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# Examining the Factors Influencing Transport Sector CO<sub>2</sub> Emissions and Their Efficiency in Central China

Huali Sun<sup>1</sup>, Mengzhen Li<sup>1</sup> and Yaofeng Xue<sup>2,\*</sup>

- <sup>1</sup> School of Management, Shanghai University, Shanghai 200444, China
- <sup>2</sup> Department of Education Information Technology, East China Normal University, Shanghai 200062, China
- \* Correspondence: yfxue@deit.ecnu.edu.cn; Tel.: +86-02166134414

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**Abstract:** The fast development of the transport sector has resulted in high energy consumption and carbon dioxide (CO<sub>2</sub>) emissions in China. Though existing studies are concerned with the factors influencing transport sector CO<sub>2</sub> emissions at the national level (or in megacities), little attention has been paid to the comprehensive impact of socio-economic, urban form, and transportation development on transport sector carbon emissions and emissions efficiency in central China. This paper examines the comprehensive impact of the transport sector's carbon emissions from six provinces in central China, during the period from 2005 to 2016, based on the panel data model. The dynamic change of CO<sub>2</sub> emissions efficiency is then analyzed using the Global Malmquist Luenberger Index. The results indicate that, firstly, economic growth, road density, the number of private vehicles, and the number of public vehicles have caused greater CO<sub>2</sub> emissions during the study period, while the freight turnover, urbanization level, and urban population density had repressing effects on CO<sub>2</sub> emissions. Secondly, an uneven distribution of CO<sub>2</sub> emissions and CO<sub>2</sub> emissions efficiency was found among different provinces in central China. Thirdly, changes in CO<sub>2</sub> emissions efficiency were mainly due to technical changes. Finally, we present some policy suggestions to mitigate transport sector CO<sub>2</sub> emissions in central China.

**Keywords:** transport sector CO<sub>2</sub> emissions; influence factors; efficiency; panel data; Global Malmquist Luenberger (GML); central China

# 1. Introduction

The main culprit in global warming is carbon dioxide (CO<sub>2</sub>), much of which is produced by the combustion of fuel [1]. On a global scale, the transport sector emitted around 8000 million tons of CO<sub>2</sub>, which is about one-quarter of the grand total in 2016. More and more countries and regions developing their transport sectors are trying to cut down on energy consumption and CO<sub>2</sub> emissions. America has historically had the highest transport sector CO<sub>2</sub> emissions levels of all regions, and this value has persisted in recent years. However, China is quickly closing the gap, with annual growth rates five times larger than America since 2000. China is also the country with the largest increase in transport sector CO<sub>2</sub> emissions. Thus, exploring the influencing factors and efficiency of CO<sub>2</sub> emissions in the transport sector is the basis of reducing transportation CO<sub>2</sub> emissions in China.

Extensive analysis of the influencing factors of Chinese transport sector  $CO_2$  emissions has been carried out [2]. The earliest literature studied the influence of socio-economic factors on transport sector carbon emissions such as per capita GDP and GDP growth [3,4]. Later, transportation development factors, such as passenger turnover and freight turnover, were determined to affect the change of  $CO_2$  emissions in the transport sector [5,6]. With the development of urbanization, some scholars began to explore the impact of urban form and urban land on traffic carbon emissions [7,8]. Most existing studies concentrate on the transport sector's  $CO_2$  emissions at the national level [9,10], while others focus

on megacities or east and south developed regions in China [8,11,12]. These studies ignore transport sector  $CO_2$  emissions and the mitigation of such emissions in central China, despite central China being a transportation hub connecting the east and west. The present study investigated the effect of socio-economic urban form and transportation development on transport sector carbon emissions in central China, which can play a pivotal role in effective emissions reduction.

Improving the efficiency of  $CO_2$  emissions has been recognized as the most effective way to reduce the greenhouse effect and achieve sustainable development, especially in manufacturing industries with high energy consumption [13,14]. Nevertheless, little literature has focused on the transport sector, and the performance of transport sector  $CO_2$  emissions has mainly been measured via data envelopment analysis (DEA) [15–18]. Nevertheless, these studies used a relatively static carbon performance measure within a cross-sectional framework without considering dynamic performance changes. The Global Malmquist Luenberger (GML) index integrates the cross-sectional and time-series performances and has some advantages in calculating dynamic changes in efficiency. Some literature discusses panel data using the GML index in many other sectors, including examinations of the industrial sector [19,20], the light industry [21], the water industry [22,23], and the iron and steel industry [24]. Zhang et al. [25] measured the dynamics of the transport sector's total  $CO_2$  emissions over time via a non-radial Malmquist  $CO_2$  emissions performance index. However, there are few studies that use GML to measure  $CO_2$  emissions efficiency in the Chinese transport sector.

