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Article

Research on the Spatial Characteristics and Impact Mechanism of Carbon Emission Efficiency of Chinese Road Freight Transport Enterprises

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Abstract: The highway transportation industry is an important component of the transportation industry and one of the key industries causing global climate change. Studying the carbon emission efficiency and influencing factors of enterprises in this industry is of great significance. To identify the carbon emission level of highway transportation enterprises, this article uses a set of table data from China's highway and waterway transportation enterprises to calculate the emissions of carbon sources from the movement of trucks in highway freight transportation enterprises using the "top-down" method. Based on this, the RAM model is used to calculate the economic efficiency, carbon emission efficiency, and unified efficiency of road freight transportation enterprises, and the characteristics of the three types of efficiency are analyzed to further explore the factors that affect the carbon emission efficiency of enterprises. The research results indicate that: (1) both economic efficiency and carbon emission efficiency exhibit spatial agglomeration characteristics, but in 2021, the degree of spatial agglomeration has decreased. (2) From 2020 to 2021, the carbon emission efficiency rankings of various regions remained relatively stable, with the western region, eastern region, central region, and northeastern region ranking in order of carbon emission efficiency; Due to the impact of the epidemic, the economic efficiency of various regions has fluctuated to some extent in 2020-2021, and the fluctuation of unified efficiency is closer to the fluctuation of economic efficiency. (3) The analysis results of the impact on carbon emission efficiency are as follows: the faster the Internet develops, the more stringent the urban environmental requirements are, the higher the carbon emission efficiency of road transport enterprises will be; The more diversified the business model and the longer the transportation distance, the higher the carbon emission efficiency of the enterprise.

Keywords: carbon emission efficiency; economic efficiency; unified efficiency; spatial distribution; large-scale road freight transportation enterprises

0. Introduction

With the development of social economy, the increasing living standards of the people, and the improvement of transportation efficiency, people's demand for transportation is becoming more and more vigorous. At the same time, energy consumption and environmental load pressure are also increasing day by day. As a major transportation country, China ranks first in the world in terms of high-speed railway mileage, highway mileage, urban rail transit operating mileage, and the number of berths with a capacity of 10000 tons or more in ports. The rapid development of transportation has brought about a rapid increase in energy consumption and carbon emissions. Since 2000, the energy consumption and carbon emission growth rate of the transportation industry have consistently remained at the forefront of various industries in China. Currently, it has become the second largest carbon-emitting sector in China after industry. The carbon peak and carbon neutrality of the

transportation industry will undoubtedly be a key link in achieving national carbon peak and carbon neutrality.

Due to the rapid growth of China's national economy and transportation, the technological level and energy structure of transportation development have not undergone fundamental changes, and the total carbon emissions in the transportation sector will continue to increase. "Action Plan for Peaking Carbon Emissions Before 2030" proposes to integrate the concept of green and low-carbon into the entire process of transportation infrastructure planning, construction, operation, and maintenance, to reduce energy consumption and carbon emissions throughout the entire lifecycle. According to estimates, the annual greenhouse gas emissions in the transportation industry account for 12% of China's total annual greenhouse gas emissions, with carbon emissions from road transportation accounting for over 80% of the total emissions. Road freight is a key area of carbon emissions in road transportation, accounting for over 60%. This means that road freight is the core battlefield for carbon reduction in the transportation sector. Based on this, this article takes road transportation enterprises as the research object and analyzes their carbon emission efficiency and its influencing factors.

By using the RAM model to measure the joint win-win performance of China's large-scale road freight transportation enterprises in balancing economy and carbon emissions, this paper fills the gap in previous research on the spatiotemporal characteristics of carbon emission efficiency of road freight transportation enterprises from an efficiency perspective; On the other hand, it solves the evaluation of the win-win performance of road freight transportation that balances economic development and carbon emissions. At the same time, factors affecting the carbon emission efficiency of road freight transportation enterprises were analyzed from both urban and enterprise dimensions, providing relevant suggestions for better improving the carbon emission efficiency and reducing carbon emissions of road transportation enterprises.

1. Literature Review

At present, there are two main types of research on carbon emission efficiency: one is on methods for evaluating carbon emission efficiency; the second is the study of factors affecting carbon emission efficiency. This article will review and comment on the literature in these two fields.

