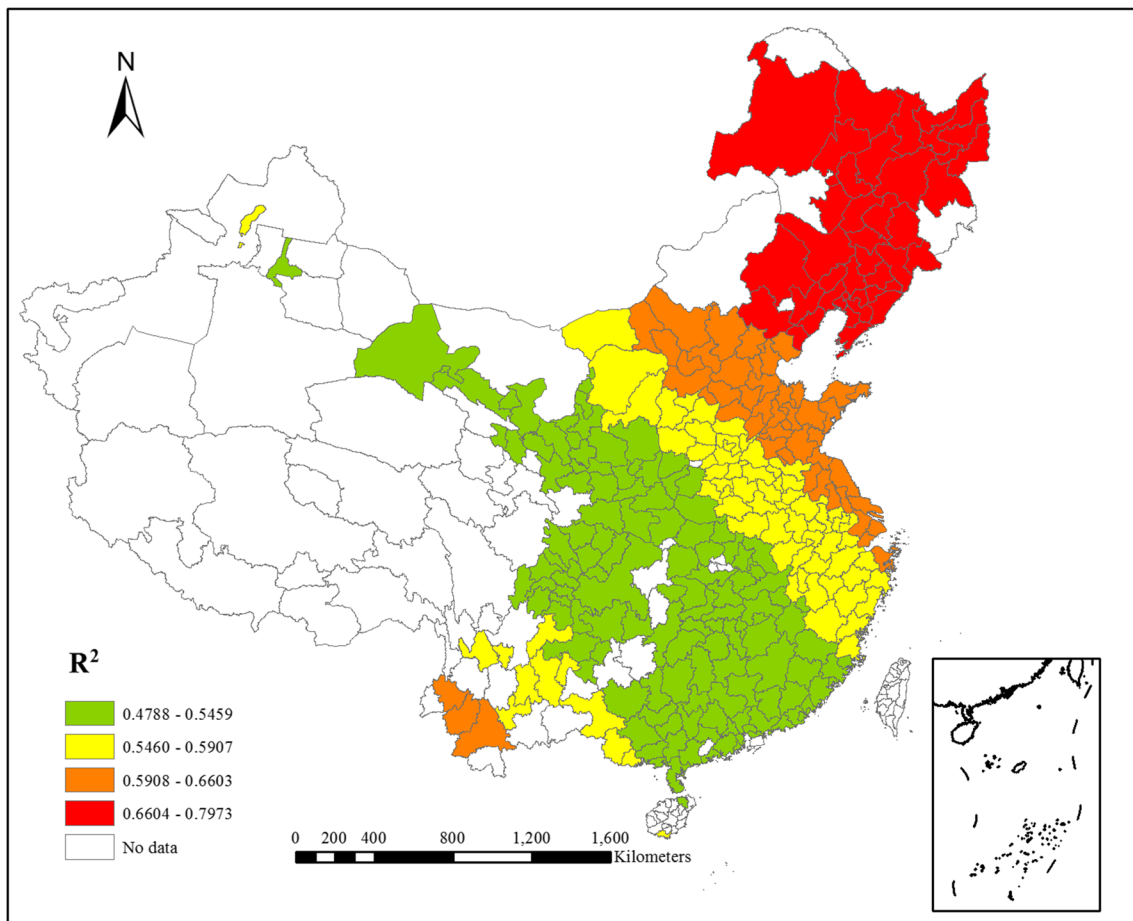


Fig. 3 Spatial distribution of  $R^2$  values

The influence coefficient of technological innovation on transportation CO<sub>2</sub> emissions is positive, and it is significant in 60.14% of cities; the degree of influence gradually increases from South to North China. Among these cities, technological innovation has the highest impact in Heilongjiang, Jilin, Liaoning, Inner Mongolia, and other

regions. Northern China is rich in energy resources and is China’s heavy industry base. It may be that patents are promoting the progress of energy consumption technology, which may lead to the substitution of energy elements for nonenergy elements and have a positive influence on transportation CO<sub>2</sub> emissions.

