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Study on Transportation Green Efficiency and Spatial Correlation in the Yangtze River Economic Belt

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Abstract: The Yangtze River Economic Belt (YREB), a crucial transportation corridor spanning China's east and west and linking coastal and inland regions, is not only pivotal in the nation's strategic development but also drives regional economic and social progress through its transportation industry. Despite rapid growth, the industry faces challenges such as low efficiency, resource supply–demand imbalances, and environmental issues. To advance green and sustainable progress, this study establishes a regional transportation green efficiency evaluation system. Using principal component analysis (PCA) to refine input data, the undesirable super-SBM model quantitatively assesses green transportation efficiency (GTE) in YREB provinces and cities, revealing regional disparities. The study also explores spatial correlations and distribution characteristics of GTE. Results indicate that ① YREB's GTE shows a U-shaped trend, with significant differences between upper, middle, and lower reaches, being stronger in the east and weaker in the west (lower > middle > upper reaches); ② GTE exhibits spatial correlation in YREB regions, with clear clustering; and ③ cold and hot spots of GTE in the middle reaches are relatively stable, with upstream areas generally cold or sub-cold, and hot spots mainly downstream.

Keywords: YREB; transportation; green efficiency; spatial correlation

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1. Introduction

The Yangtze River Economic Belt (YREB), as an important transportation channel across eastern and western China and connecting coastal and inland areas (see Figure 1), plays an important role in fostering sustainable and high-quality economic advancement of the Yangtze River Basin (YRB); the Chinese government has put forward the strategy of the YREB [1,2]. The future belt of the YRB will be developed into an inland river economic corridor with global influence and will play a demonstration function in future economic advancement, green transportation, and ecological civilization construction.

The Chinese government has consistently emphasized the advancement of the transportation sector in the YREB. In 2014, China proposed the construction of a convenient and efficient comprehensive three-dimensional transport corridor by 2020 [3]. After more than a decade of development, the transportation industry in the YREB has undergone comprehensive development, especially in infrastructure such as railways and highways (see Figure 2). According to the statistical report on China's advancement of the transportation sector, the total length of railways open to traffic in the YREB reached 45,000 km in 2021, a 10% increase from the previous year. The length of operational high-speed railways amounted to 25,000 km. The total length of highways reached 1.7 million kilometers, with 150,000 km being expressways, accounting for 11% of the country's total.

However, with the rapid economic and social development of the YREB, the issue of environmental pollution has become increasingly urgent. The regional transportation industry's demand for energy is growing, leading to a significant increase in energy consumption and the discharge of greenhouse gases. According to relevant statistical reports, China's energy consumption increased by 38.17% from 2010 to 2021. During the same period, the energy consumption of the transportation industry increased by 2.3 times; the problem of carbon dioxide emissions resulting from this massive energy consumption cannot be overlooked.

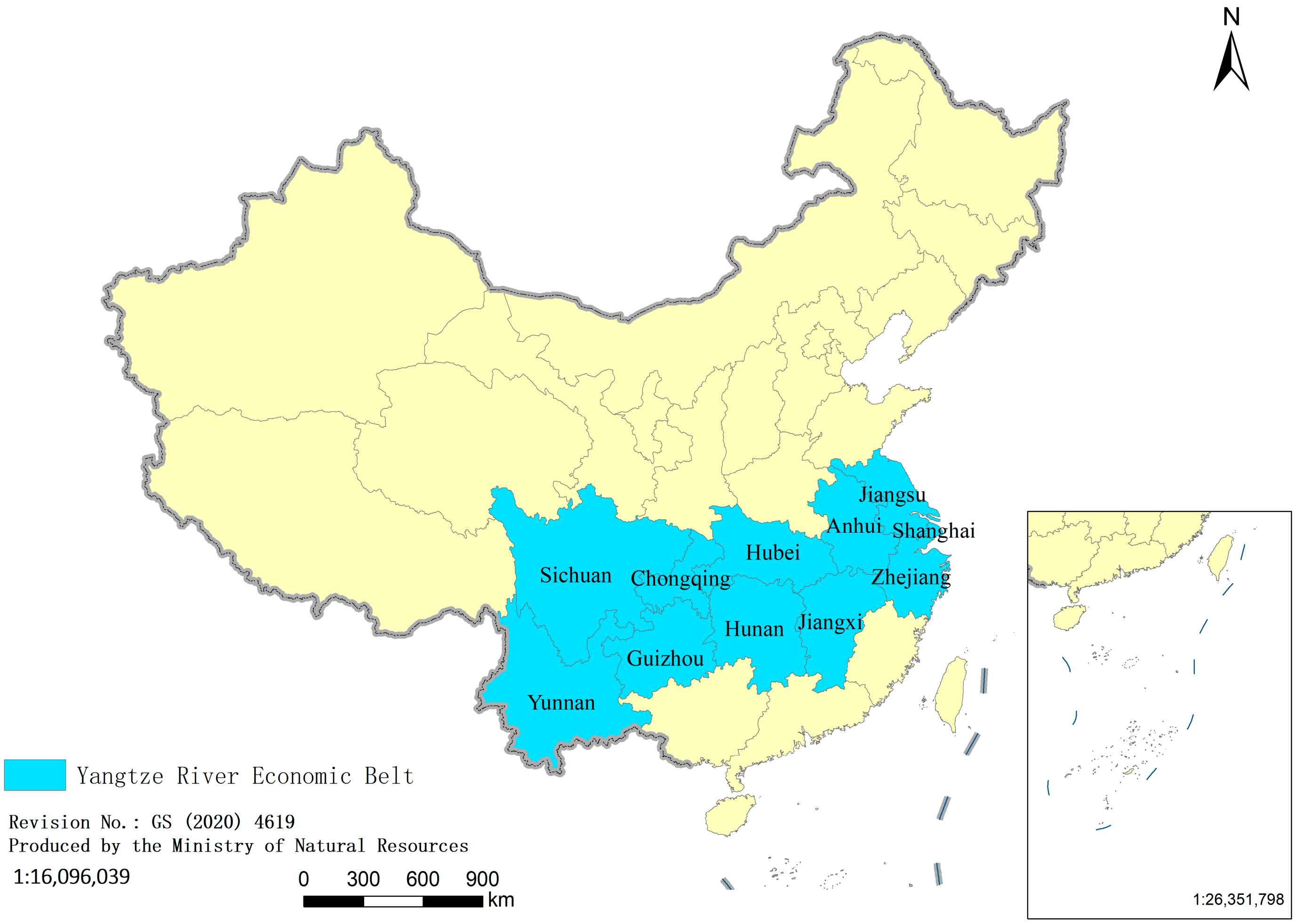

Figure 1. Spatial distribution of provinces and cities along the YREB.

At present, the transport industry in the YREB faces three major problems: first, the mismatch between transport supply and demand growth; second, backward transportation organization mode and low transportation efficiency; and third, traffic congestion, high energy consumption, and serious environmental pollution. The innovation of this paper is that it introduces the concept of green development into the measurement index system of green efficiency of regional transport and analyzes the spatial correlation and distribution characteristics of green efficiency of regional transport at the temporal and spatial level, which enriches the research in the field of transport efficiency and offers a fresh viewpoint for studying the development status of the YREB and solving the practical problems in the development.

Through combing the domestic and foreign literature, it is found that the research on transportation efficiency is expanding from single-mode transportation efficiency and urban public transportation efficiency to comprehensive transportation efficiency, by endowing different ecological, economic, and social concepts to comprehensive transportation efficiency to expand the traditional concept of transportation efficiency.

The approach to studying transportation efficiency has shifted from examining individual factors to considering the overall picture. While research on transportation efficiency using Data Envelopment Analysis (DEA) has received significant attention, the concept of green transportation efficiency (GTE), which integrates green development principles into the evaluation system, has also emerged as a research hotspot in the transportation sector.