1.1. Research on Carbon Emission Efficiency Evaluation Methods

Kaya and Yokobori (1997) were the first to propose carbon productivity (the reciprocal of carbon dioxide emissions per unit of GDP), which can be used to measure the economic efficiency per unit of carbon dioxide. Sun proposed that carbon emission intensity (carbon dioxide emissions per unit of GDP) is a reasonable indicator for comparing the emission reduction effects of different countries. Ignatius et al. (2016) proposed an analytical framework based on the Fuzzy Data Envelopment Analysis (DEA) model to evaluate the carbon efficiency of EU member states. Park et al. (2016) used the SBM model based on unexpected output to evaluate the environmental efficiency of the US transportation sector from 2004 to 2012, including environmental efficiency, carbon emission efficiency, and carbon reduction potential. At present, there are usually two methods for measuring the quality of total factor carbon emissions: Stochastic Frontier Analysis (SFA) and Data Envelopment Analysis (DEA). The use of Data Envelopment Analysis can effectively prevent the setting of relevant models and the validity analysis of assumptions bias towards normal distributions, and can obtain the expected and unexpected output rates of linear fitting-related activities. This method is superior to Random Frontier Analysis (SFA). Especially for relaxation variables, by including them in the loss function, a Slack Based Measure (SBM) model based on relaxation variables is obtained in this environment, which can effectively prevent calculation errors caused by various environments and become the main method for studying carbon emission efficiency. In terms of research methods, Data Envelopment Analysis (DEA) has been widely used in the study of energy consumption and CO₂ emissions in the logistics industry. However, traditional DEA models do not take into account the impact of the external environment, internal management, and random noise on slack variables, which may result in higher or lower efficiency measurement values compared to actual efficiency

levels. The SBM optimization model (Slack-based Measurement Model) has more advantages than the traditional DEA-based model in terms of efficiency measurement accuracy in handling unexpected output indicators.

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1.2. Research on Factors Influencing Carbon Emission Efficiency

With the increasingly acute energy issue and the growing concern about global climate change, academia has begun to pay attention to the carbon dioxide emission efficiency of transportation companies. The introduction of information technology will greatly improve the carbon dioxide emission efficiency of German freight enterprises. The existing literature mainly uses regression methods for research, involving influencing factors such as technical factors, energy consumption structure, environmental regulations, fleet age factors, cargo volume factors, fuel factors, etc. For example, Hadi-Vencheh et al. (2020) studied the impact of technology types on the carbon emission efficiency of aviation enterprises; Xu et al. (2021) used a Tobit regression model to explore the impact of fleet age and cargo volume on environmental efficiency; Wu et al. used bootstrap truncated regression method to explore the impact of fuel utilization rate on enterprise operational efficiency; Lo et al. (2020) explored the impact of fuel prices and technological advancements on carbon emissions from aviation transportation. In addition, when analyzing the driving factors of carbon emissions in the logistics industry, commonly used methods include Laspeyres decomposition, Paasche decomposition, and arithmetic mean Divisia decomposition (AMDI). The problem with these methods is that they cannot simultaneously decompose multiple influencing factors, or there is a phenomenon of excessive residual calculation after decomposition. Chikage (2015) studied the relationship between carbon emission performance and economic benefits of the aviation industry using 14 major European airlines as samples. After evaluating the relative performance of carbon emission performance and cost-effectiveness of airlines, the study found that the carbon emission efficiency of European airlines increased by 20%, while unit costs decreased by 13%, and there was a significant negative correlation between the two. Yasmeeen (2020) used the LMDI method to evaluate the carbon emissions of Pakistan's logistics industry from 1972 to 2016. After decomposing the driving factors of carbon emissions using the LMDI model, it was found that economic development factors had a positive driving effect on per capita carbon emissions, while energy structure and efficiency had a constraining effect. Andeoni et al. (2012) divided Italy into six sectors based on its level of economic development using a "top-down" model, and used the LMDI method to explain the impact of economic growth, energy consumption, and industrial structure on carbon emissions.

Andreoni (2012) analyzed the main factors contributing to changes in carbon emissions in the European water and air transport industry from 2001 to 2008. Using decomposition analysis, carbon emission intensity was decomposed into energy intensity, structural change effects, and economic growth effects. The research results indicate that the economic growth effect has always been the main factor affecting carbon emissions, and the reduction of energy efficiency is the main driving factor for carbon emissions. The improvement of emission reduction technologies also helps to reduce carbon emissions. M'Raihi et al. (2015) applied LMDI to quantitatively analyze the influencing factors of the growth of road freight CO₂ emissions in Tunisia and found that economic growth is the main driving factor of CO₂ emissions growth. Regression models include the STIRPAT model, multiple linear regression model and least square regression model.