The objective of this study is to comprehensively explore the impacts of socio-economic factors, urban forms, and transportation developments on the transport sector's carbon emissions in central China using panel data from six provinces from 2005 to 2016. In addition, to improve  $CO_2$  emissions efficiency, this paper measures the dynamics of  $CO_2$  emissions efficiency in the transport sector using panel data based on the Global Malmquist Luenberger index and comprehensively analyzes the possible reasons for the fluctuation of transport sector  $CO_2$  emissions efficiency in each province. The remainder of this paper is organized as follows: Section 2 briefly reviews the related literature; section 3 describes the impact of urban form and transportation development on transportation  $CO_2$  emissions using the panel data model; section 4 evaluates dynamic  $CO_2$  emissions efficiency changes using the Global Malmquist Luenberger index; lastly, conclusions and policy suggestions to mitigate transportation  $CO_2$  emissions are provided.

## 2. Literature Review

Many existing studies in various countries have been concerned with CO<sub>2</sub> emissions in the transport sector. For the most part, these studies separately focus on the impacts of socio-economic, transportation development, and urban form factors on CO<sub>2</sub> emissions. Most studies explore the influence of CO<sub>2</sub> emissions and socio-economic factors such as GDP, per capita GDP, energy intensity, and population size [26-31]. With the increase of urban populations in New Zealand, CO<sub>2</sub> emissions from the transport sector have increased [32]. Andreoni and Galmarini [33] found that economic growth was the main factor behind CO<sub>2</sub> emissions based on the water and aviation transport sectors in Europe. Saboori et al. [34] explored the bi-directional long-run relationship between CO<sub>2</sub> emissions from the road transport sector and economic growth in all the countries belonging to the Organization for Economic Co-operation and Development over the period from 1960 to 2008. Fan and Lei [35] found that economic growth is the dominant factor behind CO<sub>2</sub> emissions in Beijing, but influence from population size was limited. In addition to the various socio-economic factors considered by scholars, an increasing number of studies suggest that transportation development exerts an extensive and lasting influence on the level of CO<sub>2</sub> emissions. Taking Tunisia for example, road freight transport intensity is second only to economic growth in terms of  $CO_2$  emissions [36]. A similar study was also undertaken in European countries [37]. For China, passenger turnover, freight turnover, and private vehicle inventories are the three most frequently used transportation development factors impacting CO<sub>2</sub> emissions [2,5]. Some scholars have concluded that passenger transport plays a more critical role than freight transport in mitigating  $CO_2$  emissions [5]. Others have argued that the effect caused

by passenger transport is as little as one-eighth that of freight transport [6]. In the wake of rapid economic and technological developments from 1995 to 2016, the number of private cars in China has climbed from 2.49 million to 160.30 million, an increase of 64 times. The rapid development of public transportation has also played an important role in the overall development of transportation during the same period. However, the quantity of public transportation is neglected as an impacting factor for  $CO_2$  emissions in existing research.

Existing studies considered socio-economic factors and transportation development factors but ignored the impact of urban form. Urban cities are not only the center of human production and activity but also gather traffic elements and represent the pivot point of a transportation network [38,39]. Urban areas generally have a more intensive transport infrastructure, also highlighting the regional imbalance between the supply and demand of traffic. Reckien et al. [40] argued that the total built area and the total traffic area are positively related to road CO<sub>2</sub> emissions in Berlin's urban area. The impacts of urban form on CO<sub>2</sub> emissions in Chinese megacities were also explored by Ou et al. [41]. The number of patches and edge density of urban areas are factors that help quantify the urban form. Wang et al. [8] found that the compact size of urban land helps decrease CO<sub>2</sub> emissions. However, the factors involved did not consider urbanization, urban road density, and urban population level. Urban planning has an important effect on the process of building a low-carbon transport system. Further understanding of the relationship between urban forms (like urban road density, urbanization, as well as urban population level) and CO<sub>2</sub> emissions may facilitate further research. On the other hand, due to China's vast territory, significant regional differences, economic classifications, and population distribution, other studies have explored the mitigation of carbon emissions in east and south coastal China, which are areas with developed economies and dense populations [12,42]. Moreover, much scholarly attention has been drawn towards the mitigation of CO<sub>2</sub> emissions in China's megacities. Taking Beijing as an example, Wang et al. [7] indicated that urban form is a major factor for transport sector CO<sub>2</sub> emissions. The study's results on China's four megacities (Beijing, Shanghai, Guangzhou, and Tianjin) also showed that urban road density had significant negative effects on the level of CO<sub>2</sub> emissions [8].

Although the influential factors behind carbon emissions in the transport sector have been widely discussed in previous studies, few studies have evaluated the efficiency of the transport sector's  $CO_2$  emissions. Cui and Li [43] employed a virtual frontier Data Envelopment Analysis (DEA model to estimate transportation's carbon efficiency using cases from 15 countries. Zhou et al. [44] analyzed the  $CO_2$  performance of China's transport sector using undesirable DEA models, which only adopt energy and labor as the inputs. Zhang et al. [25] first proposed a non-radial Malmquist index to conduct a dynamic  $CO_2$  emissions performance change analysis for the Chinese transport industry. Total fixed assets, employees in the transport sector, and energy consumption were used as inputs in their study. Generally,  $CO_2$  emissions are an undesirable output of the production process for marketable or desirable outputs.