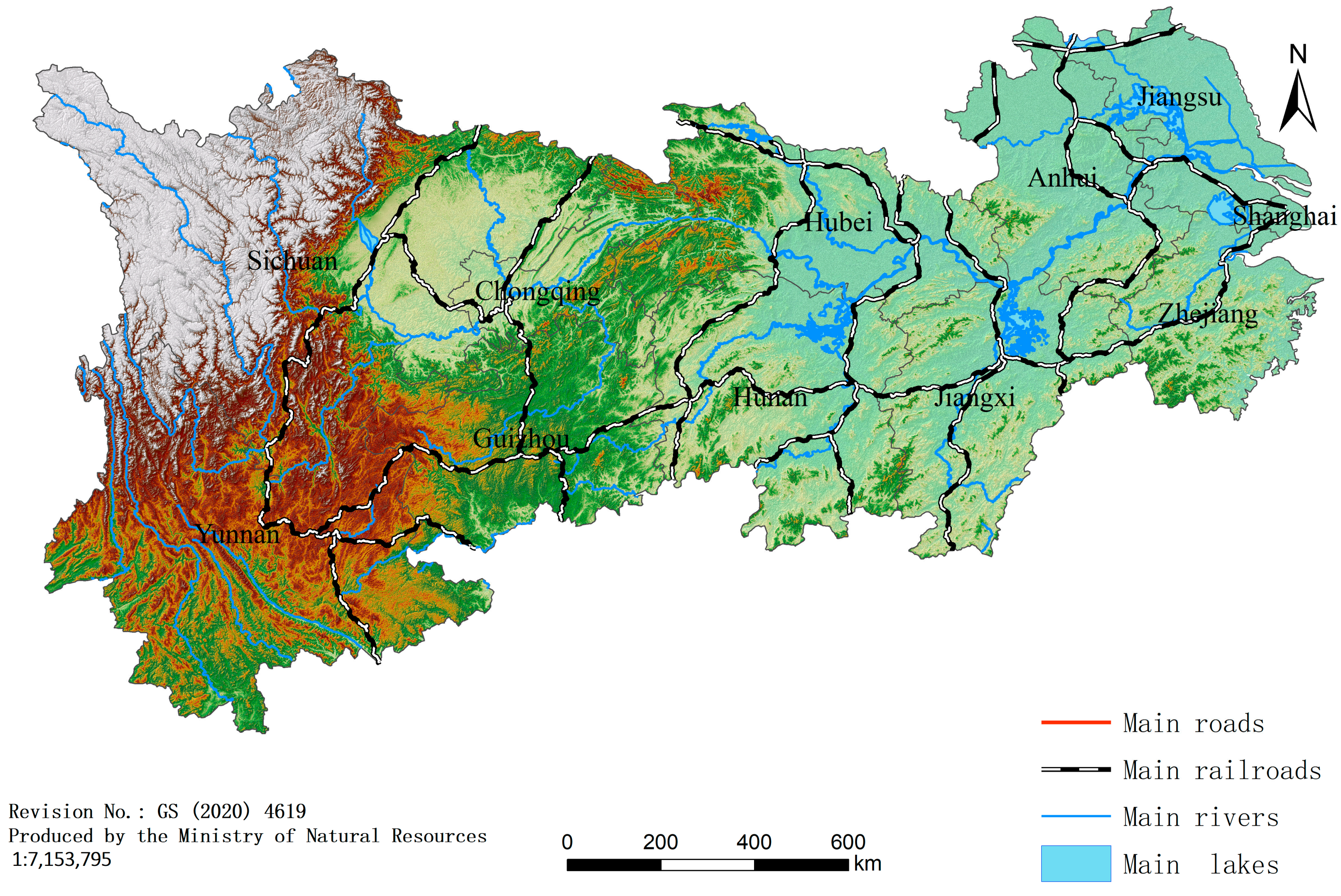

Figure 2. Overview of the YREB.

Existing research has important theoretical value for the green efficiency of transportation but there is still room for further deepening in how to clarify the spatial–temporal differentiation characteristics of efficiency, such as the following. ① In terms of the research object, we should not be limited to a single region but should fully realize that transportation is a spatial channel with regional connection. In the process of research, we should not study one unit in isolation but analyze the possible spatiotemporal characteristics of the research object with the help of the spatial differentiation analysis model. ② In terms of research methods, based on the quantitative analysis method, from the perspective of transportation efficiency measurement, the traditional DEA model is adopted based on data (Takayabu [4], 2020). More researchers choose SBM or the super efficiency SBM model to measure GTE and adopt the SBM model (Ma [5], 2022; Ma [6], 2021), given the superior efficiency SMB of the unexpected output (Lv [6,7], 2023; Ding [8], 2023; Zhou [9], 2023; Cao [10], 2019; Yuan [11], 2017) to measure GTE. Some researchers also used the DDF model with the directional distance function (Beltran-Esteve [12], 2015). To improve the traditional DEA model, the three-stage SBM-DEA model (Zheng [13], 2023), DEA game cross-efficiency model (Jiang [14], 2022), and the improved SMAA-DEA method (Wei [15], 2021) to deal with data uncertainty are adopted. By introducing the non-discretionary input DEA eco-efficiency evaluation method (Song [16], 2022), a new double-boundary DEA common weight model (Kiani [17], 2019) was established. From the perspective of spatial characteristics and spatial spillover of transportation green efficiency, researchers used the Global Moran's I index to verify the spatial autocorrelation of factors affecting transportation carbon emissions (Li [18], 2023) and LISA (Local Indications of Spatial Association, LISA) (Yuan [11], 2017). The Dagum Gini coefficient is utilized to examine the spatial non-equilibrium of comprehensive transportation green efficiency (Ma [5], 2022). The Spatial Autoregressive (SAR) model is employed to test for spatial spillover effects (Ding [8], 2023). The CD test is used to assess the independence of efficiency value samples (Rehman [19], 2023). ③ From the perspective of analyzing the influence and driving factors; the IV-GMM model is used to investigate its impact on green TFP (Zhao [2], 2023) and the index decomposition analysis (IDA) is used (Takayabu [4], 2020). Combined with the Malmquist total factor productivity index model and regression model (Ma [6], 2021), the spatial–temporal geographical weighted regression model (GTWR) (Lv [7], 2023) analyzed the main influencing factors of efficiency based on efficiency value and improved the Malmquist index model (Zheng [13], 2023). The panel econometric model (Zhou [9], 2023), the panel Tobit model (Cao [10], 2019), and the IV-GMM model (Zhao [2], 2023) are employed to estimate the degree of influence of various factors.

Through the review of relevant research, it can be found that the current research on GTE has been conducted by researchers at home and abroad and rich results have been achieved. Based on the existing research, this paper constructs a set of regional green efficiency index systems of transportation. The undesirable super-SBM model is used to measure the efficiency. Finally, the spatial correlation and distribution characteristics of green efficiency are deeply explored through the spatial statistical analysis model.

2. Research Methods

2.1. Calculation Model of Green Efficiency of Regional Transportation

2.1.1. Principal Component Analysis

Principal Component Analysis (PCA) is an extensively used technique for data optimization. It extracts the most relevant features from high-dimensional data and transforms them into a lower-dimensional representation while preserving most of the information in the original data. The core concept of PCA is to project the original data into a new coordinate system after linear transformation, where the variance in the data decreases. After projection, the principal components (PC) capture variance in descending order, meaning each PC is a linear combination of the original features, retaining much of the information from indicator data.

The number of PCs is typically selected based on the cumulative variance contribution rate. Generally, an eigenvalue greater than 1 or a cumulative contribution rate greater than 0.85 is used as the selection criterion. The mathematical model of PCA is as follows:

$$\begin{cases} y_1 = \mu_{11}x_1 + \mu_{12}x_2 + \cdots + \mu_{1p}x_p \\ y_2 = \mu_{21}x_1 + \mu_{22}x_2 + \cdots + \mu_{2p}x_p \\ \vdots \\ y_p = \mu_{p1}x_1 + \mu_{p2}x_2 + \cdots + \mu_{pp}x_p \end{cases} \quad (1)$$

In Equation (1), $\mu_{i1}^2 + \mu_{i2}^2 + \cdots + \mu_{ip}^2 = 1, i = 1, 2, \ldots, p$.

The following principles exist for the formula:

(1) y_i and y_j are independent of each other, $i \neq j$; $i, j = 1, 2, \ldots, p$;

(2) $y_1, y_2, \cdots y_p$ is arranged according to the variance in each linear combination from large to small, y_1 represents the linear combination with the largest variance, y_2 is next, and y_p represents the linear combination with the smallest variance.

2.1.2. Undesirable Super-SBM Model

DEA was initially proposed in 1957. It has gained wide acceptance among researchers because it can calculate efficiency without the need to construct a production function. DEA is frequently employed to assess the production efficiency of systems characterized by multiple inputs and outputs. Subsequent developments include the introduction of the

BCC (Banker-Charnes-Cooper) model by Banker et al. and the non-radial SBM (Slack-Based Measure) model proposed by Tone (2001) [20].

Considering the characteristics of the regional transportation industry, when calculating the GTE, input–output indicators cannot increase or decrease in the same proportion. Therefore, the non-radial model SBM in DEA can be used to obtain a more accurate GTE value, while the highest efficiency value calculated by the ordinary SBM model is 1. Multiple GTE values may be equal to 1 at the same time. In order to facilitate comparison and analysis in this case, the super-SBM model is an extension [21]. It takes into account more complex production processes and the uncertainty of market demand. Its resulting efficiency values can be greater than 1, allowing direct comparison of different efficiency values. To sum up, the undesirable super-SBM model is selected as the calculation model of regional transportation green efficiency under the condition of considering the undesirable output. The model calculation formula is as follows:

$$\min\rho^* = \frac{1+\frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{ik}}}{1-\frac{1}{q_1+q_2}\left(\sum_{r=1}^{q_1}\frac{s_r^{g+}}{y_{rk}}+\sum_{t=1}^{q_2}\frac{s_t^{b-}}{y_{tk}}\right)}$$

$$\text{s.t.}\begin{cases} \sum\limits_{j=ij\neq k}^{n} x_{ij}\lambda_j - s_i^- \leq x_{ik} \\ \sum\limits_{j=ij\neq k}^{n} y_{ij}^{q}\lambda_j + s_r^{g+} \geq y_{jk}^{g} \\ \sum\limits_{j=ij\neq k}^{n} y_{tj}^{b}\lambda_j - s_i^{b-} \leq y_{tk}^{b} \\ 1-\frac{1}{q_1+q_2}\left(\sum\limits_{r=1}^{q_1}\frac{s_r^{g+}}{y_{jk}}+\sum\limits_{i=1}^{q_2}\frac{s_t^{b-}}{y_{tk}}\right) > 0 \\ s^-, s^{g+}, s^{b-}, \lambda \geq 0 \\ 1=1,2,\cdots,m; r=1,2,\cdots,q; j=1,2,\cdots n(j+k) \end{cases} \tag{2}$$

In Formula (2), p represents the GTE in all provinces and cities along the YREB; λ_j represents the weight of evaluation indicators for each province and city; k represents provinces and cities; x represents the input index of transport industry; y^g represents the output index of transport industry; y^b represents the green undesirable output standard of transport industry; and s^-, s^{g+}, s^{b-} represent the slack variables associated with the input, desired output, and undesired output indicators of the transportation industry in each province and city along the YREB, respectively.