2. Research Methodology

2.1. Carbon Emissions

The carbon emissions of road transportation enterprises mainly include the direct carbon emissions from the operation of road transportation vehicles and the indirect carbon emissions from the production and operation process of road transportation enterprises. Among them, direct carbon emissions include the direct carbon emissions generated by fuel combustion during the operation of vehicles, and indirect carbon emissions refer to the emissions generated by the transfer of electricity or heat during the production and operation of road transportation enterprises. This study takes specific data of road transport vehicles in China as an example and only considers direct carbon emissions. According to the carbon emission coefficient method provided by the Intergovernmental Panel on Climate Change (IPCC), the carbon emissions of various energy sources can be calculated. The “top-down” method is the earliest greenhouse gas accounting method proposed by the IPCC for various industries. Using this method to calculate the carbon emissions of transportation is easy to obtain and calculate, and has been widely used in the international community. According to the energy consumption data of road transportation enterprises collected in a set of table systems for transportation enterprises, the total carbon emissions generated by fuel consumption of each enterprise can be calculated. The carbon emissions generated by each fuel consumption can be summarized to obtain the carbon emissions of each enterprise. The calculation formula is as follows:

$$P_i = \sum_K M_{i,k} \times NCV_k \times EF_k \times O_k \times 44 / 12 \quad (1)$$

In the formula, P_i represents the carbon emissions caused by the production of road transportation enterprise i ; $M_{i,k}$ represents the input amount of the k -th fuel in the production process of road transportation enterprise i ; δ_k represents the carbon emission coefficient of the k -th fuel; NCV_k , EF_k , and O_k represent the calorific value, carbon content, and carbon oxidation rate of the k -th fuel, respectively. 44 and 12 represent the molecular weights of CO_2 and C, respectively.

2.2. Carbon Emission Efficiency

Data Envelopment Analysis (DEA) measures “relative efficiency” With the increasingly prominent environmental issues, many scholars have included environmental factors in DEA models for efficiency evaluation. Haynes et al. (1997) incorporated pollutants as input factors into traditional DEA models to measure efficiency. However, the traditional DEA model suffers from a “radial” problem, which requires input and output factors to change proportionally. When there are non-slack variables, it can lead to poor efficiency differences among different decision-making units. To solve such problems, Chung et al. (1997) proposed the Directional Distance Function in 1997 to measure efficiency values, and this model has been favored by many scholars. However, both directional distance functions and traditional DEA models have the problem of “angle”, which means that in the efficiency measurement process, it is necessary to choose between input oriented and output oriented, and simply considering from one angle will lead to inaccurate calculation results. Sueyoshi et al. (2011) pointed out in 2011 that previous models had subjectivity in direction setting, which may cause computational bias. Based on this, they proposed the Range Adjusted Measure (RAM) model for the environment, which does not have input-output orientation and is non radial, thus effectively measuring the efficiency of decision units that include the environment. In addition, the model has an additive structure, which can achieve separate measurement of economic efficiency and carbon emission efficiency in the transportation industry, as well as integrate economic efficiency and carbon emission efficiency into one framework to explore the win-win performance of transportation industry economic development and carbon emissions (unified efficiency), and can be compared with each other to explore the root of unified efficiency. Therefore, this article uses the RAM model to calculate the economic efficiency, carbon emission efficiency, and unified efficiency of the transportation industry, with transportation carbon emissions as the unexpected output.

Meanwhile, in previous DEA studies, energy consumption was generally treated as a common input, while Renshaw (1981) pointed out that this measurement may not reflect the substitution effect of energy factors on efficiency. Meanwhile, Zhou (2008) pointed out that the increase of an alternative energy source may lead to a significant decrease in the consumption of other energy sources, which in turn may lead to an improvement in efficiency, that is, an increase in the consumption of certain energy sources does not necessarily mean a deterioration in efficiency. Furthermore, for transportation, the promotion and use of new energy will to some extent reduce the use of other high emission energy sources, leading to an improvement in carbon emission efficiency. Therefore, referring to Zhou's research, this article assumes the existence of J enterprises, each containing N common input factors, M energy factors, P expected outputs, and I unexpected outputs. At the same time, the energy slack variable s_m^e is defined in the RAM model to represent the distance between energy input and optimal energy input.

(1) RAM Model for Economic Efficiency of Road Transport Enterprises

Based on the above assumptions and referring to Aida's (1998) research, the Economic Efficiency (EE) RAM model of road transportation enterprises is:

$$\left\{ \begin{array}{l} \max \sum_{n=1}^N R_n^x s_n^x + \sum_{m=1}^M R_m^e s_m^e + \sum_{p=1}^P R_p^y s_p^y \\ \sum_{j=1}^J x_{nj} \lambda_j + s_n^x = x_n^j, \forall n; \\ \sum_{j=1}^J y_{pj} - s_p^y = y_{pj}, \forall p; \\ \sum_{j=1}^J e_{mj} \lambda_j + s_m^e = e_{mj}, \forall m \\ \sum_{j=1}^J \lambda_j = 1, \lambda_j \geq 0, \forall j; s_p^y \geq 0, \forall p \end{array} \right. \quad (2)$$