Table 3 Descriptive statistics of regression coefficients in GWR model

	Coefficients				Percent of cities by significance of <i>T</i> test		
	Max	Min	Mean	Std. Dev.	$p < 0.1$	+(%)	– (%)
CAR	0.734	0.112	0.599	0.070	99.30	100.00	0.00
TI	0.549	0.049	0.196	0.108	60.14	100.00	0.00
PD	0.191	–0.220	–0.008	0.090	29.37	47.55	52.45
UR	–0.014	–0.180	–0.060	0.026	29.37	0.00	100.00
UA	–0.077	–0.246	–0.126	0.031	83.92	0.00	100.00
TS	–0.034	–0.157	–0.100	0.027	73.78	0.00	100.00
IS	0.164	–0.230	–0.025	0.096	41.26	38.11	61.89
RGDP	0.215	0.006	0.063	0.028	15.03	100.00	0.00
BUS	0.224	–0.163	–0.048	0.062	30.77	0.00	100.00
ER	0.069	–0.147	–0.081	0.054	52.45	0.00	100.00



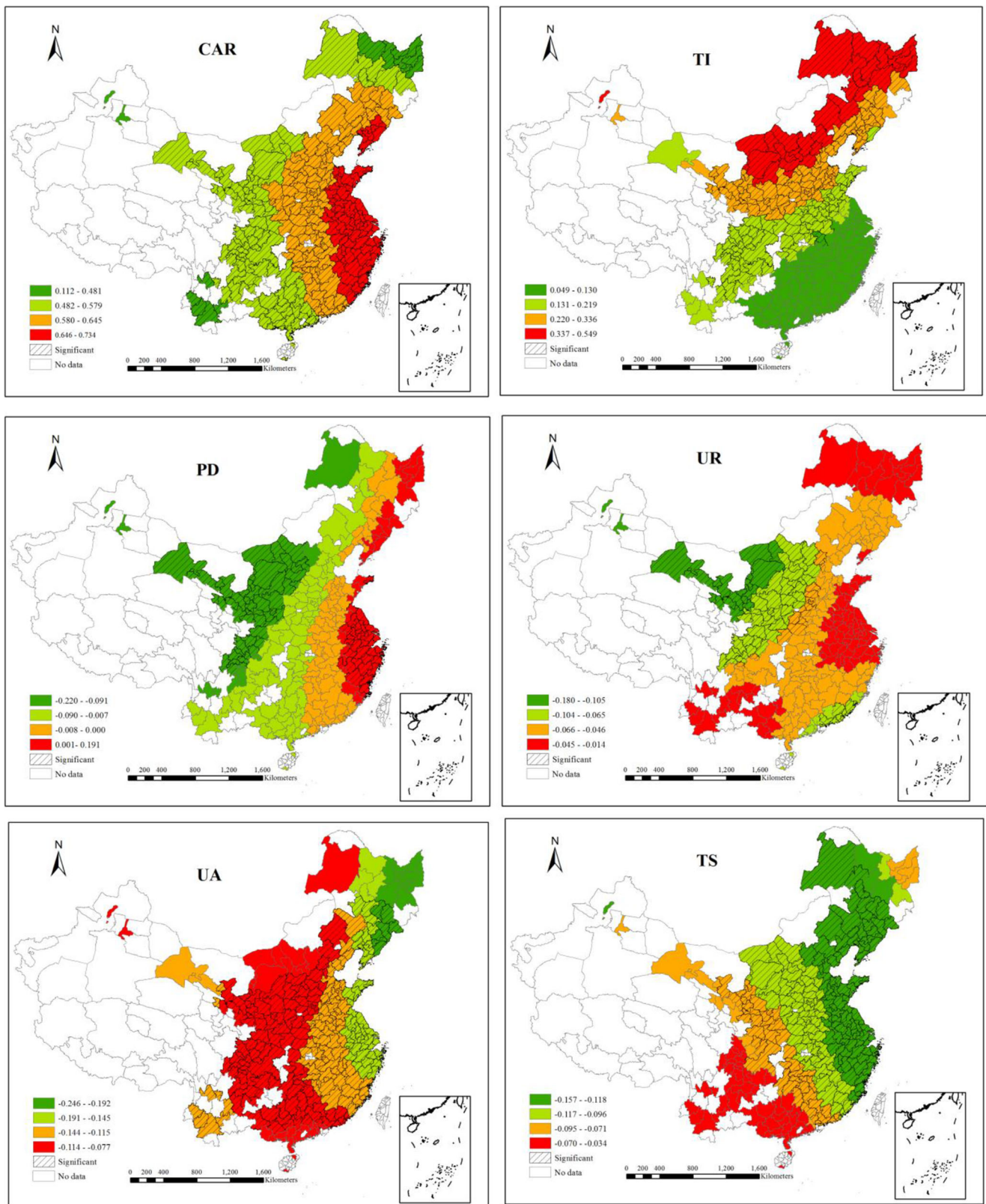