As mentioned above, there remain some research gaps that merit closer study. Firstly, previous studies focused on the national or megacity level, where economic growth has promoted global economic development.  $CO_2$  emissions have significantly affected global warming in the Organization for Economic Co-operation and Development (OECD) countries, New Zealand, coastal regions of China, and Chinese megacities. Central China is an ignored study area, where economic growth and transportation have been developing rapidly in recent years. Secondly, it is clear that the impact of socio-economic, urban form, or transportation development on  $CO_2$  emissions is not enough to illustrate the whole picture in the transport sector. Comprehensive systematic studies of the transport sector's  $CO_2$  emissions and their efficiency in central China, incorporating socio-economic factors, urban forms, and transportation developments, are relatively less common. Finally, investigating  $CO_2$  emissions efficiency plays an important role in developing reduction policies for  $CO_2$  emissions efficiency spane developments, and steel sectors. There are few studies about transport

sector CO<sub>2</sub> emissions efficiency, and even fewer studies employ Global Malmquist Luenberger to estimate CO<sub>2</sub> emissions efficiency in the transport sector dynamically.

As the geographical heart of China, central China is an important raw-material base with abundant coal and non-ferrous metals. Central China is, therefore, the economic development and transportation hub connecting east and west China. China has a vast territory, and because of its differences in geographical locations, economic foundations, regional policies, and transportation developments, the country's ability to mitigate regional emissions is not balanced. With the implementation of the strategy called "the rise of central China", the development of transportation infrastructure has been accelerated, effectively driving the development of transportation in the central region. For this reason, six provinces (Anhui, Shanxi, Jiangxi, Hubei, Hunan, and Henan) in central China were selected as the related areas in this study. The aim of this study is to explore and improve the transport impact on  $CO_2$  emissions efficiency. The present study first examines the impacts of socio-economic factors, urban forms, and transportation developments on  $CO_2$  emissions in central China using panel data for six provinces from the National Bureau of Statistics of China (NBSC). The differences in  $CO_2$  emissions efficiency for the transport sector were then dynamically analyzed using the Global Malmquist Luenberger Index. Finally, some suggestions for improving  $CO_2$  emissions efficiency and reducing  $CO_2$  emissions from transportation in central China are proposed.

## 3. Influencing Factors on Transport Sector CO<sub>2</sub> Emissions

## 3.1. Transportation Carbon-emissions Estimation

Inspired by Xu et al. [2], calculation of transport sector  $CO_2$  emissions for the six provinces in central China from 2005 to 2016 was based on the quantity of the various types of fossil fuels consumed, as well as their  $CO_2$  emissions factors, which were taken from the 2006 Intergovernmental Panel on Climate Change (IPCC) reports and China's National Development and Reform Commission [45]. The model is described by the following equation:

$$CO_2 = \sum_{i=1}^5 CO_{2i} = \sum_{i=1}^5 Ener_i \times Conf_i$$
(1)

where  $CO_2$  means the amount of  $CO_2$  emissions in the transport sector, *i* represents the variety of fossil fuel (gasoline, kerosene, diesel, fuel oil, and natural gas); *Ener<sub>i</sub>* is the total consumption of fossil fuel *i* in the whole transport sector; and *Conf<sub>i</sub>* means the  $CO_2$  emissions coefficient for *i* type of fossil fuel. The carbon emissions coefficients for fossil fuels are shown in Table 1. All data are collected from China Statistical Yearbook (2006–2017) and the provincial statistical yearbooks (2006–2017).

Table 1. Different Fossil Fuels' Carbon Emissions Coefficients.

Fuel	Gasoline	Kerosene	Diesel	Fuel Oil	Natural Gas
Emissions coefficient	0.5538	0.5714	0.5921	0.6185	0.4483

As a result, Figure 1 presents the dynamic changes in the transport sector's  $CO_2$  emissions for six provinces in central China. It was found that the  $CO_2$  emissions of these provinces maintained an increase between 2005 and 2016. Both Henan and Jiangxi province had a sharp increase in 2011. Hubei province was exposed to be the largest emitter. Between 2005 and 2016, the emissions of Hubei province increased from 2442.18 million tons to 5323.20 million tons. Before 2006, Jiangxi Province had lower  $CO_2$  emissions than other provinces (Hubei, Henan, Hunan, Shanxi, and Anhui), but close to those of Shanxi province since 2014. In addition, the minimum emission level (Anhui, at 2173.00 million tons) is two-fifths that of the maximum (Hubei, at 5323.20 million tons) in 2016. This result implies that provincial differences exist for the  $CO_2$  emissions in the transport sector in central China.



Figure 1. The CO<sub>2</sub> emissions of six provinces in central China's transport sector.

# 3.2. Influencing Factors

#### 3.2.1. Socio-economic Factors

The economy in central China has grown rapidly since the policies of "the Rise of Central China" were issued. The income of the region's residents has gradually increased, which was followed by private car ownership, which caused an increase in the transport sector's CO<sub>2</sub> emissions. In this study, per capita GDP (pGDP) was selected as the variable for the socio-economic development level. Figure 2 describes the trend of per capita GDP for provinces in central China. This trend shows steady growth, except in Shanxi province. In particular, Hubei province has the highest per capita GDP among the six provinces in central China. The per capita GDP growth rates of the other provinces (Hunan, Henan, Jiangxi, and Anhui) are similar to each other. This similarity means that the overall economic growth in central China is balanced.



Figure 2. The per capita GDP of six provinces in central China.