2.2. Spatial Correlation Analysis Model of Green Efficiency of Regional Transportation

2.2.1. Global Spatial Autocorrelation Analysis

This method was first proposed by Ansel using the Moran's I [22]. The index reflects the statistical correlation of specific attribute values across space, revealing the spatial distribution characteristics and interdependencies of green transportation efficiency in different regions. Moran's I include Global Moran's I (Global Moran's index), which primarily evaluates overall spatial correlation. When Global Moran's I is significant, Local Moran's I (Local Moran's index) can be used to further explore local spatial autocorrelation. The formula for Global Moran's I is as follows:

$$\text{Global-Moran's I} = \frac{\sum\limits_{i=1}^{n}\sum\limits_{j=1}^{n} w_{ij}(x_i-\overline{x})(x_j-\overline{x})}{s^2\sum\limits_{i=1}^{n}\sum\limits_{j=1}^{n} w_{ij}} \tag{3}$$

In Equation (3), n represents the number of study objects, x_i and x_j represent the GTE values of different regions, $\overline{x}$ represents the average GTE of all study objects, and s^2

represents the variance in the GTE of the study objects ($s^2 = 1/n \times \sum_{i=1}^{n} (x_i - \overline{x})^2$). w_{ij} is the spatial weight matrix of element (i, j), where this study selects the adjacency matrix as the spatial weight matrix, i.e., the adjacency matrix element is set to 1 when regions i and j are adjacent in space; otherwise, it is set to 0. The analysis results of the Global Morans'I are shown in the table below (see Table 1).

Table 1. Analysis of Global Moran's I result.

Global Moran's I	Correlation Posture	Distribution Characteristics
The closer it is to −1	The stronger the spatial negative correlation	Dispersed
The closer the value is to 0	No correlation	Random
The closer to 1	The stronger the positive correlation	Clustered

In spatial autocorrelation analysis, it is crucial to calculate the standardized Z statistic and its corresponding p-value alongside the Global Morans'I to assess the significance of spatial correlation. The formula for the Z value is

$$Z = \frac{I - E(I)}{\sqrt{VAR(I)}} \tag{4}$$

Equation (4) defines $E(I)$ and $VAR(I)$ as the expected value and variance in Global Moran's I, respectively. Table 2 below illustrates the hypothesis testing for Z-values.

Table 2. Correspondence of Z-value hypothesis testing statistics.

Z	*p*	*Confidence Level*
<−1.65 or >1.65	<0.10	0.9
<−1.96 or >1.96	<0.05	0.95
<−2.58 or >2.58	<0.01	0.99

2.2.2. Local Spatial Autocorrelation Analysis

Global Moran's I can analyze spatial autocorrelation from an overall perspective but it cannot provide specific spatial autocorrelation among different regions. In research, Local Moran's I is typically combined with LISA (Local Indicators of Spatial Association) distribution maps to analyze local spatial correlation. Its calculation formula is as follows:

$$I' = \frac{n(x_i - \overline{x}) \sum_{j=1}^{n} W_{ij}(x_j - \overline{x})}{S^2} \tag{5}$$

In Equation (5), I' is the Local Moran index; n represents the quantity of study province; x_i and x_j represent the GTE of the province; $\overline{x}$ represents the average value of GTE in all study provinces; and w_{ij} represents the spatial adjacency matrix.

2.2.3. Cold and Hot Spot Analysis

Cold/hot spot analysis commonly uses the G_i^* coefficient by GTE and Ord to measure spatial clustering of attribute values, visualizing regional transportation green efficiency. This study identifies cold/hot spots in YREB's transportation green efficiency using ArcGIS' GTE is-Ord G_i^* statistic. The methodology focuses on ArcGIS' hot spot analysis tool, specifically the GTE is-Ord G_i^* statistic, to pinpoint cold hotspots in YREB's transportation green efficiency.

$$G_i^* = \frac{\sum_j^n w_{ij} x_j}{\sum_j^n x_j} \tag{6}$$

In Equation (6), n is the total number of research objects, $\omega_{\iota\varphi}$ is the spatial weight matrix of object i and object j, and x_j is the green transportation efficiency of province j.

3. Calculation and Difference Analysis of GTE

In this section, the optimized index data will be incorporated into the undesirable super-SBM model to realize the measurement of the GTE in the YREB and a detailed difference analysis will be conducted on the measured efficiency values from different perspectives.

3.1. Indicators and Data

3.1.1. Selection of Indicators

In order to measure the green efficiency of regional transport, we should first grasp the actual characteristics of regional transport industry development and select appropriate input–output indicators. The following table summarizes the input–output indicators used in the research field of GTE at home and abroad in the past decade (see Table 3).

Table 3. Indicators used in the research field of green efficiency in transportation.

Serial Number	Reference	Time	Input Metrics	Output Indicators	Undesired Output Measure
1	[23]	2011	Personnel input, infrastructure input, vehicle input and energy input	Road transport economic benefits, road passenger services and road freight services	
2	[24]	2013	Energy, labor, capita	Value added	CO_2 emissions
3	[25]	2014	Energy, labor, capital	Freight turnover, volume, passenger, turnover volume	
4	[26]	2015	Labor input, infrastructure input, energy input	Convert turnover	Deaths, CO_2 emissions
5	[27]	2016	Energy, labor, capital	Gross domestic product	SO_2 emissions
6	[28]	2018	Investment in fixed assets, energy input	Passenger turnover of urban rail transit	
7	[29]	2018	Land resource input, human resource input, capital input	Freight scale level, freight efficiency level	
8	[30]	2018	Labor, capital, energy use	Value added	CO_2 emissions, NO_2 emissions, CO emissions, BC emissions
9	[31]	2019	Network factor input, labor input, equipment and facilities input, capital input, energy input	Transportation output, capital output	
10	[32]	2019	Total assets, operating expense, employee, energy consumption	Revenue, net income	CO_2 emissions

Table 3. *Cont.*

Serial Number	Reference	Time	Input Metrics	Output Indicators	Undesired Output Measure
11	[33]	2020	Input in passenger transport, input in cargo transport	Output of passenger transport, output of cargo transport	
12	[34]	2020	Capital stock, employed	passenger, turnover, freight turnover	CO_2 emissions
13	[5]	2022	Transport infrastructure, capital, human resources	Value added of transport industry, social development index	CO_2 emissions from the transport sector
14	[16]	2022	capital, labor, energy	Passenger turnover volume, Freight turnover volume	CO_2 emission

Based on the research in related fields, it can be seen that the input indicators in the index system established by researchers often include capital [5,16,23–25,27–31,34], labor [5,16,17,23,25–27,29–31,34], and energy [16,17,23–25,27,28,30,31]. This is in line with the theory of production factors in economics, that is, capital and labor are the main production factors. On the other hand, energy is also considered as an important basis. Therefore, in the related field research of transportation green efficiency, capital, labor, and energy input are considered as the key input indicators.

Therefore, based on the research in related fields and the actual situation of current research, this paper chooses the indicator system of green efficiency of regional transportation as shown in the following table (see Table 4). Considering the characteristics of China's transport industry development, in addition to selecting the capital input at the social level, this paper also selects the capital input at the government level to represent the capital input of regional transport development. Simultaneously, employees in the transport industry and energy consumption in the transport industry are selected to represent labor input and energy input, respectively. In addition, the important input of the transportation industry should also include the input of infrastructure and transportation equipment. Transportation infrastructure and transportation equipment are the basis for the normal operation of the transportation industry. Infrastructure, such as railways, highways, and waterways is the "skeletal system" of the transportation industry. Without perfect infrastructure, the transportation industry cannot operate efficiently. And transportation equipment, such as cars, ships, etc., is the main carrier of transportation. Without transportation equipment, it is impossible to carry out transportation operations. Therefore, investment in these two aspects is also an important part of the regional transportation industry.

For the selection of expected output, this paper selects the turnover of goods and the added value of the transport industry to represent the output of the regional transport industry from the physical and economic perspectives of cargo transport, respectively. From the material point of view, the turnover of goods can better represent the output of freight transportation because it reflects the actual flow of goods in the process of transportation. From an economic point of view, the value-added of the transport industry reflects the economic value created by the transport industry from the production process, so it can be used as an indicator to represent the output of the transport industry. At the same time, these two indicators can also complement each other to reflect the output status of the regional transport industry more comprehensively.