Among them, x_{nj} , e_{mj} and y_{pj} respectively represent the input factors, energy factors and expected output factors of the enterprise; R_n^x , R_m^e and R_p^y are relaxation variables, and s_n^x , s_m^e and s_p^y are adjustment ranges, respectively; λ_j is the weight of enterprise j . Among them, the expressions for R_n^x , R_m^e and R_p^y are:

$$\begin{aligned} R_n^x &= \frac{1}{(N + M + P) [\text{Max}(x_{nj}) - \text{Min}(x_{nj})]}; R_p^y = \frac{1}{(N + M + P) [\text{Max}(y_{pj}) - \text{Min}(y_{pj})]}; \\ R_m^e &= \frac{1}{(N + M + P) [\text{Max}(e_{mj}) - \text{Min}(e_{mj})]}; \end{aligned} \quad (3)$$

Assuming that λ^* represents the weight of the cross-sectional observations of the maximum relative efficiency that each province may achieve in the transportation production process when taking the optimal solution of model (2); s_n^{x*} , s_m^{e*} and s_p^{y*} are the relaxation variables of input and output in the optimal solution state. At this point, the RAM transportation economic efficiency of enterprise j during period t can be transformed into:

$$0 \leq \theta_p = 1 - \left(\sum_{n=1}^N R_n^x s_n^{x*} + \sum_{m=1}^M R_m^e s_m^{e*} + \sum_{p=1}^P R_p^y s_p^{y*} \right) \leq 1 \quad (4)$$

(2) RAM Model for Carbon Emission Efficiency of Road Transport Enterprises

The Carbon Emission Efficiency (CE) RAM model for transportation is:

$$\left\{ \begin{array}{l} \max \sum_{n=1}^N R_n^x s_n^x + \sum_{m=1}^M R_m^e s_m^e + \sum_{i=1}^I R_i^b s_i^b \\ \text{s.t.} \sum_{j=1}^J x_{nj} \lambda_j + s_n^x = x_{nj}, \forall_n; \\ \sum_{j=1}^J b_{ij} \lambda_j + s_i^b = b_{ij}, \forall_i \\ \sum_{j=1}^J e_{mj} \lambda_j + s_m^e = e_{mj}, \forall_m; \\ \sum_{j=1}^J \lambda_j = 1, \lambda_j \geq 0, \forall_j; s_n^x \geq 0, \forall_n; s_m^e \geq 0, \forall_m; s_i^b \geq 0, \forall_i \end{array} \right. \quad (5)$$

If b_{ij} represents the unexpected output factor of the i -th enterprise, then according to the above model (5), the RAM transportation carbon emission efficiency of enterprise j during period t can be obtained as follows:

$$0 \leq \theta_E = 1 - \left(\sum_{n=1}^N R_n^x s_n^{x*} + \sum_{m=1}^M R_m^e s_m^{e*} + \sum_{i=1}^I R_i^b s_i^{b*} \right) \leq 1 \quad (6)$$

(3) RAM Model for Unified Efficiency of Road Transport Enterprises

Transportation economic efficiency refers to the pursuit of transportation economic benefits without any environmental regulations; The carbon emission efficiency of transportation is the reverse expectation that carbon emissions tend to decrease through energy structure adjustment, energy technology improvement, and optimization of resource allocation with other inputs, that is, the emission performance under energy-saving and emission reduction policies. Tian and Qi (2004) research has shown that under the concept of "low-carbon economy", we cannot unilaterally consider economic benefits or pursue energy conservation and emission reduction. Focusing on any aspect is one-sided. Therefore, this article uses the additive structure of the RAM model to balance economic efficiency and carbon emission efficiency, measures the unified efficiency (UE) of transportation, and evaluates the coupling degree between transportation economic growth and energy conservation and emission reduction control, that is, the win-win performance of balancing economic growth and energy conservation and emission reduction. The specific model is:

$$\left\{ \begin{array}{l} \max \left(\sum_{n=1}^N R_n^x s_n^x + \sum_{m=1}^M R_m^e s_m^e + \sum_{p=1}^P R_p^y s_p^y + \sum_{i=1}^I R_i^b s_i^b \right) \\ \text{s.t.} \sum_{j=1}^J x_{nj} \lambda_j + s_n^x = x_{nj}, \forall_n; \\ \sum_{j=1}^J e_{mj} \lambda_j + s_m^e = e_{mj}, \forall_m; \\ \sum_{j=1}^J y_{pj} \lambda_j - s_p^j = y_{pj}, \forall_p \\ \sum_{j=1}^J b_{ij} \lambda_j + s_i^b = b_{ij}, \forall_i; \\ s_m^e \geq 0, \forall_m; s_p^j \geq 0, \forall_p; s_i^b \geq 0, \forall_i; \end{array} \right. \quad (7)$$