Fig. 4 Spatial distribution of regression coefficients based on the GWR model

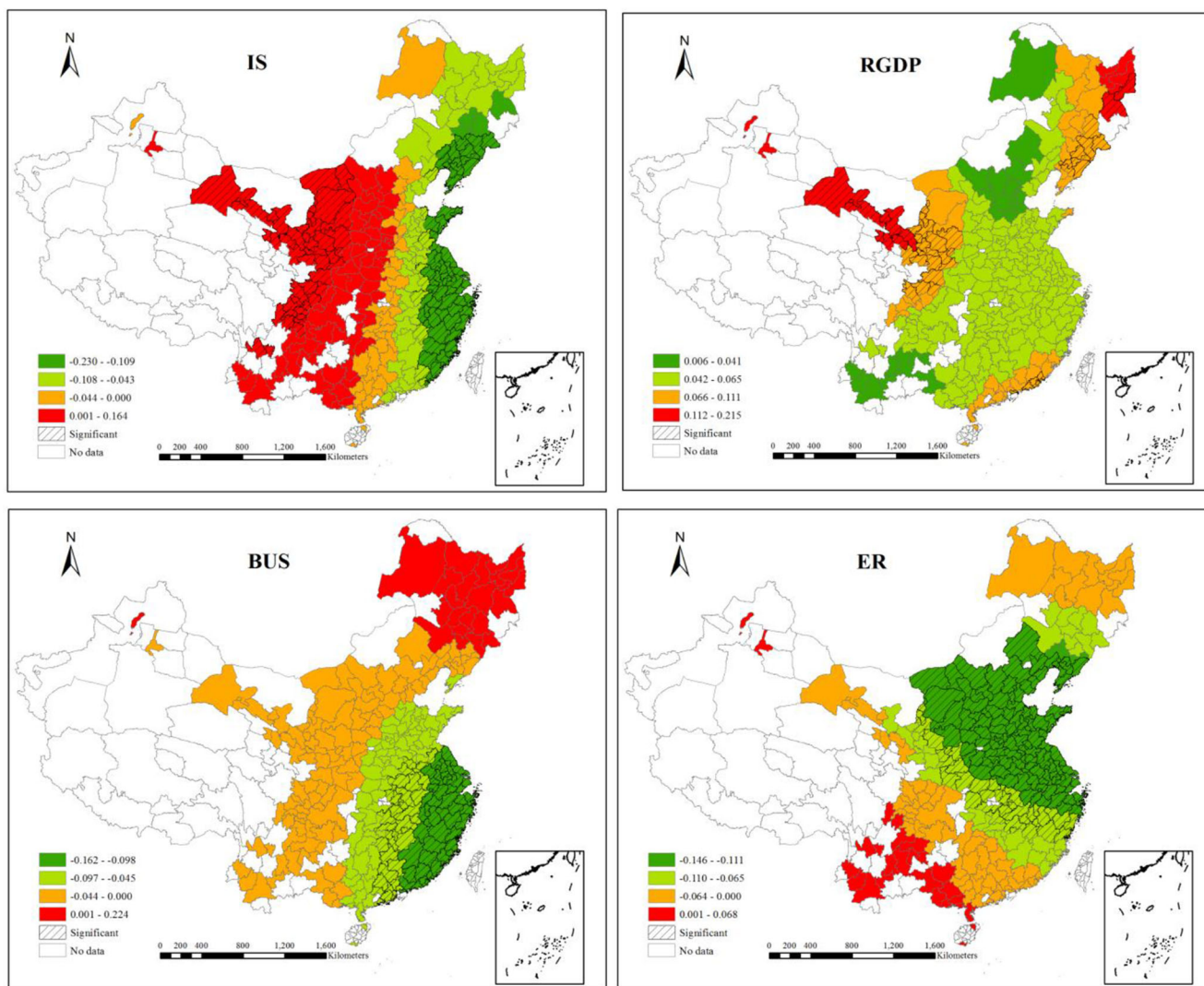


Fig. 4 (continued)

Population density has a two-way effect on transportation CO<sub>2</sub> emissions: significantly positive in eastern cities and significantly negative in other western cities. The influencing coefficient between the two regions is not significant and cannot be revealed by the OLS model. There are many employment opportunities in the eastern coastal cities attracting a large amount of talent, and the population density is high, which will lead to increased demand for travel and infrastructure, resulting in increased CO<sub>2</sub> emissions (Wang and Lin 2016).