Table 4. Regional transportation green efficiency indicator system.

Angle	First Indicator	Secondary Indicators	Indicator Description	Data Sources
Input metrics	Capital	X1: Capital input at the government level (CNY 100 million)	Local fiscal expenditure on transportation (CNY 100 million)	Statistical yearbooks of all provinces and cities
		X2: Capital input at the social level (CNY 100 million)	Investment in transportation, warehousing, and postal activities (CNY 100 million)	China Fixed Asset Investment Statistical Yearbook
	Labor force	X3: Employees employed (ten thousand)	Employment in urban units in transportation, storage and postal services (ten thousand)	Statistical yearbooks of all provinces and cities
	Energy consumption	X4: Energy consumption (ten thousand tons)	Standard coal for energy consumption in transportation industry (ten thousand tons)	China Energy Statistical Yearbook
	Transportation Infrastructure	X5: Mileage of railways in operation (10,000 km)	Mileage of railways in operation (10,000 km)	China Traffic Statistical Yearbook
		X6: Highway mileage (10,000 km)	Road mileage (10,000 km)	China Traffic Statistical Yearbook
		X7: Length of inland waterways (10,000 km)	Inland Waterway length (10,000 km)	China Traffic Statistical Yearbook
	Transportation equipment	X8: Transport vessel ownership	Number of civil motor transport ships (vessels)	Statistical yearbooks of all provinces and cities
		X9: Ownership of transport vehicles	Number of civil truck ownership (ten thousand)	Statistical yearbooks of all provinces and cities
Expected output	Freight volume	Y1: Cargo turnover (100 million ton-km)	Cargo turnover (100 million ton-km)	China Traffic Statistical Yearbook
	Capital	Y2: Added value of transportation industry (CNY 100 million)	Value added in transportation, warehousing, and postal activities (CNY 100 million)	China Traffic Statistical Yearbook
Unexpected output	Environmental pollution	U1: Carbon emissions (ten thousand tons)	Carbon emissions from transportation (ten thousand tons)	China Energy Statistical Yearbook

In terms of the choice of undesirable output, the concept of green development is combined with global efforts to cope with climate change, reduce carbon, and reduce the greenhouse effect. This paper selects transportation carbon emissions as the undesirable output [16,17,24,32,34].

3.1.2. Data Sources

The primary data sources include the China Transportation Yearbook (2012–2022), China Energy Statistical Yearbook (2012–2022), China Fixed Asset Investment Statistical Yearbook (2012–2022), and statistical yearbooks of YREB (2012–2022). Transportation infrastructure and equipment data primarily come from the Statistical Yearbook. Capital and labor data are sourced from the statistical yearbooks of 11 provinces and cities in the YREB (2012–2022). Energy consumption and carbon emission data require further calculation using the China Energy Statistical Yearbook 2022. Carbon emission data can be obtained through the standardized conversion of energy types using the standard coal conversion coefficient issued by the China Energy Statistical Yearbook. These data serve as the basis for energy consumption in the transportation industry and are combined with China's energy structure. The carbon emission index is used as an environmental constraint, referencing Zhang Shining's "top-down" carbon emission measurement method based on terminal energy consumption [35].

$$\begin{aligned} T &= \sum_{i=1}^{m} E_i \times c_i \times 44/12 \\ &= \sum_{i=1}^{m} E_i \times \mathrm{ALV}_i \times v_i \times r_i \times 44/12 \end{aligned} \tag{7}$$

In Formula (7), T represents the cumulative CO_2 emissions from the transportation sector; i is the type of energy; E_i is the consumption of the second type of energy; c_i is the energy carbon emission factor; ALV_i stands for the mean lower heating value of energy sources; V_i is the carbon content per calorific value; and r_i is the carbon conversion rate [35].

After collecting and calculating the relevant index data, the SPSS Statistics 27 software was used for preliminary statistical analysis of the relevant indicators. The following table summarizes the descriptive statistics of the 11 provinces and cities in the YREB (see Table 5).

Table 5. Results of descriptive statistics for indicators.

Indicator	Minimum	Maximum	Average	Standard Deviation	Variance
Local fiscal expenditure on transportation (CNY 100 million)	80.43	792.73	355.58	144.14	20,776.19
Fixed investment in transportation, storage and postal services/RMB100 million	456.83	5957.37	1949.71	1282.69	1,645,285.02
Employment in urban units of transportation, storage and postal services (ten thousand)	9.10	51.50	27.25	11.59	134.40
Energy consumption Standard coal (ten thousand tons)	347.55	2219.15	1185.06	487.20	237,361.52
Railway operating mileage (10,000 km)	0.04	0.59	0.32	0.14	0.02
Highway mileage (10,000 km)	1.20	39.89	18.49	8.15	66.45
Length of inland waterways (10,000 km)	0.00	2.00	0.73	0.62	0.38
Number of civil motor transport ships (vessels)	880.00	39,645.00	9460.36	10,834.58	117,388,203.42
Number of civil truck ownership (ten thousand)	19.49	172.66	76.33	33.23	1104.42
Cargo turnover (100 million ton-km)	947.33	34,074.60	6756.14	6562.62	43,067,982.74
Value added of transportation, storage and postal services (RMB 100 million)	244.90	3671.90	1246.39	664.28	441,269.17
Carbon emissions (ten thousand tons)	12,508.20	83,274.55	33,631.55	16,414.21	269,426,210.24

As shown in Table 5, there are notable differences in each selected input–output index in this study, showing a low degree of similarity and significant variations among the regions of the YREB. To further explore the potential information in the input–output index data, this study constructs scatter plots of energy consumption and carbon emission types, as well as investment and output types of the transportation industry in the 11 provinces and cities along the YREB. This analysis is conducted from the perspective of promoting regional energy conservation, emission reduction, and economic output.

From the perspective of energy consumption and carbon emissions (see Figure 3), plotting the energy consumption against carbon emissions for each province along the YREB from 2010 to 2021 reveals their relative positions. Using 100 million tons of energy consumption and 450 million tons of carbon emissions as thresholds, the provinces can be classified into four categories: low or high energy consumption and low or high carbon emissions. With the help of a scatter diagram, it can be found that only Jiangsu province occupies the region of high energy consumption and high emission. The main reason is that Jiangsu has a developed economy, a high level of economic development, and an earlier industrialization process, which has attracted a large number of enterprises and projects to invest. With the rapid economic development, the regional transportation industry has also been significantly improved and transportation facilities such as expressways and railways in Jiangsu have been developed. By 2023, the length of expressways in Jiangsu reached 5087 km and the total length of operational railways in the province reached 4276.9 km. Nationally, Jiangsu ranks approximately fifth in terms of highway mileage and third in terms of railway mileage. While the operation of transportation requires a lot of energy, it also produces a lot of carbon emissions. It is noteworthy that there are no provinces or cities in the low energy consumption and high emission region. The main reason may be that China is actively trying to reduce energy consumption and emissions and achieve low-carbon development in various aspects such as economic development, energy structure transformation, industrial upgrading, policy guidance, environmental awareness, and scientific and technological innovation. Therefore, Hunan, Hubei, Zhejiang, Sichuan, Shanghai, and other regions have high energy consumption but low carbon emissions, while Anhui, Guizhou, Yunnan, Jiangxi, and Chongqing belong to the low energy consumption and low emission regions.

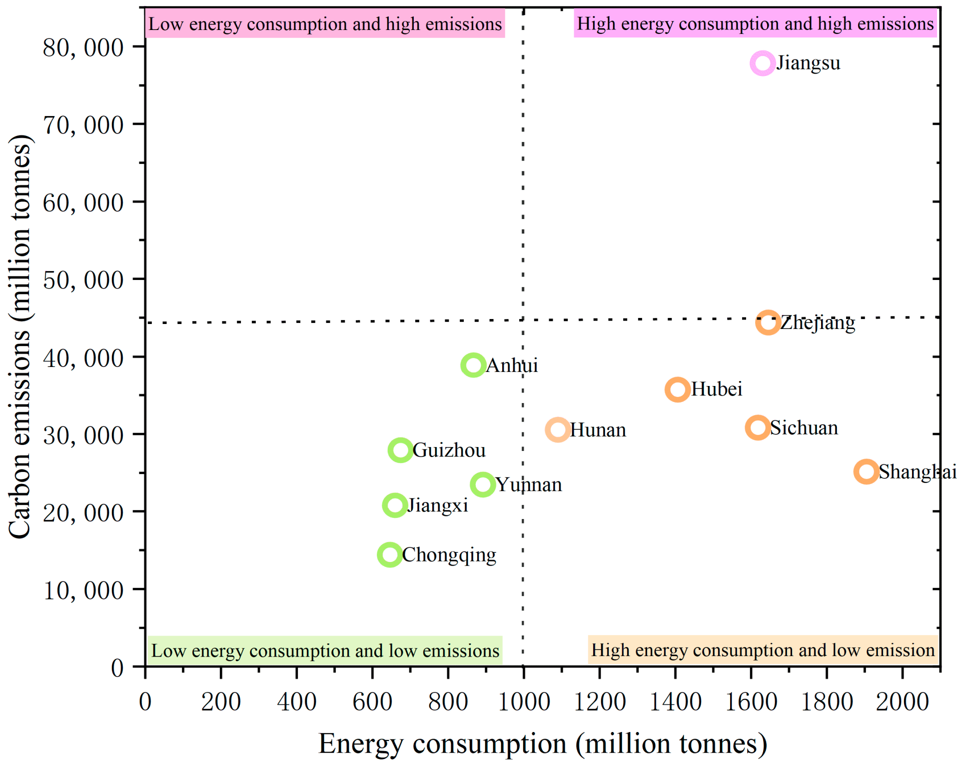

Figure 3. Scatter diagram of energy consumption and carbon emission types in the transportation industry.