## 3.2.2. Transportation Development Factors

In order to better understand the impacts of transportation development on  $CO_2$  emissions, we selected three variables according to existing researches, comprising the number of private vehicles per 10,000 people (PRV), the number of public vehicles per 10,000 people (PUV), and freight turnover (FT) [9]. As residents' living standards have improved, and the number of private vehicles per 10,000 people in the central region has grown from 515 in 2005 to 5582 in 2016. These results are shown in

Figure 3a. An increasing number of both energy consumption and  $CO_2$  emissions occurred because, before 2016, private cars could not function without consuming gasoline and diesel. At the same time, the structure of mobile vehicles in the central region is unbalanced, and the proportion of private cars is increasing by the year, but the proportion using public transport seldom fluctuates (Figure 3b). In China, emissions from moving freight (tkm) is growing faster than that of moving passengers (person·km) [6]. In this way, the trend in central China is the same as the trend in the entire country. By the end of 2016, the freight transportation service turnover consisted of 3.57 trillion tkm in the central region. Since 2007, the freight turnover in these provinces has been growing rapidly (Figure 4). This growth unavoidably results in high growth in energy consumption and  $CO_2$  emissions.









3.2.3. Urban Form Factors

Between 2000 and 2015, the proportion of people living in urban areas in China increased rapidly from 35.87% to 55.61% and has exceeded the world average since 2013 [46]. With this rapid urban expansion, many urban dwellers have begun to drive cars that consume biofuels, which has precipitated a climbing increase in CO<sub>2</sub> emissions generated by cities. We chose three indicators to quantify the urban form: road density per 100 square meters (RD), urban population density (UPD), and urbanization level (UL). As shown in Figure 5, the proportion of the urban population showed a steady increase. Table 2 shows a statistical description of all the variables in this study.



Figure 5. The proportion of the urban population.

	Variable	Definition	Mean	SD	Min	Max	Observation
Dependent variable	С	$CO_2$ emissions in transport sector (10 <sup>4</sup> ton)	2603.02	1141.28	824.87	5323.20	72
Socio-economic factor	pGDP	Per capita GDP (CNY/person)	26,574.22	11477.23	8670	55665	72
Urban form factors	RD	The average road length per 100 km <sup>2</sup> (km)	88.14	36.62	31.30	160.12	72
	UL	Population living in urban areas divided by total population	0.42	0.09	0.21	0.58	72
	UPD	Urban population divided by total urban size	2896.69	1465.92	466.00	5967.00	72
Transportation development factors	PRV	Vehicles number of private cars per 10,000 population	313.41	302.02	19.16	1284.47	72
	PUV	Number of public vehicles per 10,000 population	8.82	2.17	3.80	15.13	72
	FT	Traffic volume multiplied by the transport distance	3520.34	2767.70	653.60	13,500.60	72

Table 2. Variable description.

## 3.3. Panel Data Models and Results

The Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) model was proposed by Dietz and Rosa [47] to analyze the influences of impacting factors on the environment, as follows:

1

$$T_i = a P_i^b A_i^c T_j^d e_i \tag{2}$$

where *P* is the population size, *A* means the average affluence, and *T* denotes the technology index; *a* represents the constant term, *b*, *c*, and *d* are the parameters for the environmental impacts as they relate to *P*, *A*, and *T*, respectively, and *e* is a random error. In empirical research, this model is often used in its logarithmic form. Based on the above analysis, the established model is as follows:

$$\ln C_{it} = c_i + \beta_1 \ln UL_{it} + \beta_2 \ln UPD_{it} + \beta_3 \ln RD_{it} + \beta_4 \ln PUV_{it} + \beta_5 \ln PRV_{it} + \beta_6 \ln FT_{it} + \beta_7 \ln pGDP_{it} + \varepsilon_{it}$$
(3)

where *C* is the amount of CO<sub>2</sub> emissions in the transport sector, *UL* is the urbanization level, *UPD* means urban population density, *RD* represents the urban road density, *PUV* denotes the number of public vehicles per 10,000 people, *PRV* represents the number of private vehicles per 10,000 people, *FT* describes turnover of freight traffic, *pGDP* is per capita GDP,  $\varepsilon$  is random error, and *i* and *t* represent province and year, respectively. All variables are expressed in their logarithmic forms to facilitate the estimation.

Before estimating the regression models for the panel data, it is necessary to ensure that the variables are stationary. The results could show spurious relationships if they do not meet this condition. The most common stationary test is the unit root test. We employed the widely used Levin-Lin-Chu (LLC) and Phillips-Perron (PP-Fisher) unit root tests. In the unit root test, the optimal lag order was determined according to the Akaike Information Criterion (AIC). The unit root test results are

shown in Table 3, which means that all these variables except UL are not stationary at the level and contain a panel unit root at the 5% significance level. When assessing the first-order differences, all the variables reject the null hypothesis of being non-stationary. This result indicates that all the variables are stationary after the first-order difference.