The impact of the urbanization rate on transportation CO<sub>2</sub> emissions is negative and only significant in 29.37% of cities. These cities are mainly located in Gansu, Qinghai, Ningxia, Shaanxi, and other western provinces, and the impact is not significant in other regions. The possible reason is that the urbanization rate of most cities in the eastern region is relatively high, and urban development has entered a relatively ideal stage. The urban infrastructure has been improved, and the urbanization rate has reached a high level, so the impact on transportation CO<sub>2</sub> emissions is very small.

The influence of per capita urban road area on transportation CO<sub>2</sub> emissions is negative and significant in 83.92% of cities, which shows that improvement in road traffic conditions is conducive to reducing transportation CO<sub>2</sub> emissions. The degree of influence decreases from East to West China. In the eastern cities, the impact of per capita urban road area on transportation CO<sub>2</sub> emissions is the highest, while the impact is much smaller in the western cities. The possible reasons are the rapid urbanization process in the eastern region, the high degree of urban construction and land utilization, and the scarcity of land resources, which together encourage local governments to use more environmentally friendly energy to replace traditional energy and vigorously develop public transport.

The influence of transportation structure on transportation CO<sub>2</sub> emissions is negative and significant in 73.78% of cities, and the degree of influence weakens from East to West China. The transportation structure in the eastern coastal area has the strongest restraining effects, which may be due to better

infrastructure and more developed railway transportation conditions in that area, especially the large-scale construction of high-speed railways in China in recent years, which has mainly occurred in the eastern area. In southwestern areas, such as Guizhou, Yunnan, and Guangxi, the inhibition effect of the transportation structure is the weakest and not significant, which may be because these areas are basically remote mountainous areas, with less railway mileage and low passenger and freight volumes, making it difficult to inhibit transportation CO<sub>2</sub> emissions.

There are two-way effects of industrial structure on transportation CO<sub>2</sub> emissions. In the eastern coastal cities, the impact coefficient is significantly negative, while it is significantly positive in the western cities. The possible reason is that secondary industry in coastal provinces has become relatively developed, especially in recent years, and after industrial transfer and structural upgrading, some enterprises with high-energy consumption have moved to the western region. The characteristics of the upgraded industrial structure are obvious, resulting in low-carbon emissions (Zhao and Yin 2011). However, to catch up and surpass demand, the central and western cities have no choice but to introduce some high-energy consumption enterprises when engaging in industrial transfer, and the demand for raw materials and the transportation of goods is increasing daily. Therefore, significant demand for transportation in the process of industrialization will inevitably lead to an increase in carbon emissions.

The impact coefficient of per capita GDP on transportation CO<sub>2</sub> emissions is always positive but only significant in 15.03% of the cities. These cities are mainly located in Heilongjiang, Jilin, Gansu, Ningxia, Shaanxi, and other western regions. In most other cities, the impact of per capita GDP is not significant. This result shows that at present, economic development is still an important factor leading to CO<sub>2</sub> emissions in West China, the relationship between the environment and the economy are still on the left side of the EKC, and the level of economic development has not reached the inflection point. Of course, the impact of per capita GDP on transportation CO<sub>2</sub> emissions is no longer significant in developed cities, such as Beijing, Tianjin, Shanghai, Hangzhou, and Suzhou. According to the current development trend, there may be a turning point in the near future (Wang and Feng 2019). In fact, the CO<sub>2</sub> emissions of developed regions over the years are higher, and they have a greater responsibility to reduce CO<sub>2</sub> emissions.