From the perspective of investment and output in the transportation sector (see Figure 4), capital input at the social level is the abscissa to represent investment and the added value of the transportation industry is the ordinate to represent output. With capital input at the social level of CNY 200 billion and added value of the transportation industry of CNY 150 billion as the boundary, it is mainly divided into four regions: low investment with low output, high investment with low output, high investment with high output, and low investment with high output.Among them, the economically developed Jiangsu and Zhejiang belong to the regions of high investment and high output, while Yunnan and Sichuan belong to the regions of high investment and low output in the transportation industry. The main reason is that Yunnan and Sichuan are located in the upper reaches of the YREB and the transportation infrastructure construction of the two regions is relatively lagging behind. This brings great challenges to the construction of transport infrastructure. In order to solve the problems caused by the topography, a lot of capital and technology need to be invested, which leads to high investment and low output. Finally, Shanghai, Chongqing, Jiangxi, Guizhou, Hunan, and Anhui are all located in the area of low investment and low output. The provinces in the YREB have not yet seen the phenomenon of low investment and high output in the transportation industry. The main reason is that the provinces and cities in the YREB are still in the growth stage of infrastructure construction. At this stage, regions need to invest a lot of money to carry out transportation infrastructure construction, such as expressways, railways, ports, etc. The investment cost of these infrastructure projects is high and the payback period is long, resulting in relatively low benefits of overall investment output.

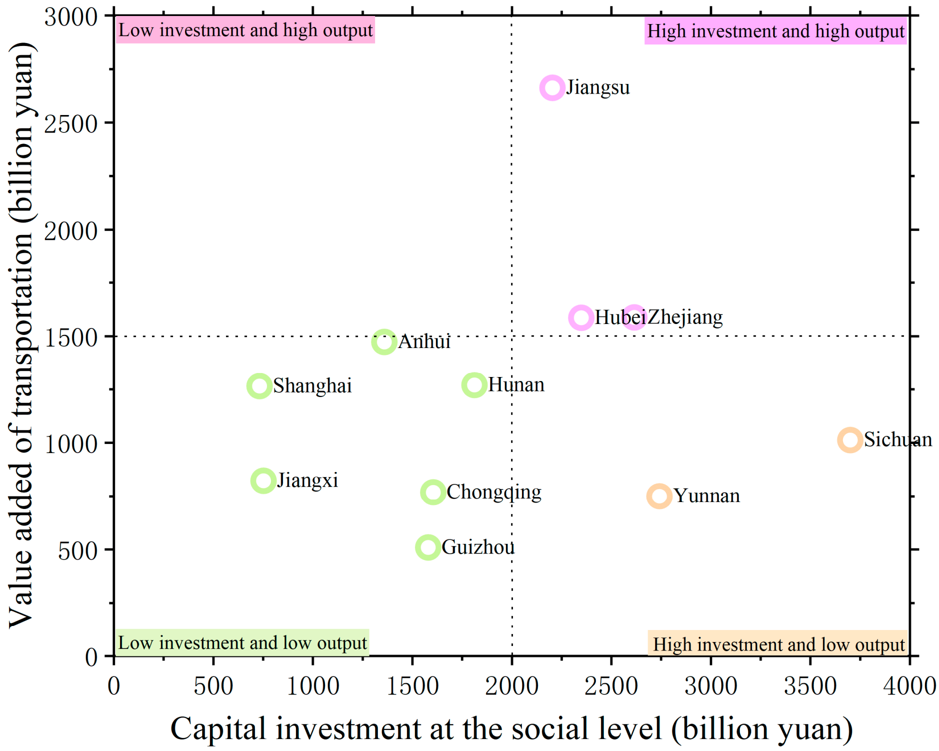

Figure 4. Scatter diagram of investment and output types in the transport sector1.

In order to further study the transportation industry in the YREB, with the improvement in infrastructure and regional coordinated development, the transportation industry in the YREB will have greater development potential in the future. Therefore, in the process of analyzing the GTE in the YREB, it is necessary to fully consider the actual situation of each region and formulate targeted GTE policies and support measures to improve overall efficiency.

3.1.3. Data Processing

According to the regional transportation green efficiency index system, the system contains more secondary indicators, especially those related to input. On the one hand, there is a certain overlap of information between transportation infrastructure and transportation equipment; for example, there is often a mutual influence relationship between highway mileage and the ownership of transportation vehicles. On the other hand, when applying the undesirable super-SBM model in practice, the appropriate number of indicators should be selected based on the research purpose and the actual situation. Generally, the number of Decision-Making Units (DMUs) should be greater than the number of indicators to ensure the effectiveness of the evaluation. Therefore, reducing the number of input–output indicators through PCA in this study helps mitigate issues of multicollinearity, reduces the burden of data processing for the undesirable super-SBM model, and avoids problems associated with high computational complexity and the difficult interpretation of evaluation results.

Therefore, this paper uses PCA to optimize the two input indicators of transportation infrastructure and equipment investment (see Figure 5) and uses SPSS software to reduce the dimension and optimize the five secondary indicators of X5 railway mileage, X6 highway mileage, X7 inland waterway mileage, X8 transport ship ownership, and X9 transport vehicle ownership. It also uses PCA to determine the potential principal component factors and incorporate them into the undesirable super-SBM model as the new Principal Component of Transportation Network (PCNT) and to calculate the GTE value of each province in the YREB. In order to ensure that the optimization indicators are correlated rather than independent, we need to carry out the KMO and Bartlett tests of sphericity.

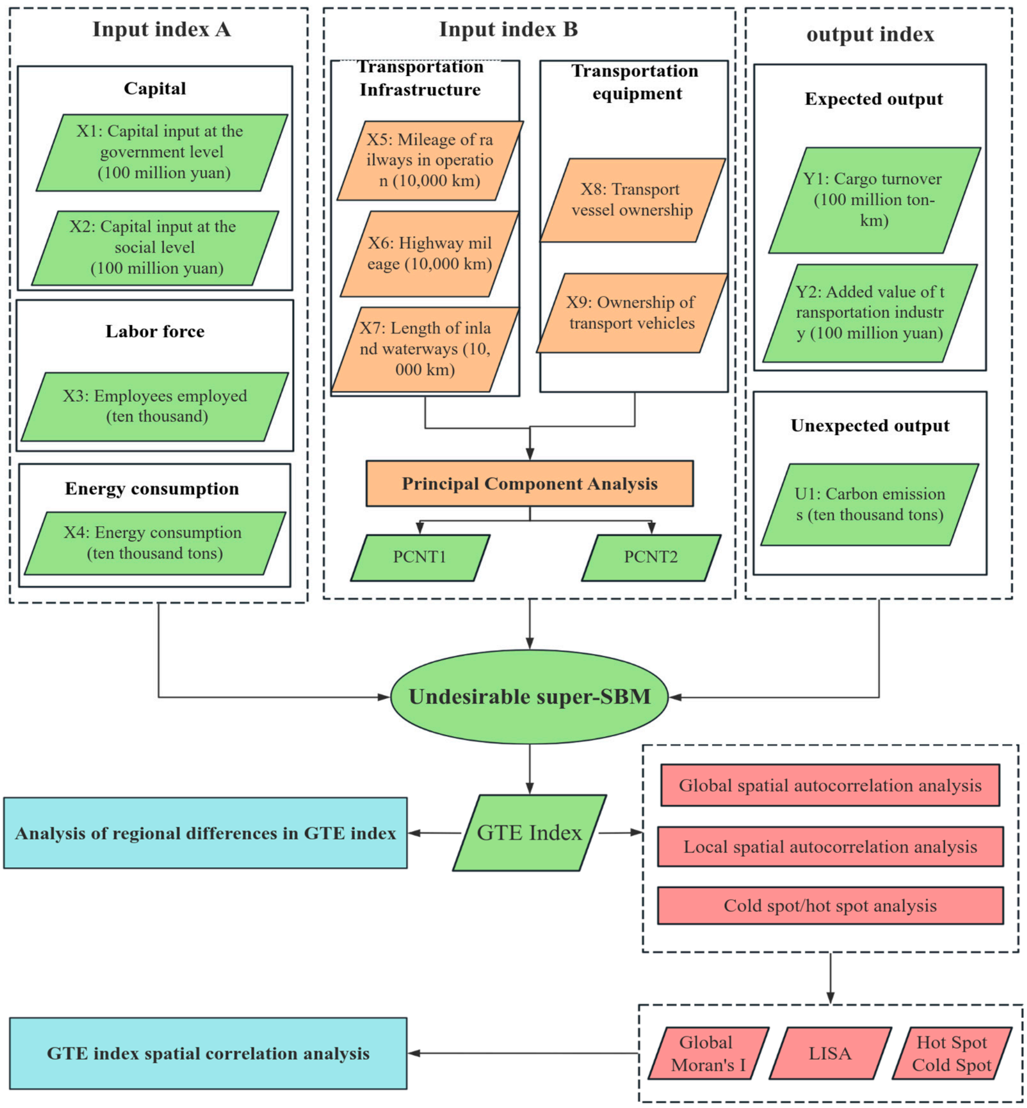

Figure 5. Technology roadmap.