Correspondingly, according to model (7), the RAM transportation unified efficiency of enterprise j during period t can be obtained as follows:

$$0 \leq \theta_U = 1 - \left(\sum_{n=1}^N R_n^x s_n^{x*} + \sum_{m=1}^M R_m^e s_m^{e*} + \sum_{p=1}^P R_p^y s_p^{y*} + \sum_{i=1}^I R_i^b s_i^{b*} \right) \leq 1 \quad (8)$$

2.3. Spatial Correlation Analysis

(1) Moran'I

Spatial correlation, also known as spatial dependence, refers to the phenomenon in which the economic efficiency, carbon emission efficiency, and unified efficiency of road transport enterprises in a certain province or region are affected or directly or indirectly affected by the economic efficiency, carbon emission efficiency, and unified efficiency of road transport enterprises in surrounding provinces and cities. In other words, there are diffusion and spillover effects on the efficiency of adjacent provinces or regions. It is a representation of the degree of interaction and spatial clustering characteristics of the economic efficiency, carbon emission efficiency, and unified efficiency of road transport enterprises in adjacent provinces and cities. The spatial autocorrelation is generally measured by the Global Moran's I index, which has the following formula:

$$\text{Moran's } I = \frac{n}{\sum_{i=1}^n (x_i - \bar{x})^2} \frac{\sum_{i=1}^n \sum_{j=1}^n (x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^n \sum_{j=1}^n W_{ij}} \quad (9)$$

Among them, W_{ij} is the spatial weight matrix; n is the number of provinces or regions included, x_i and x_j represent the efficiency values of provinces or regions i and j , respectively, and \bar{x} is the average value of the corresponding efficiency. Generally speaking, the range of values for spatial autocorrelation coefficient is $[-1, 1]$. When its value is -1 , it indicates that the efficiency has a completely negatively correlated spatial characteristic; when its value is 1 , it indicates that the efficiency has a spatial characteristic of complete positive correlation; when its value is 0 , it indicates that there is no spatial correlation between adjacent provinces.

(2) OLS Model

Using econometric regression models to examine the factors that affect the carbon emission efficiency of large-scale road transportation enterprises, analyze the reasons for the low carbon emission efficiency of road transportation enterprises, and focus on improving the carbon emission efficiency of road transportation enterprises from multiple aspects.

$$y_i = \alpha_0 + \alpha_1 spa_i + \alpha_2 \bullet X_i + \lambda_i + \varepsilon_i \quad (10)$$

Where, y_i represents the carbon emission efficiency of enterprise i , and x is the core explanatory variable. This paper mainly includes two aspects: (1) select the Internet development degree of the city where the enterprise is located and whether it is subject to environmental regulation, which are expressed by *Inter* and *ER* respectively; (2) choose whether the enterprise operates in a diversified manner and the average transportation distance of the enterprise, represented by *Div* and *Dis* respectively. λ_i is the fixed effect of the enterprise, and ε_i is the random error term that follows a standard normal distribution.

(3) Geographically Weighted Regression

Compared to traditional OLS regression models, Geographically Weighted Regression (GWR) utilizes spatial relationships to reflect the non-stationary characteristics of parameters at different spatial unit positions, allowing the relationships between research variables to vary with changes in spatial unit positions. The model structure is:

$$y_i = \beta_0(u_i, v_i) + \sum_k \beta_k(u_i, v_i)x_{ik} + \varepsilon_i \quad (11)$$

In the formula, y_i is the dependent variable value at the geographic location (u_i, v_i) , (u_i, v_i) is the geographic center coordinate of the sample space unit, $\beta_0(u_i, v_i)$ is the constant value at the geographic location (u_i, v_i) , $\beta_k(u_i, v_i)$ is the value of the function $\beta_k(u, v)$ at the sample space location i , and ε_i represents the spatial random residual. The idea of using the GWR model to study the level of urbanization coordination is as follows: first, examine the spatial structural characteristics of carbon emission efficiency in each region, then select the kernel function, use AIC (Akaike information criterion) to determine the optimal bandwidth, and finally construct a GWR model for carbon emission efficiency in each region. Based on the model results, analyze and discuss the driving factors.