		Unit Root Test					
Variab	le	LLC	PP-Fisher				
	-	<i>p</i> -Value	<i>p</i> -Value				
I C	level	0.0656	0.9487				
Ln C	(D)	0.0002 ***	0.0003 ***				
Ln UL	level	0.0004 ***	0.0049 **				
	(D)	0.0000 ***	0.0001 ***				
Ln UPD	level	0.9958	0.0000 ***				
	(D)	0.0031 **	0.0000 ***				
	level	1.0000	0.0000 ***				
Ln KD	(D)	0.0000 ***	0.0000 ***				
Ln PUV	level	0.0015 **	0.2788				
	(D)	0.0000 ***	0.0000 ***				
	level	0.7693	0.2311				
Ln PKV	(D)	0.0023 **	0.0207 **				
Ln FT	level	0.9423	0.8942				
	(D)	0.0000 ***	0.0000 ***				
In nCDP	level	0.1835	0.0458 **				
LII pGDF	(D)	0.0006 ***	0.0015 **				

Table 3. Results of the unit root test.

\*\* for *p* < 0.05, \*\*\* for *p* < 0.01.

Models for panel data often allow for autocorrelation and heteroskedasticity (as well as being cross-sectional), which result in an estimated parameters bias. In this paper, a modified Wald test for groupwise heteroskedasticity, a Breusch–Pagan test for cross-sectional independence, and a Wooldridge test for serial correlation for the residuals of a fixed effect regression model are employed. The results show that there are autocorrelation (F value = 48.05, *p*-value = 0.0010) and heteroscedasticity (R-square value = 0.8106, *p*-value = 0.0000) problems without cross-sectional dependency, as shown in Table 4. The panel corrected standard error (PCSE) estimation method introduced by Beck and Katz [48] is an innovation of the panel data model estimation method. This method can effectively deal with complex panel error structures, such as autocorrelation, heteroscedasticity, sequence correlation, etc. It is especially useful when the sample size is not large enough for other methods. In existing empirical applications, especially when estimating the panel data of national and provincial types, the PCSE method is widely used to deal with complex panel error structures [5,49,50].

Table 4. Correlation matrix of residuals
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	Shanxi	Henan	Hubei	Hunan	Jiangxi	Anhui
Shanxi	1.0000					
Henan	-0.2078	1.0000				
Hubei	-0.5433	0.2209	1.0000			
Hunan	0.1243	0.1980	0.1085	1.0000		
Jiangxi	-0.5187	-0.2069	0.4124	-0.1185	1.0000	
Anhui	-0.2718	0.3634	0.3716	-0.5988	-0.0022	1.0000
		Chi2 (15)	= 19.826, P	r = 0.1787		

The estimation results for the PCSE model are shown in Table 5. The significance test for the regression equation (Chi-square value = 308.09, *p*-value = 0.0000) indicates that the comprehensive

influence of the independent variables on the dependent variable has statistical significance. All independent variables are significant at the 1% significance level. Based the empirical results, the per capita GDP had the most positive effects on the dependent variable, which shows that a 1% GDP increase would cause a 1.04% increase of CO<sub>2</sub> emissions in the transport sector. Among transportation development factors, the number of private vehicles (0.445) and public vehicles (0.717) had positive effects on transportation CO<sub>2</sub> emissions, while the quantitative coefficient of the freight turnover is -0.444. The number of private vehicles and public vehicles is the main contributor to CO<sub>2</sub> emissions, while freight turnover is negatively related to  $CO_2$  emissions in the transport sector. Road density (0.470) also had positive effects on transportation CO<sub>2</sub> emissions. The elasticity of the urbanization level and urban population density are -3.454 and -0.620, respectively. To a certain extent, urban development and the improvement of road capacity promote  $CO_2$  emissions from transportation. The increase in urbanization level leads to an increase in built-up urban areas and promotes the convenience of urban transportation, which could curb  $CO_2$  emissions from the transport sector. Though public transportation development is low-carbon and environmentally friendly to a certain extent, excessive allocation of public transportation will also lead to a rise in carbon emissions. Growing vehicle ownership, accompanied by rapid economic development, has enhanced CO<sub>2</sub> emissions. Freight turnover is a comprehensive reflection of the need for freight transport and the total amount of freight transport work provided and has a negative effect on  $CO_2$  emissions in the transport sector.

Table 5. Results of the variable intercept model of panel corrected standard error (PCSE).

Coef.	Std. err.	t	p
1.044 ***	0.262	(3.82)	0.000
0.470 ***	0.134	(4.09)	0.000
-3.454 ***	0.558	(-6.37)	0.000
-0.620 ***	0.087	(-7.58)	0.000
0.445 ***	0.111	(7.26)	0.000
0.717 ***	0.205	(4.58)	0.000
-0.444 **	0.080	(-4.06)	0.000
-3.195	1.793	(-1.80)	0.072
quared		0.8106	
	Coef. 1.044 *** 0.470 *** -3.454 *** -0.620 *** 0.445 *** 0.717 *** -0.444 ** -3.195 quared	Coef.         Std. err.           1.044 ***         0.262           0.470 ***         0.134           -3.454 ***         0.558           -0.620 ***         0.087           0.445 ***         0.111           0.717 ***         0.205           -0.444 **         0.080           -3.195         1.793           quared         1.793	Coef.Std. err.t $1.044 ***$ $0.262$ $(3.82)$ $0.470 ***$ $0.134$ $(4.09)$ $-3.454 ***$ $0.558$ $(-6.37)$ $-0.620 ***$ $0.087$ $(-7.58)$ $0.445 ***$ $0.111$ $(7.26)$ $0.717 ***$ $0.205$ $(4.58)$ $-0.444 **$ $0.080$ $(-4.06)$ $-3.195$ $1.793$ $(-1.80)$ quared $0.8106$

\*\* for *p* < 0.01, and \*\*\* *p* < 0.001.