The test results are shown in the following table (see Table 6). It can be seen from the following table that KMO is 0.613, which is greater than 0.6, and Bartlett's test of sphericity ($p < 0.05$) means that the data related to infrastructure and transportation equipment are suitable for PCA.

Table 6. KMO and Bartlett's test of sphericity.

Test Items		Test Results
KMO Sampling Appropriateness Quantity		0.613
Bartlett's test of sphericity	Approximate chi-square	425.746
	Degrees of freedom	10
	Salience	000

Analysis was conducted using the SPSS software and the results are presented in the following table (see Table 7). The table lists the PC in descending order of the variance percentages of the initial eigenvalues. According to the PCA analysis, the first two PC (PC1 and PC2) have eigenvalues greater than 1, with variance explanation rates of 54.906% and 31.008%, respectively. The cumulative variance explanation rate reaches 85.994%, exceeding the critical value of 85%. Hence, choosing these two PCs can capture a substantial portion of the information in the input indicator data and represent its characteristics.

Table 7. Variance interpretation table of PCA.

PC	Initial Eigenvalues		
	Total	Percent Variance	Cumulative %
PC1	2.745	54.906	54.906
PC2	1.554	31.088	85.994
PC3	0.397	7.937	93.931
PC4	0.191	3.816	97.747
PC5	0.113	2.253	100.000

According to the extraction of PC, X5 railway mileage, X6 highway mileage, X7 inland river and waterway mileage, X8 transport ship ownership, X9 transport vehicle ownership, the five secondary indexes can extract two PCs of the transportation network (PCNT), and the component score coefficients of the two PCs of the transportation network.Where PC1 is extracted as PCNT1 and PC2 as PCNT2 (see Table 8).

Table 8. Component score coefficients table of PCA.

Raw Variables	PC	
	PCNT1	PCNT2
X5: Operating mileage of railways (10,000 km)	0.813	−0.509
X6: Highway mileage (ten thousand kilometers)	0.679	−0.663
X7: Length of inland waterways (10,000 km)	0.788	0.474
X8: Transport vessel ownership	0.538	0.790
X9: Transport vehicle ownership	0.845	0.078

The following are calculated from Table 8:

$$PCNT1 = 0.813X5 + 0.679X6 + 0.788X7 + 0.538X8 + 0.845X9$$
$$PCNT2 = -0.509X5 - 0.663X6 + 0.474X7 + 0.790X8 + 0.078X9$$

3.2. Difference Analysis of GTE

3.2.1. Analysis of Differences in GTE at the Regional Level

According to the delineation by the Office of the Leading Group for Promoting the Development of the YREB, the YREB can be divided into three regions by basin: the upstream region comprises four provinces and municipalities including Yunnan; the midstream region includes Jiangxi, Hubei, and Hunan; and Zhejiang and four other provinces and municipalities, which are located in the downstream region [36]. Drawing on statistical data, the study created curves depicting the GTE of the YREB and its upstream, midstream, and downstream areas from 2010 to 2021. These curves were used to analyze the evolving characteristics of GTE across the entire YREB and its various regions (see Figure 6).

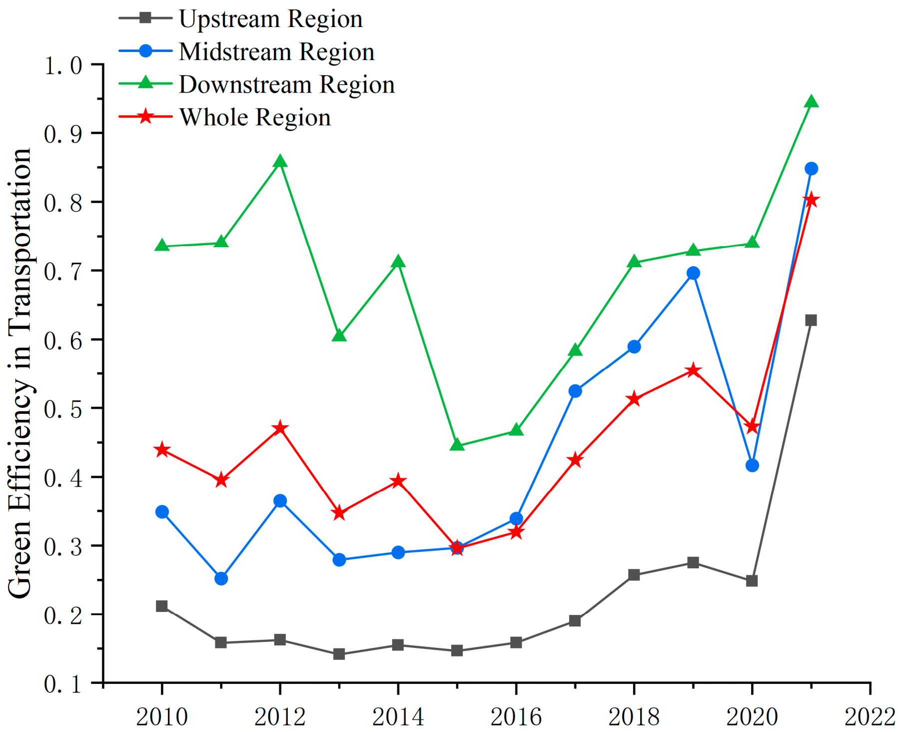

Figure 6. The changing trend of transportation green efficiency in the YREB.

As depicted in Figure 6, the GTE of the YREB and its upstream, midstream, and downstream regions exhibited a U-shaped pattern from 2010 to 2021, initially declining and then rising, primarily from 2015 onwards. During the period from 2010 to 2013, the Ministry of Transport issued the Opinions on Accelerating the Integrated Development of Transport in the YREB, which outlined general requirements and specific measures to expedite the integrated development of transport in the region. Additionally, the General Office of the State Council issued the Outline of the Development Plan for the YREB, which outlined the overall objectives, key tasks, policies, and measures for the region's development, emphasizing the need to strengthen transport infrastructure construction and enhance water transport capacity.

The policies during this period indicate a gradual increase in investment in transport industry infrastructure construction in the YREB. However, due to the long input–output cycle of transport industry infrastructure construction, regional transport's green efficiency was affected during this period. With China's economy and transport industry experiencing rapid development, government departments have become increasingly concerned about the transport industry's negative impact on energy consumption and environmental pollution.

In response to global climate change and the need for ecological and environmental protection, the Chinese government decided to accelerate the green development of transportation to reduce its adverse environmental impact. In 2015, the CPC Central Committee and the State Council jointly issued the Opinions on Accelerating the Green Development of Transportation, calling for the vigorous development of green transportation, improvement in energy efficiency, reduction in pollutant emissions, and protection of the ecological environment. Since 2015, the GTE in the YREB has gradually improved.

In addition, there are obvious differences in the GTE in the YREB and its upper, middle, and lower reaches, showing an obvious trend of the east being stronger than the west, that is, "lower reaches > middle reaches > upper reaches" (see Figure 7). The development trend of the middle reaches and the overall development trend of the YREB converge to the spatial pattern. Generally speaking, Jiangsu, Shanghai, and other places in the lower reaches of the YREB are the economic centers and transportation hubs of the YREB, with relatively perfect transportation infrastructure construction, advanced green transportation equipment and efficient transportation modes, and relatively high green transportation efficiency. Compared with the downstream regions, Hubei and Hunan in the middle reaches of the YREB lag behind in economic development; the development of transportation facilities and green transportation is relatively slow and the GTE is relatively low. Sichuan, Chongqing, and other places in the upper reaches of the YREB have relatively rugged terrain, difficult-to-construct transportation facilities, high construction costs, and need more resource input under the condition of the same transportation output, resulting in relatively low GTE in the upper reaches of the YREB.