3. Empirical Analysis

3.1. Characteristic Analysis of Carbon Emission Efficiency

To explore the spatial distribution characteristics of economic efficiency, carbon emission efficiency, and unified efficiency of Chinese road transportation enterprises, this article divides 30 provinces and cities in China into four regions: eastern, central, western, and northeastern. Table 3.1 shows the changes in economic efficiency, carbon emission efficiency, and unified efficiency of road transportation enterprises in the four major regions of China in 2020 and 2021. It can be observed that there is a slight difference in spatial distribution between 2020 and 2021. In 2020, the economic efficiency of Chinese road transportation enterprises was generally higher in the western and eastern regions than in the whole country, while the economic efficiency in the central and northeastern regions was comparable; in 2021, the economic efficiency of the Northeast region showed significant growth, and the gap in economic efficiency between different regions decreased. The eastern region became the largest region in terms of economic efficiency among the four major regions; the carbon emission efficiency remains relatively stable, with little difference between 2020 and 2021. However, due to the sudden outbreak of the epidemic in 2020, which had a certain impact on the production and operation of enterprises, the economic efficiency has undergone significant changes. In terms of spatial distribution, the carbon emission efficiency of road transportation enterprises in different regions, from highest to lowest, is in the western, eastern, central, and northeastern regions, consistent with the research conclusions of Zhang et al.(2018) and others. For unified efficiency, the changes and rankings of unified efficiency in different regions are closer to the changes in economic efficiency.

Table 1. Economic efficiency, carbon emission efficiency, and unified efficiency of road transportation enterprises in different regions.

		ALL	Eastern Region	Central Region	Western Region	Northeast Region
EE	2020	0.9472	0.9488	0.9437	0.9506	0.9354
	2021	0.9678	0.9689	0.9656	0.9687	0.9635
CE	2020	0.9968	0.9968	0.9966	0.9972	0.9964
	2021	0.9971	0.9972	0.9968	0.9974	0.9962
JE	2020	0.9466	0.9481	0.9430	0.9499	0.9346
	2021	0.9670	0.9681	0.9647	0.9677	0.9624

From Table 2, it can be seen that in 2020 and 2021, China's economic efficiency, carbon emission efficiency, and unified efficiency have obvious spatial positive correlation characteristics. Among them, the Moran index of economic efficiency and unified efficiency shows an upward trend, while the Moran index of carbon emission efficiency slightly decreases. The reason may be that China vigorously promotes a series of energy-saving and emission reduction policies, such as new energy vehicles, electrification of transportation hubs, ports, and logistics parks, which have led to a convergence of carbon emission efficiency in road transportation enterprises. However, there are significant differences in the implementation intensity, capital investment management, and technical support in various regions, resulting in the heterogeneity of carbon emission efficiency in different regions, deepening the spatial dispersion distribution characteristics, and reducing the aggregation characteristics.

Table 2. Moran'I Index of Efficiency of Road Transport Enterprises in China from 2020 to 2021.

	EE			CE			JE		
	Mean	2020	2021	Mean	2020	2021	Mean	2020	2021
Moran's I	0.5242	0.5227	0.5255	0.5263	0.5263	0.5262	0.5242	0.5226	0.5254
P-value	0.0013	0.0012	0.0007	0.0009	0.0011	0.0011	0.0012	0.0008	0.0010
Z	15.441	15.384	15.488	15.508	15.506	15.510	15.438	15.381	15.487
	3	6	7	7	7	5	9	1	2

Note 1: The data in the table was compiled by the author based on the calculation results of GEODA software.

Through the above analysis, it can be found that the economic efficiency and carbon emission efficiency of road transportation enterprises in 2020-2021 are basically in a relatively stable state, and have formed a certain spatial distribution pattern. Therefore, in order to develop suitable carbon reduction measures for transportation, this article uses the average economic efficiency and carbon emission efficiency of road transportation enterprises from 2020 to 2021 as a threshold to explore the joint state characteristics of economic efficiency and carbon emissions in 30 provinces and cities in China. The specific results are shown in Table 3.

Table 3. Joint Distribution of Average Economic Efficiency and Carbon Emission Efficiency of Road Transportation Enterprises in Various Provinces.