#### 4. CO<sub>2</sub> Emissions Efficiency of the Transport Sector

To measure the efficiency of  $CO_2$  emissions with the development of the transportation and develop detailed  $CO_2$  emissions reduction policies, a Global Malmquist Luenberger (GML) index, based on DEA, is employed to estimate the  $CO_2$  emissions efficiency in central China's transport sector as an undesirable factor and explores the key factors contributing to efficiency (from the standpoints of technological progress and scale efficiency).

We chose five inputs, three desirable outputs, and  $CO_2$  emissions as the undesirable output. Labor input (*L*) is represented by employees in the transport sector; this information is collected directly from the China Statistical Yearbook. Here, the amount of capital input (*K*) is represented by the number of private vehicles per 10,000 people, the number of public vehicles per 10,000 people, and the road density. The rest input is represented by energy consumption (*E*). Three desirable outputs are passenger turnover (*P*), freight turnover (*F*), and value-added from the transport sector (*V*).

## 4.1. Global Malmquist Luenberger Model

Regarding each province as a decision-making unit (DMU), there are six provinces in the Central region:  $i = 1, \dots, K(K = 6)$ . Each province uses N (N = 5) inputs to produce M (M = 3) desirable outputs and L (L = 1) undesirable outputs in T time periods ( $t = 1, \dots, T$ ) defined, respectively, as:  $\mathbf{X} = (x_1, \dots, x_N) \in \mathbb{R}^N_+, \mathbf{Y} = (y_1, \dots, y_M) \in \mathbb{R}^M_+$ , and  $\mathbf{Y}\mathbf{u} = (u_1, \dots, u_L) \in \mathbb{R}^L_+$ . Hence, the environmental production technology set can be expressed as:  $P(X) = \{(\mathbf{x}, \mathbf{y}, \mathbf{u}) | \mathbf{x} \text{ can produce } (\mathbf{y}, \mathbf{u})\}$ . A global

benchmark technology is defined as  $P^G = P^1 \cup P^2 \cup \cdots \cup P^T$ . The GML index, proposed in this paper, is defined as follows:

$$GML^{t,t+1}(\mathbf{x}^{t}, \mathbf{y}^{t}, \mathbf{u}^{t}, \mathbf{x}^{t+1}, \mathbf{y}^{t+1}, \mathbf{u}^{t+1}) = \frac{1 + D^{G}(\mathbf{x}^{t}, \mathbf{y}^{t}, \mathbf{u}^{t})}{1 + D^{G}(\mathbf{x}^{t+1}, \mathbf{y}^{t+1}, \mathbf{u}^{t+1})}$$
(4)

where the directional function,  $D^G(\mathbf{x}, \mathbf{y}, \mathbf{u}) = \max\{\beta | (\mathbf{y} + \beta \mathbf{y}, \mathbf{b} - \beta \mathbf{b}) \in P^G(\mathbf{x})\}$ , is defined based on the global technology set  $P^G$ . If the  $GML^{t,t+1} > 1$ ,  $CO_2$  emissions efficiency increases, and the evaluated unit is capable of producing more of the desired output with less of the undesired output. However, if  $GML^{t,t+1} = 1$ , then performance remains unchanged, and  $GML^{t,t+1} < 1$  signals a performance decline.

The GML index can also be decomposed into *efficiency change* (EC) and *best practice gap change* (BPC), as follows:

$$GML^{t,t+1}(\mathbf{x}^{t}, \mathbf{y}^{t}, \mathbf{u}^{t}, \mathbf{x}^{t+1}, \mathbf{y}^{t+1}, \mathbf{u}^{t+1}) = EC^{t,t+1} \times BPC^{t,t+1}$$

$$= \frac{1+D^{t}(\mathbf{x}^{t}, \mathbf{y}^{t}, \mathbf{u}^{t})}{1+D^{t+1}(\mathbf{x}^{t+1}, \mathbf{y}^{t+1}, \mathbf{u}^{t+1})} \times \left[\frac{(1+D^{G}(\mathbf{x}^{t}, \mathbf{y}^{t}, \mathbf{u}^{t}))/(1+D^{t}(\mathbf{x}^{t}, \mathbf{y}^{t}, \mathbf{u}^{t})}{(1+D^{G}(\mathbf{x}^{t+1}, \mathbf{y}^{t+1}, \mathbf{u}^{t+1}))/(1+D^{t+1}(\mathbf{x}^{t+1}, \mathbf{y}^{t+1}, \mathbf{u}^{t+1}))}\right]$$
(5)

where  $EC^{t,t+1}$  means a change in the efficiency between the time period t and t + 1. $BPC^{t,t+1}$  denotes the best practice gap change and measures technical change during the two time periods. The improvement in EC suggests progress in management skills. Unlike the change in efficiency, technological change can be achieved by adopting new technologies to reduce the amount of bad output under the premise of a quantitative input.