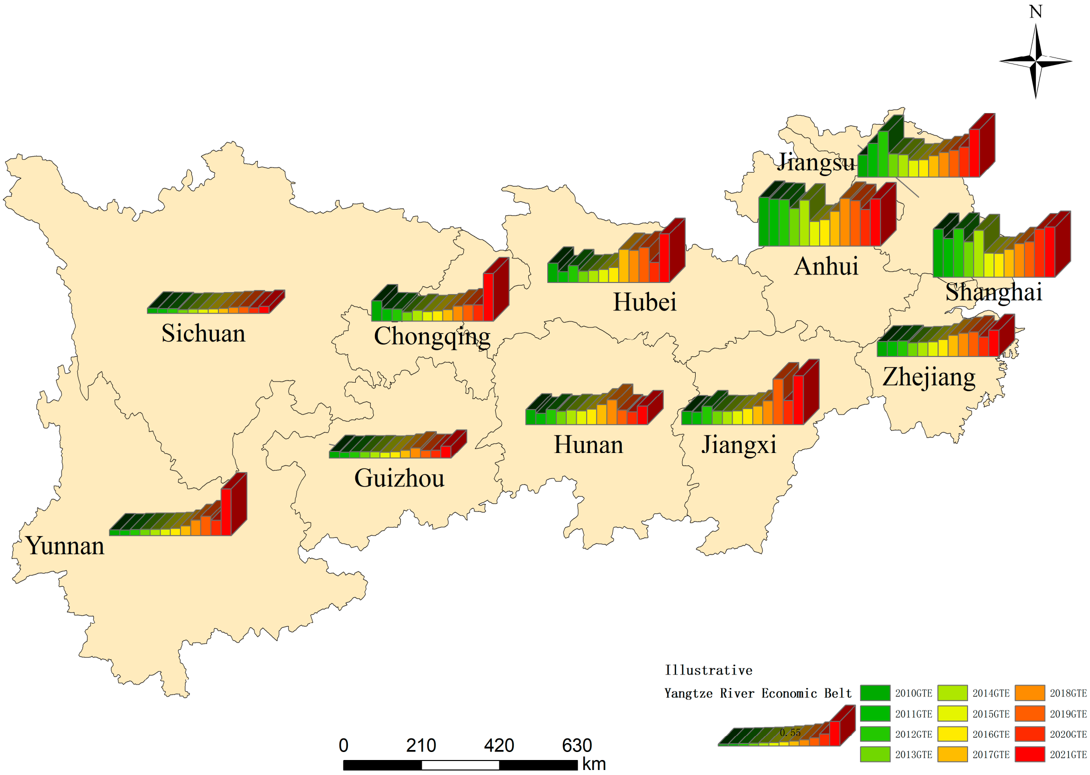

Figure 7. Visualization of the spatial layout of transport green efficiency in the YREB.

3.2.2. Analysis of Differences in GTE at the Provincial Level

The undesirable super-SBM model is used to estimate the phased GTE in the YREB from 2010 to 2021, which is shown in the following figure (see Figure 8).

It is evident from Figure 8 that there are some discrepancies in the GTE among provinces and cities in the YREB. The average GTE in Anhui from 2010 to 2021 is 0.898, which is closest to the efficiency frontier. The average of the GTE in the YREB is 0.452. The GTE in Anhui, Shanghai, Jiangsu, Hubei, and Jiangxi is higher than the average level, while the GTE in the other six provinces and cities is lower than the average level, indicating that the GTE in the YREB is unbalanced at the provincial level. The GTE in Sichuan ranks last in the four stages, while the GTE in Anhui, Hubei, Hunan, Chongqing, Sichuan, Yunnan, and other provinces and cities is lower than the average level. The GTE in Shanghai, Jiangsu, Zhejiang, Anhui, Jiangxi, Guizhou, and other provinces is higher than the average level.

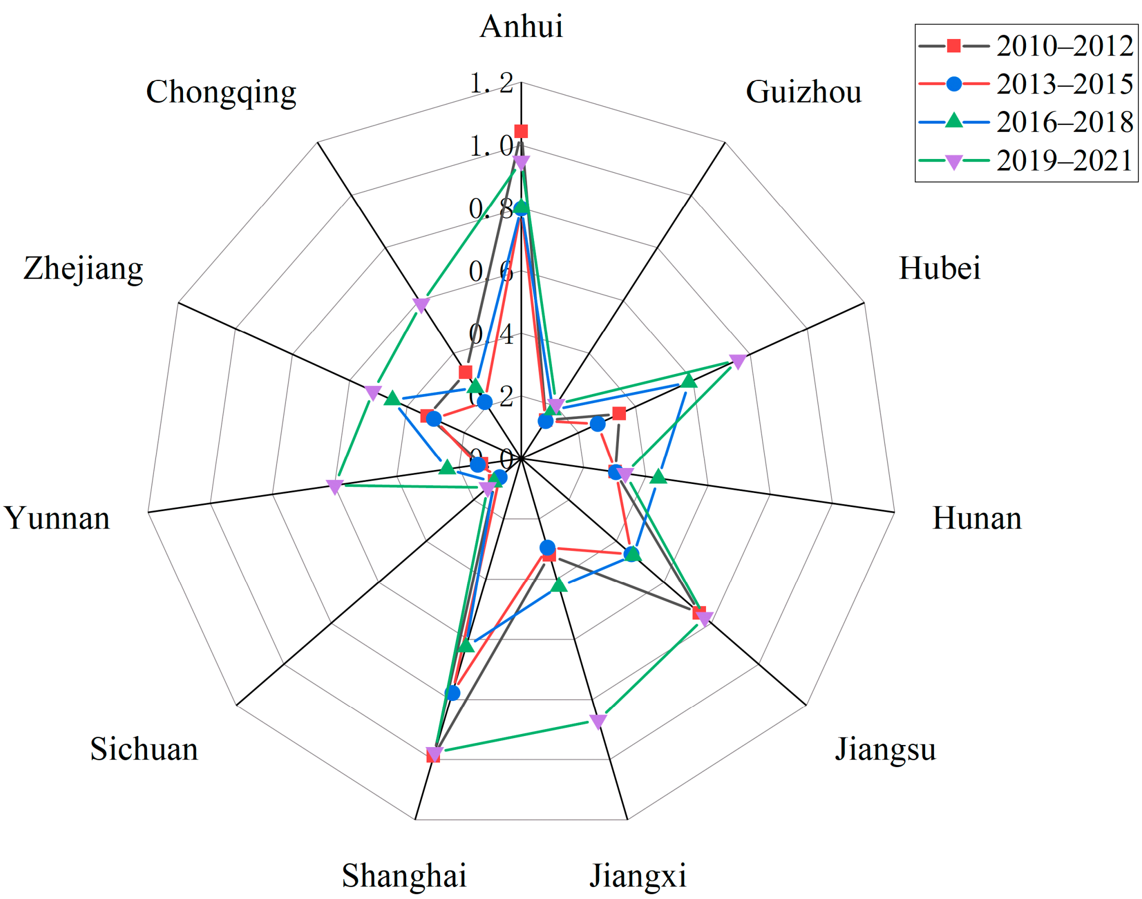

Figure 8. Four stages of change in GTE in the YREB.

In general, the GTE in Shanghai and Anhui ranks top among the 11 provinces and cities in the YREB. In particular, the GTE in Shanghai has been steadily increasing since 2015, mainly due to the perfect transport infrastructure in Shanghai: Shanghai has the largest port and airport in China and it is also one of the most important transportation centers of railway, highway, and pipeline in China. As a result, the cost of transportation infrastructure construction in Shanghai is relatively low. On the other hand, the Shanghai municipal government has formulated a series of policies and measures to promote green transportation, such as encouraging the use of clean energy vehicles, optimizing the transportation structure, and strengthening the publicity of green travel. In 2021, the output value of new energy vehicles in Shanghai exceeded CNY 160 billion, with a 200% year-on-year increase.

At the same time, Shanghai issued the Implementation Plan to Accelerate the Development of the New Energy Vehicle Industry (2021–2025). By 2025, the annual output of new energy vehicles in Shanghai is projected to exceed 1.2 million, with an output value exceeding CNY 350 billion, accounting for over 35% of the city's automobile manufacturing output value. The GTE in the upper reaches of the YREB, including Sichuan, Guizhou, Yunnan, and other regions, is generally not lower than the average value of the YREB. This is mainly due to the high proportion of mountainous and plateau areas in these regions, the complex and undulating terrain, relatively poor transportation conditions, and high costs of transportation infrastructure construction. For example, in Sichuan, in 2010, government-level capital investment and social-level capital investment in Sichuan Province reached CNY 19.2 billion and CNY 157.6 billion, respectively, with both increasing approximately 3.7 times from 2010 to 2021. High investment is a common challenge faced by provinces in the upper reaches of the YREB. Therefore, the Chinese government should provide appropriate policy support to Sichuan, Guizhou, and other areas in the upper reaches of YREB with weak transportation infrastructure.

4. Analysis of Spatial Correlation and Distribution Characteristics of GTE

The above preliminary analysis of the GTE in the YREB is made from the perspectives of the regional level and provincial levels. Through the calculation results and analysis, it can be seen that there are obvious gaps in the GTE among the 11 provinces and cities in the YREB. In this chapter, the global spatial autocorrelation, local spatial autocorrelation, and cold and hot analysis models will be used to analyze the spatial correlation and distribution characteristics of the GTE in the YREB.

4.1. Global Spatial Autocorrelation

Firstly, the Global Moran's I of transportation carbon emissions in the YREB was calculated by using the spatial analysis tool of Arcgis10.8 software and the calculated results were statistically analyzed and tested (see Table 9).

Table 9. Test results of Global Moran's I.