	EE>M _E	EE<M _E
CE>M _C	Anhui, Hubei, Yunnan, Beijing, Liaoning, Inner Mongolia, Guangxi, Hunan, Sichuan, Guangdong, Fujian, Chongqing, Qinghai	Shaanxi, Guizhou, Jiangsu, Shanghai, Tianjin, Jiangxi, Hainan, Xinjiang
CE<M _C	Hebei	Heilongjiang, Zhejiang, Shandong, Henan, Jilin, Gansu, Shanxi

Based on the average, four joint states of economic efficiency and carbon emission efficiency were obtained for 30 provinces and cities in China, namely: ① Double High Efficiency Regions (EE>M_E, CE>M_C). Including multiple provinces such as Anhui, Hubei, Yunnan, Beijing, Liaoning, Inner Mongolia, Guangxi, Hunan, Sichuan, Guangdong, Fujian, Chongqing, Qinghai, etc., the economic efficiency and carbon emission efficiency of road transportation enterprises are at the leading level in the country, and are also at or close to the forefront of production, indicating that road transportation enterprises in these provinces have achieved a win-win situation of carbon reduction and economic growth Areas with high economic efficiency and low carbon emission efficiency (EE>M_E, CE<M_C), including only Hebei, generally have high economic efficiency but low

carbon emission efficiency. At the same time, due to their significantly lower carbon emission efficiency than $CE < AC$, the unified efficiency of this group of provinces is significantly lower, indicating that it is a key target for carbon reduction in future road transportation enterprises. Low Economic Efficiency High Emission Efficiency Regions ($EE < ME$, $CE > Mc$). Including 8 provinces including Shaanxi, Guizhou, Jiangsu, Shanghai, Tianjin, Jiangxi, Hainan, and Xinjiang. Double low efficiency areas ($EE < ME$, $CE < Mc$). This group includes 7 provinces including Heilongjiang, Zhejiang, Shandong, Henan, Jilin, Gansu, and Shanxi. The economic efficiency and carbon emission efficiency of road transportation enterprises in this group of provinces are both at a low level. Therefore, it is urgent to promote the development of carbon reduction while driving the economy, and promote the improvement of dual efficiency.

3.2. Analysis of Factors Influencing Carbon Emission Efficiency

The second column is an analysis of the factors affecting the carbon emission efficiency of 5296 large-scale road transport enterprises. From the regression results, it can be seen that the impact coefficient of environmental regulations on the carbon emissions of road transport enterprises is positive, and at a significant level of 10%, that is, urban level environmental regulations can promote the increase of carbon emission efficiency of local enterprises. For example, the measures of low-carbon city pilot play a certain supervisory role in the carbon emissions of road transportation enterprises. The construction of urban low-carbon transportation system should adopt low-carbon fuels, actively develop new energy transportation such as trams and hydrogen, and achieve low-carbon emissions. For the eastern and central regions, environmental regulations have a positive impact on the carbon emission efficiency of enterprises above the road scale within the region, that is, environmental regulations can effectively promote the improvement of enterprise carbon emission efficiency. However, the impact of environmental regulations on the western and northeastern regions is not significant, mainly because there are fewer cities with environmental regulations in these two regions, which cannot timely demonstrate the impact of enterprise carbon emission efficiency. The central region is more affected by environmental regulations than the eastern region, attributed to the relatively developed urban economy in the eastern region, where some transportation companies have already updated their equipment. Therefore, environmental regulations have relatively little impact on road transportation companies in the eastern region.

From the perspective of urban Internet development, the impact coefficient of Internet development on the carbon emission efficiency of road transport enterprises is positive and significant at the level of 1%, which means that the increase of Internet development can effectively promote the improvement of carbon emission efficiency of enterprises. In recent years, with the rapid development of the Internet, the network freight platform was born, and with its strong permeability, platform sharing and other characteristics, it reduces the search cost of enterprises to obtain goods sources and transportation information, effectively alleviates the information asymmetry problem of the freight transport market, improves the efficiency of resource allocation, so as to promote enterprises to reduce the empty rate of trucks, reduce the carbon emissions generated by empty vehicles, and improve the carbon emission efficiency. For different regions, the Internet development has a greater role in promoting the carbon emission efficiency of road transport enterprises in the western region, which means that the Internet development change in the western region has a more obvious role in driving the carbon emission efficiency of road transport enterprises. This is due to the fact that compared with other regions, the Internet development in the western region is more backward, and the marginal impact of Internet development in this region is more significant.

From the perspective of enterprise production and operation, diversified production and operation have a negative impact on the carbon emission efficiency of enterprises, which means that the carbon emission efficiency of road transportation enterprises operating multiple businesses is lower than that of road transportation enterprises operating a single business. This is attributed to the fact that transportation enterprises operating a single business have a more fixed source of goods, are more familiar with transportation routes, reduce the search cost of goods, reduce carbon emissions in an unloaded state, and improve carbon emission efficiency. For different regions, the

impact coefficient of road transport enterprises on carbon emission efficiency is negative, and only the impact coefficients in the eastern and central regions pass the significance test. This is attributed to the relatively large number of road transport enterprises above designated size in the eastern and central regions, and the regression results are relatively reliable.