There are two-way effects of public transport on transportation CO<sub>2</sub> emissions. In Shanghai, Zhejiang, Jiangsu, Fujian, and other coastal cities in East China, the impact coefficient is significantly negative, indicating that the development of public transport can inhibit transportation CO<sub>2</sub> emissions. The possible reason is that public transport in East China is developed and obviously superior to that in other cities. People have a strong willingness to go green, and residents are relatively

more willing to choose public transport. Compared with private cars, using public transportation can reduce CO<sub>2</sub> emissions (Ercan et al. 2016). The impact of public transport in other cities is not significant, which may be because they lack development in these cities, so it would be difficult for them to have a negative effect on CO<sub>2</sub> emissions.

There are two-way effects of the environmental regulation level on transportation CO<sub>2</sub> emissions. In Beijing, Tianjin, and other northern cities, the impact coefficient is significantly negative, indicating that environmental regulation can inhibit transportation CO<sub>2</sub> emissions. The possible reason is that for a long time, the northern region has been the most developed heavy industrial area and the most polluted region in China. Therefore, in recent years, the government has strengthened environmental regulation and taken various traffic measures, such as restrictions on the number of cars and on the volume of traffic, which will not only improve air quality but also reduce transportation CO<sub>2</sub> emissions. In other cities, the impact coefficient is not significant, which may be due to the weak level of environmental regulation in these areas, and there is also a tradeoff between environmental governance and economic development.

## Conclusions and policy implications

### Conclusions

In this paper, 286 cities in China are taken as samples to analyze the spatial distribution characteristics of transportation CO<sub>2</sub> emissions considering the global and local dimensions using the ESDA method, and the GWR model is used to study the spatial differences in the factors affecting urban transportation CO<sub>2</sub> emissions by considering the spatial effects among regions. The main conclusions are as follows.

First, the transportation CO<sub>2</sub> emissions in China's cities show significant spatial clustering characteristics. The cities with high transportation CO<sub>2</sub> emissions are mainly concentrated in Beijing, Shanghai, Chongqing, Chengdu, Nanjing, and other regions, while the cities with low transportation CO<sub>2</sub> emissions are mainly concentrated in Gansu, Guizhou, Yunnan, and other underdeveloped provinces in the midwestern region. For areas with high transportation CO<sub>2</sub> emissions, collaborative emission reduction policies should be formulated when addressing CO<sub>2</sub> emissions.

Second, from the perspective of the overall national evolution of the factors affecting transportation CO<sub>2</sub> emissions, private car ownership, technological innovation, and industrial structure are the main promoters of transportation CO<sub>2</sub> emissions, while population density, urbanization rate, per capita urban road area, and transportation structure are the main restraints on transportation CO<sub>2</sub> emissions. The impact of per



capita GDP, public transport, and environmental regulation on transportation CO<sub>2</sub> emissions is not significant.

Third, the coefficient of each driving factor is shown locally by the GWR model. The impact of private car ownership on transportation CO<sub>2</sub> emissions is always positive and is significant in 99.3% of the cities; in the eastern cities, it has the highest impact coefficient. The impact coefficient of technological innovation on transportation CO<sub>2</sub> emissions is positive and significant in 60.14% of cities. In the northern cities, the impact coefficient is the highest, and the rebound effect of technological progress is more obvious. Population density has a two-way impact on transportation CO<sub>2</sub> emissions, as it is significantly positive in eastern cities and significantly negative in western cities. The impact of the urbanization rate on transportation CO<sub>2</sub> emissions is negative and only significant in 29.37% of cities, which are mainly located in the western region. The impact of per capita urban road area on transportation CO<sub>2</sub> emissions is negative and significant in 83.92% of cities. The degree of influence decreases from East to West China, which shows that the improvement in road traffic conditions is conducive to reducing transportation CO<sub>2</sub> emissions. The impact of transportation structure on transportation CO<sub>2</sub> emissions is negative and significant in 73.78% of cities. The degree of influence is weakened from East to West China, which shows that railway transportation is conducive to reducing transportation CO<sub>2</sub> emissions. There are two directions for the effects of industrial structure on transportation CO<sub>2</sub> emissions; these are significantly negative in eastern coastal cities and significantly positive in western cities. The impact of per capita GDP on transportation CO<sub>2</sub> emissions is positive and only significant in 15.03% of the cities that are located in the western regions. There are two-way effects of public transport on transportation CO<sub>2</sub> emissions. In the eastern coastal cities, the impact coefficient is significantly negative, while the impact coefficient is positive but insignificant in other cities. There are two-way effects of environmental regulation on transportation CO<sub>2</sub> emissions. In the northern cities, the impact coefficient is significantly negative.