## 4.2. The Results of GML and Discussion

Based on the GML model, the results of energy and  $CO_2$  emissions efficiency in the transport sector of central China are shown in Table 6. Only Shanxi province was observed to experience a positive efficiency growth (1.1%), while half of the provinces (Hubei = -1.3%, Jiangxi = -0.5%, and Anhui = -0.7%) showed negative growth. This result shows that Shanxi province has actively responded to the low-carbon development policies for the transport sector. Other provinces in central China have made remarkable progress in the transport sector, but have ignored the importance of low-carbon transportation.

Global Malmquist Luenberger Index									
	Henan	Shanxi	Hubei	Hunan	Jiangxi	Anhui	Central		
2005–2006	1.000	0.998	1.000	0.940	0.980	0.981	0.983		
2006-2007	1.000	1.080	1.000	0.990	0.972	0.982	1.004		
2007-2008	1.000	1.016	1.000	1.074	1.021	1.038	1.025		
2008-2009	1.000	0.838	0.941	0.995	0.977	1.000	0.959		
2009-2010	1.000	1.208	1.063	1.005	0.967	1.000	1.040		
2010-2011	1.000	1.000	1.000	1.000	1.022	1.000	1.004		
2011-2012	1.000	0.967	0.908	1.000	1.065	1.000	0.990		
2012-2013	1.010	0.919	1.101	1.000	0.985	1.000	1.002		
2013-2014	0.990	1.016	0.882	1.000	0.969	1.000	0.976		
2014-2015	1.000	1.063	0.986	1.000	0.966	0.917	0.989		
2015-2016	1.000	1.016	0.978	1.000	1.018	1.005	1.003		
Mean	1.000	1.011	0.987	1.000	0.995	0.993	0.998		

Table 6. CO<sub>2</sub> emissions efficiency in the provincial transport sector, 2006–2016.

Under the inclination for green transportation outputs in this study, when the number of expected outputs (i.e.; passenger volume, freight volume, and value-added from the transport sector) increases based on a given set of inputs, efficiency will increase. The trends of the GML index and its decomposition in the transport sector are shown in Figure 6. As indicated by GML, the average

 $CO_2$  emissions efficiency shows a decline of -0.2% during the study period. It was found that the fluctuation of the BPC index is similar to that of the GML index, while the EC index seldom fluctuated, indicating that a change in  $CO_2$  emissions efficiency is primarily caused by technological change. It is recommended that the government invest in green technologies for the transport sector, such as buses and taxis with renewable fuels in Shanxi province, road construction with renewable material in Henan province, and the installation of an Intelligent Transportation System (IST) in Hunan province.



Figure 6. The GML index and its decomposition in the transport sector.

The EC and BPC indexes of energy and  $CO_2$  emissions efficiency among the six provinces are shown in Table 7. Shanxi province is rich in coal resources, so its freight transport demand is particularly large. However, the transportation  $CO_2$  emissions of Shanxi province have barely increased since 2009. According to the GML index, only Shanxi had an average increase in  $CO_2$  emissions efficiency (of 1.1%). In other words, Shanxi performed well in reducing its transportation  $CO_2$  during the study period. As seen in Table 6, both the EC and BPC indexes are greater than 1, which indicates that Shanxi has adopted new technology and management skills to achieve their  $CO_2$  emissions mitigation goals. Over the last decade, the capacity for scientific and technological innovation in the transport sector has been enhanced. Traditional buses have been gradually replaced by hybrid or pure electric buses. There are many projects that demonstrate  $CO_2$  reduction goals, including key transport process monitoring and management services in 2013 and the application of renewable energy in the construction and operation of the "Gaoqin expressway" in 2014.

Table 7. The EC and BPC of the provincial transport sector, 2005–2016.

DMUs	He	nan	Sha	inxi	Hu	bei	Hu	nan	Jiaı	ngxi	An	hui
	EC	BPC										
2005–2006	1.000	1.000	1.000	0.998	1.000	1.000	1.000	0.940	1.000	0.980	1.000	0.981
2006-2007	1.000	1.000	1.000	1.080	1.000	1.000	1.000	0.990	0.960	1.013	1.000	0.982
2007-2008	1.000	1.000	1.000	1.016	1.000	1.000	1.000	1.074	1.042	0.980	1.000	1.038
2008-2009	1.000	1.000	1.000	0.838	1.000	0.941	1.000	0.995	1.000	0.977	1.000	1.000
2009-2010	1.000	1.000	1.000	1.208	1.000	1.063	1.000	1.005	0.991	0.975	1.000	1.000
2010-2011	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.009	1.013	1.000	1.000
2011-2012	1.000	1.000	1.000	0.967	1.000	0.908	1.000	1.000	1.000	1.065	1.000	1.000
2012-2013	1.000	1.010	0.914	1.004	1.000	1.101	1.000	1.000	1.000	0.985	1.000	1.000
2013-2014	1.000	0.990	1.029	0.987	1.000	0.882	1.000	1.000	0.984	0.985	1.000	1.000
2014-2015	1.000	1.000	1.062	1.000	1.000	0.986	1.000	1.000	0.985	0.981	1.000	0.917
2015-2016	1.000	1.000	1.000	1.016	1.000	0.978	1.000	1.000	1.019	1.000	1.000	1.005
Mean	1.000	1.000	1.001	1.010	1.000	0.987	1.000	1.000	0.999	0.996	1.000	0.993