For transportation modes, transportation distance has a positive promoting effect on the carbon emission efficiency of road transportation enterprises above a certain scale, that is, long-distance transportation of enterprises will improve carbon emission efficiency. Due to the relatively high cost of empty-load transportation for enterprises engaged in long-distance transportation, under the pressure of cost, enterprises engaged in long-distance transportation will have more motivation to search for sources of goods and reduce the empty-load rate of trucks. Under the condition of unchanged carbon emissions, long-distance transportation enterprises have higher freight volume and higher operating income, thereby improving carbon emission efficiency.

Table 5. Empirical Results on the Influencing Factors of Carbon Emission Efficiency of Large-scale Road Transportation Enterprises.

VARIABLES	ALL	Eastern region	Central region	Western Region	Northeast region
<i>ER</i>	0.306* (0.170)	0.265** (0.215)	0.697** (0.467)	-0.0623 (0.340)	-0.988 (1.064)
<i>Inter</i>	0.388*** (0.0995)	0.348*** (0.133)	0.431* (0.232)	0.544*** (0.159)	0.474 (0.725)
<i>Dis</i>	0.422*** (0.0655)	0.332*** (0.0900)	0.621*** (0.162)	0.353*** (0.103)	0.965*** (0.340)
<i>Div</i>	-0.369** (0.158)	-0.447** (0.223)	-0.536* (0.354)	-0.193 (0.255)	-0.0674 (0.851)
<i>Constant</i>	-2.259* (1.280)	-7.671*** (1.680)	9.098*** (3.100)	1.525 (2.223)	9.534 (7.123)
<i>Observations</i>	5,296	2,977	1,234	814	271
<i>R-squared</i>	0.018	0.028	0.022	0.034	0.035

Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1.

Based on ArcGIS spatial autocorrelation tool, this article calculates the carbon emission efficiency of road transport enterprises in the urban dimension in 2020 and 2021, and obtains Moran's I values of 0.5263 and 0.5262, respectively. This indicates that the carbon emission efficiency of road transport enterprises in various prefecture level cities is not randomly distributed in space, but has spatial autocorrelation. Therefore, this article compares and analyzes the influencing factors of carbon emission efficiency through OLS and GWR models.

In this paper, four types of factors affecting the carbon emission efficiency of road freight enterprises are geographically weighted regression based on city level data. From the mean and median values, the impact coefficients of environmental regulation, Internet development and long-distance transportation of enterprises on the carbon emission efficiency of enterprises are positive, while the impact coefficient of enterprises' multi-business operation is negative, which is consistent with the OLS regression results, which means that environmental regulation, the improvement of Internet degree and enterprises' long-distance transportation can positively promote the carbon emission efficiency of urban road transport enterprises, while the diversification of enterprises inhibits the carbon emission efficiency of road transport enterprises, which proves that the above regression is robust.

Table 6. Regression Results of GWR Model.

	Mean	Min	Max	Med
<i>ER</i>	0.297	-0.800	0.924	0.337
<i>Inter</i>	1.003	-0.272	6.871	0.586
<i>Dis</i>	0.228	-0.142	0.382	0.233
<i>Div</i>	-0.721	-1.896	1.163	-0.835

4. Conclusions and Policy Implication

This article uses the method published by IPCC (2006) to calculate the transportation carbon emissions of road transport enterprises. Based on this, the additive structure of the RAM model is used to incorporate economics and carbon emissions into a unified research framework. The economic efficiency and carbon emission efficiency of road transport enterprises are measured, and the unified efficiency that balances economics and carbon emissions of road transport enterprises is also measured. Based on the above analysis, it can be concluded that:

(1) Due to the sudden outbreak of the epidemic in 2020, the transportation and production of enterprises were affected to a certain extent, resulting in certain changes in the economic efficiency values and rankings of various regions in 2020 and 2021; And the carbon emission efficiency rankings of each region are relatively stable, in descending order of numerical ranking: Western region, Eastern region, Central region, and Northeast region.

(2) From the perspective of spatial distribution, both economic efficiency and carbon emission efficiency exhibit spatial agglomeration characteristics. However, in 2021, the Moran index has decreased, indicating a decrease in the degree of spatial agglomeration.

(3) Based on OLS and geographical weighted average method, the factors affecting the carbon emission efficiency of road transport enterprises are calculated, and the impact coefficient of Internet development, environmental regulation, and enterprises' long-distance transportation on the carbon emission efficiency of road transport enterprises is positive, which effectively promotes the improvement of enterprises' carbon emission efficiency; The diversified operation of road transportation enterprises has a negative impact on their carbon emission efficiency, which to some extent inhibits the improvement of carbon emission efficiency. Moreover, the impact coefficients of different factors on carbon emission efficiency vary in different regions.

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