## Policy implications

The above conclusions have certain significance for the formulation and adjustment of China's environmental policy. Because the development process, natural resources, and geographical location of each city differ, environmental policies should be formulated in line with the characteristics of each region. According to the conclusions of this paper, the following suggestions are proposed.

First, the government should strictly control the number of private fuel vehicles; continue to vigorously promote the development of pure electric, hybrid, hydrogen energy and other new energy vehicle industries; and promote the application of new energy for public transport, large passenger cars, and

trucks. Second, energy-biased technological progress should be reduced to weaken the rebound effect. Especially in its northern cities, China should focus on the development of new energy technology and low-carbon technology and introduce market mechanisms to ensure the development and application of low-carbon technology. Third, we should attract population transfer to central and western cities by means of industrial transfer, which will reduce population pressure in large cities in the East and promote urbanization in the central and western regions. Some effective talent introduction policies should be implemented to promote the rational flow of population. Fourth, the existing land resources should be used to widen the urban road area. For the newly planned urban area in particular, the design standard of the road area should be improved, such as changing from four lanes to six lanes. Fifth, railway construction should be accelerated in Southwest China, and road transport should be transferred to railways, inland river transport, and other more environmentally friendly transport modes as much as possible to promote the low-carbon development of comprehensive transport systems. Overload and overrun should be strictly controlled so that the transportation of bulk goods will shift from highway transportation to railway transportation for the sake of cost and carrying capacity. Sixth, the central and western cities should be encouraged to change their economic development mode and constantly optimize their industrial structure. In particular, central and western cities should not blindly accept foreign high-energy consumption industries but should choose low pollution and low emission green industries. Only by changing from the original extensive economic development mode, optimizing the economic growth structure, and striving to achieve a balance between the economy and the environment can the low-carbon development of transportation be ensured. Seventh, in the eastern developed areas, China should strengthen investment in the construction of the public transport system, eliminate the old means of transport, accelerate the construction of low-carbon transport systems such as mass transit and urban rail transit, provide more convenient and efficient transport services, and encourage the use of shared bicycles. Finally, it should further strengthen environmental regulation, consider the heterogeneity of regional economic development and carbon emission intensity, and adopt differentiated environmental regulation tools. For the eastern developed cities, China should consider people's increasing demand for environmental quality and green products and adopt a higher intensity of environmental regulation. The intensity of environmental regulation should be moderate for the less developed cities in the central and western regions.