Among the six provinces in central China, Hubei province produced the highest  $CO_2$  emissions in the transport sector during the study period. The average GML index is measured as -1.3%, which

indicates a declining trend of  $CO_2$  emissions efficiency. The main reason for this result is that the BPC index decreased, especially after 2013, while Hubei was deteriorating from an efficient province to an inefficient one. From 2013 to 2016, the BPC index experienced a yearly decline of 11.8%, 1.4%, and 2.2%, respectively. During the research period, massive investment and fast construction allowed Hubei to form a comprehensive transportation hub, which provided a skeleton network of "four vertical, four horizontal, and one ring" highways. These results indicate that low-carbon technological innovation for the transport sector in Hubei has been neglected during the process of transportation development.

For Henan and Hunan province, GML = 1—indicating no improvement in  $CO_2$  emissions efficiency. A possible cause for this might be the stabilization of management style and technological innovation. The remaining provinces (Jiangxi and Anhui) had a  $CO_2$  emissions efficiency index less than 1 in most of the time periods, and both improvements and declines occurred during these 12 years. However, during 2015–2016, the GML index was 1.018 in Jiangxi and 1.005 in Anhui, indicating that these provinces were increasing their efforts to improve their efficiency. For example, by the end of 2016, public transport in Anhui province accounted for 40.66% of motor vehicle trips, gradually realizing full coverage of public transport star services. The "Changzhang expressway reconstruction and expansion project" in Jiangxi province actively applied new technology for green recycling, which reduced transport sector  $CO_2$  emissions by more than 30,000 tons in 2016.

## 5. Conclusions

China is currently facing environmental pressures, which are the result of the rapidly increasing pace of energy consumption and  $CO_2$  emissions in the transport sector. Issues of  $CO_2$  emissions and mitigation in the transport sector have attracted intense attention from both governments and academics. This paper explores the factors driving transport  $CO_2$  emission and the differences in  $CO_2$  efficiency in the central region of China and provides some policy suggestions for the Chinese government.

On the base of the provincial panel data of six provinces in central China, this paper constructed an FGLS model that was used to investigate the impact of urban form and transportation development on the  $CO_2$  emissions of the transport sector. Furthermore, the Global Malmquist Luenberger index was used to quantify  $CO_2$  emissions efficiency in the transport sector, and possible reasons for the fluctuation of transportation carbon emissions efficiency in each province were comprehensively analyzed.

Transportation  $CO_2$  emissions in central China increased continuously from 2005 to 2016. The overall efficiency of  $CO_2$  emissions in the central region of China fluctuated during this period. BPC was the main driver of GML growth, which indicates that the technical efficiency needed to accelerate transport development must be further improved.

Some policy suggestions have been generated based on the above explorations. Firstly, there are provincial differences in the CO<sub>2</sub> emissions efficiency in the transport sector of central China. Hubei should strengthen the construction of its talented team in the transport sector and support the research and development of key technologies and core equipment for transportation to improve CO<sub>2</sub> emissions efficiency. Hunan and Henan should optimize their transportation systems to improve their CO<sub>2</sub> emissions efficiency. Jiangxi and Anhui could learn advanced management skills and introduce advanced technologies from other provinces with higher CO<sub>2</sub> emissions efficiency such as Shanxi. Secondly, there is a positive correlativity between the number of public vehicles and  $CO_2$ emissions during the study period. The government should improve public transport organization and reduce the energy consumption of public transport. On the other hand, developing urban light rail transit with the potential to mitigate CO<sub>2</sub> and expanding the utilization of fuel-cell-driven and power-driven vehicles are critical to controlling emissions in urban public transport. Thirdly, policies aimed at the ownership of private vehicles should be strengthened. Due to rapid economic growth and low energy efficiency, private vehicles have become the main contributors to  $CO_2$  emissions. Moreover, hybrid and battery electric vehicles with renewable electricity can significantly contribute to CO<sub>2</sub> mitigation in car transport [51]. Accordingly, the government ought to tighten traditional energy-intensive vehicle purchase standards and advocate and subsidize the purchase and utilization

of hybrid and electric-powered vehicles. The government must also improve the R&D of green vehicles and renewable electricity technology using fiscal instruments. Fourthly, road transport is still an important part of freight transport but relies on an unreasonable freight structure. Pollution-free road transport and low-energy rail transport should be further developed for freight transport. In addition, improving intelligent traffic systems may also help reduce freights' empty-load rates, which may also help mitigate  $CO_2$ . Finally, urban planning and transportation organization play an increasingly important role in the mitigation of  $CO_2$  emissions in central China. This suggests that urban planners should work to improve the connection between the pace of urbanization and road programs to reduce  $CO_2$  emissions. Furthermore, technical methods could be used to strengthen the recycling of renewable materials to improve  $CO_2$  emissions efficiency.

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