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## References

- Abdull N, Yoneda M, Shimada Y (2020) Traffic characteristics and pollutant emission from road transport in urban area. *Air Qual Atmos Health*
- Ahmed Z, Wang ZH, Ali S (2019) Investigating the non-linear relationship between urbanization and CO<sub>2</sub> emissions: an empirical analysis. *Air Qual Atmos Health* 12:945–953
- Asian Development Bank (2019) Addressing climate change in transport. <https://www.adb.org/sectors/transport/key-priorities/climate-change/>. Accessed 1 Feb 2020
- Bai CQ, Zhou L, Xia ML, Feng C (2020) Analysis of the spatial association network structure of China's transportation carbon emissions and its driving factors. *J Environ Manag* 253:109765
- Bastani P, Heywood JB, Hope C (2012) The effect of uncertainty on US transport-related GHG emissions and fuel consumption out to 2050. *Transp Res A-POL* 46:517–548
- Cai BF, Yang WS, Cao D, Liu LC, Zhou Y, Zhang ZS (2012) Estimates of China's national and regional transport sector CO<sub>2</sub> emissions in 2007. *Energy Policy* 41:74–483
- Cai B, Guo H, Cao L, Guan D, Bai H (2018) Local strategies for China's carbon mitigation: an investigation of Chinese city-level CO<sub>2</sub> emissions. *J Clean Prod* 178:890–902
- Chang CC, Chung CL (2018) Greenhouse gas mitigation policies in Taiwan's road transportation sectors. *Energy Policy* 123:299–307
- Elhorst JP (2012) Matlab software for spatial panels. *Int Reg Sci Rev* 37:389–405
- Ercan T, Onat NC, Tatari O (2016) Investigating carbon footprint reduction potential of public transportation in United States: a system dynamics approach. *J Clean Prod* 133:1260–1276
- Feng C, Huang J, Wang M (2019) The sustainability of China's metal industries: features, challenges and future focuses. *Resour Policy* 60:215–224
- Han X, Xu Y, Kumar A, Lu X (2018) Decoupling analysis of transportation carbon emissions and economic growth in China. *Environ Prog Sustain Energy* 37:1696–1704
- Huang J, Luo Y, Feng C (2019) An overview of carbon dioxide emissions from China's ferrous metal industry: 1991–2030. *Resour Policy* 62:541–549
- International Energy Agency (2018) CO<sub>2</sub> emissions from fuel combustion. <https://webstore.iea.org/co2-emissions-from-fuel-combustion-2018-highlights>. Accessed 9 Feb 2020
- Liu Y, Feng C (2020) Decouple transport CO<sub>2</sub> emissions from China's economic expansion: a temporal-spatial analysis. *Transp Res D-TR E* 79:102225
- Liu X, Ma SF, Tian JF, Jia N, Li G (2015) System dynamics approach to scenario analysis for urban passenger transport energy consumption and CO<sub>2</sub> emissions: a case study of Beijing. *Energy Policy* 85:253–270
- Liu YS, Yan B, Zhou Y (2016) Urbanization, economic growth, and carbon dioxide emissions in China: a panel cointegration and causality analysis. *J Geogr Sci* 26:131–152
- Lu S, Jiang H, Liu Y, Huang S (2017) Regional disparities and influencing factors of average CO<sub>2</sub> emissions from transportation industry in Yangtze River Economic Belt. *Transp Res D-TR E* 57:112–123
- Lv Q, Liu HB, Yang DY, Liu H (2019) Effects of urbanization on freight transport carbon emissions in China: common characteristics and regional disparity. *J Clean Prod* 211:481–489
- Nocera S, Galati OI, Cavallaro F (2018a) On the uncertainty in the economic valuation of carbon emissions from transport. *J Transp Econ Policy* 52:68–94
- Nocera S, Ruiz-Alarcón-Quintero C, Cavallaro F (2018b) Assessing carbon emissions from road transport through traffic flow estimators. *Transp Res C-EMER* 95:125–148
- Pei Y, Zhu YM, Liu SX, Wang XC, Cao JJ (2019) Environmental regulation and carbon emission: the mediation effect of technical efficiency. *J Clean Prod* 236:117599
- Qin HT, Huang QH, Zhang ZW, Lu Y, Li MC, Xu L, Chen ZJ (2019) Carbon dioxide emission driving factors analysis and policy implications of Chinese cities: combining geographically weighted regression with two-step cluster. *Sci Total Environ* 684:413–424
- Shen J, Wei YD, Yang Z (2017) The impact of environmental regulations on the location of pollution-intensive industries in China. *J Clean Prod* 148:785–794
- Wang M, Feng C (2019) Decoupling economic growth from carbon dioxide emissions in China's metal industrial sectors: a technological and efficiency perspective. *Sci Total Environ* 691:1173–1181
- Wang X, Lin B (2016) How to reduce CO<sub>2</sub> emissions in China's iron and steel industry. *Renew Sust Energ Rev* 57:1496–1505
- Wang H, Ou X, Zhang X (2017) Mode, technology, energy consumption, and resulting CO<sub>2</sub> emissions in China's transport sector up to 2050. *Energy Policy* 109:719–733
- Wu LF, Xu ZC (2019) Analyzing the air quality of Beijing, Tianjin, and Shijiazhuang using grey Verhulst model. *Air Qual Atmos Health* 12:1419–1426
- Wu D, Yuan C, Liu H (2018) The decoupling states of CO<sub>2</sub> emissions in the Chinese transport sector from 1994 to 2012: a perspective on fuel types. *Energy Environ* 29:591–612
- Yang L, Wang YQ, Han SS, Liu YY (2019) Urban transport carbon dioxide (CO<sub>2</sub>) emissions by commuters in rapidly-developing cities: the comparative study of Beijing and Xi'an in China. *Transp Res D-TR E* 68:65–83
- Yang L, Wang YQ, Lian YJ, Han SS (2020) Factors and scenario analysis of transport carbon dioxide emissions in rapidly-developing cities. *Transp Res D-TR E* 80:102252
- Zhao X, Yin H (2011) Industrial relocation and energy consumption: evidence from China. *Energy Policy* 39:2944–2956

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