Year	Global Moran's I	Expectations Index	Variance	*Z*-Score	*p*-Value	Dispersed	Random	Clustered
2010	0.120312	0.1	0.034028	1.194324	0.232351		√	
2011	0.373645	0.1	0.036752	2.470659	0.013486			√
2012	0.466015	0.1	0.039421	2.850767	0.004361			√
2013	0.329313	0.1	0.035699	2.272191	0.023075			√
2014	0.17722	0.1	0.033234	1.520663	0.128344		√	
2015	0.505669	0.1	0.037853	3.113055	0.001852			√
2016	0.571661	0.1	0.038239	3.434759	0.000593			√
2017	0.505038	0.1	0.039854	3.03072	0.00244			√
2018	0.407812	0.1	0.034399	2.737974	0.006182			√
2019	0.467689	0.1	0.040269	2.828966	0.00467			√
2020	0.409686	0.1	0.034842	2.730547	0.006323			√
2021	0.099302	0.1	0.040089	0.003484	0.99722		√	
2010–2021	0.428665	0.1	0.037338	2.735941	0.00622			√

An analysis of the trend in relevant indices shows that from 2010 to 2021, the green transportation efficiency in the YREB exhibited an overall U-shaped distribution. The highest values for the Global Morans'I and Z-score were observed in 2016, at 0.57 and 3.43, respectively, while the lowest values were observed in 2021, at −0.099 and 0.003, respectively. Only the Moran's I values for 2010, 2014, and 2021 were close to 0 and their *p*-values did not pass the 10% significance test, indicating no clear trend of agglomeration or dispersion. All other years passed the test, suggesting a significant spatial aggregation pattern. Therefore, the global spatial distribution of GTE in the YREB from 2010 to 2021 is not random but shows significant spatial clustering. This indicates that the GTE in different YREB regions exhibits spatial dependence, implying that regions with higher GTE are likely to be adjacent to each other, while regions with lower efficiency also tend to be adjacent. This spatial dependence may be influenced by factors such as the geographical location and transportation network.

4.2. Local Spatial Autocorrelation

The YREB exhibits spatial autocorrelation overall. However, to analyze the correlation characteristics between regions more specifically, it is necessary to conduct a local analysis of the clustering characteristics of provinces. Using Arcgis10.8 software, the changes in local spatial autocorrelation in the provinces of the YREB from 2010 to 2021 were calculated. The Jenks Natural Breaks method was employed to categorize the Z values of the Local Morans'I into four intervals: high–high cluster, low–low cluster, high–low outlier, and low–high outlier. "Not Significant" indicates locations where there is no statistically significant correlation.

Due to limited space and the relatively stable spatial clustering characteristics of provincial transport carbon emissions over time, we divided the period from 2010 to 2021 into four stages, with each stage representing three years. This division allowed us to study the changes in local spatial autocorrelation in each province in the YREB over time. Consequently, LISA (Local Indicators of Spatial Association) aggregation maps for the periods 2010–2012, 2013–2015, 2016–2018, and 2019–2021 were created using ArcGIS 10.8 software (see Figure 9).

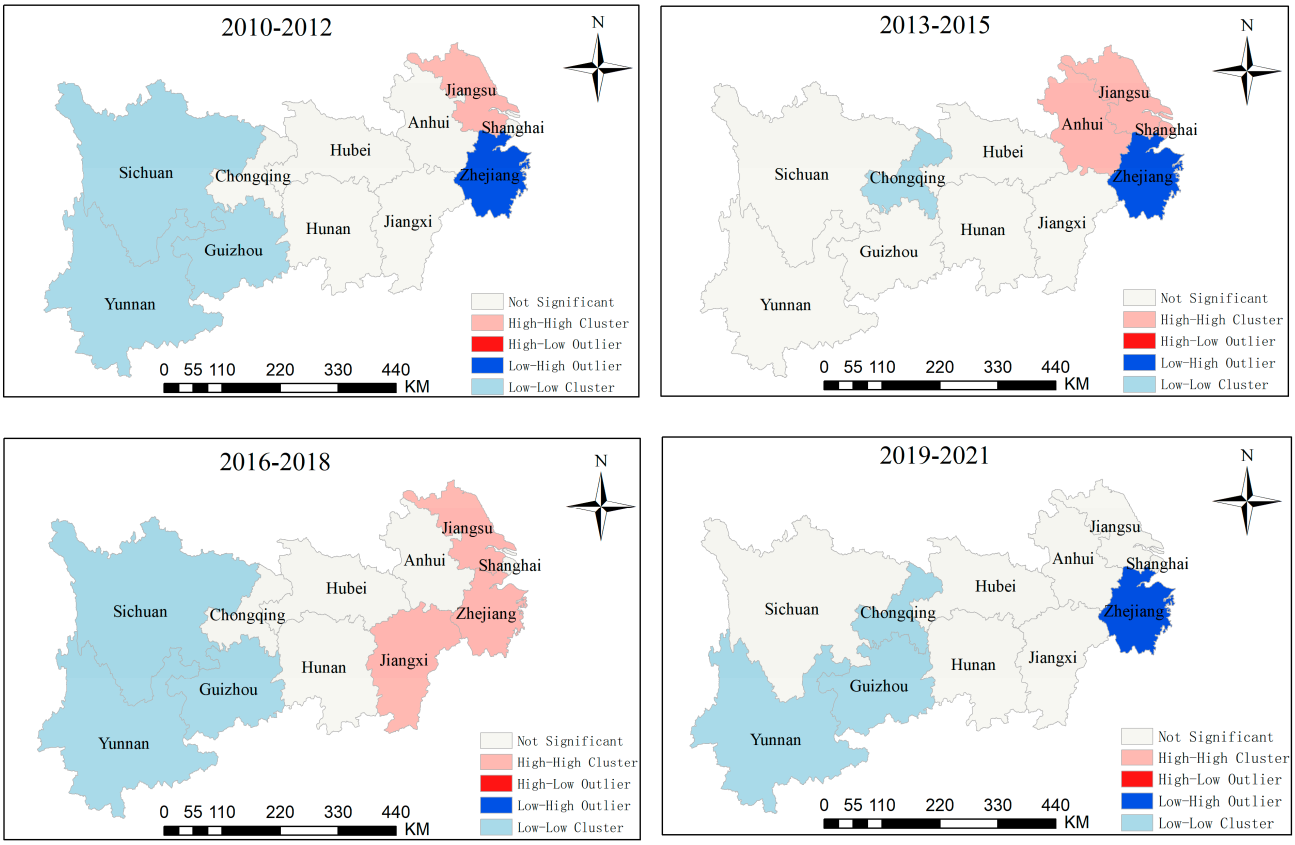

Figure 9. LISA agglomeration and evolution diagram of transportation green efficiency in the YREB.

From 2010 to 2021, the spatial clustering pattern of Chongqing, Sichuan, Guizhou, and Yunnan in the upper reaches of the YREB experienced fluctuations but generally maintained a low–low clustering state for most of the time. This indicates high spatial autocorrelation among the provinces and cities in the upper reaches of the YREB. The main reason for this is that compared to downstream areas, the upstream areas are relatively economically backward, with transportation infrastructure construction lagging behind. The complex geographical environment and undulating terrain in the upper reaches result in high costs for transportation construction and network maintenance, exacerbating the infrastructure lag. These factors contribute to a low GTE in the upper reaches, affecting the overall coordinated development of the YREB. To address this, the Chinese government has increased investment in the upper reaches, particularly in transportation infrastructure. For instance, in Sichuan, fixed investment in the transportation industry (including transportation, storage, and postal services) rose from CNY 157.6 billion in 2010 to CNY 595.7 billion in 2021, a 3.8-fold increase over 12 years.

In the downstream region of the YREB, Shanghai and Jiangsu have long been in a high–high cluster, mainly due to their status as one of the most developed regions in China with a large amount of manufacturing and processing industries. The transportation of raw materials and products in these areas consumes a considerable amount of energy and produces excessive carbon dioxide. Therefore, both regions have implemented a series of measures to improve green efficiency in transportation, such as promoting the use of new energy vehicles, constructing intelligent transportation systems, and optimizing traffic network planning. These efforts have led to reduced energy consumption and emissions, as well as improved transport efficiency and sustainability. The high–high clustering indicates that Shanghai and Jiangsu have significant advantages in GTE, serving as a model for other YREB regions to enhance their GTE. In the middle reaches, only Jiangxi exhibited high–high clustering from 2016 to 2018. Overall, the analysis of global and local spatial autocorrelation indicates a spatial clustering feature of GTE in the YREB from 2010 to 2021, with a notable positive spatial correlation.

4.3. Cold Spot/Hot Spot Analysis

On the basis of clustering and outlier analysis, Arcgis10.8 software was used to analyze hot spots in the YREB and visualize them (see Figure 10). The evolution of GTE cold hot spots in the YREB has the following characteristics: in general, the pattern of GTE cold hot spots in the middle reaches of the YREB is relatively stable and the change is relatively gentle. In particular, Hubei Province and Hunan Province have basically no change in the four stages, while the evolution of the cold and hot spots in the upstream and downstream regions is more prominent.

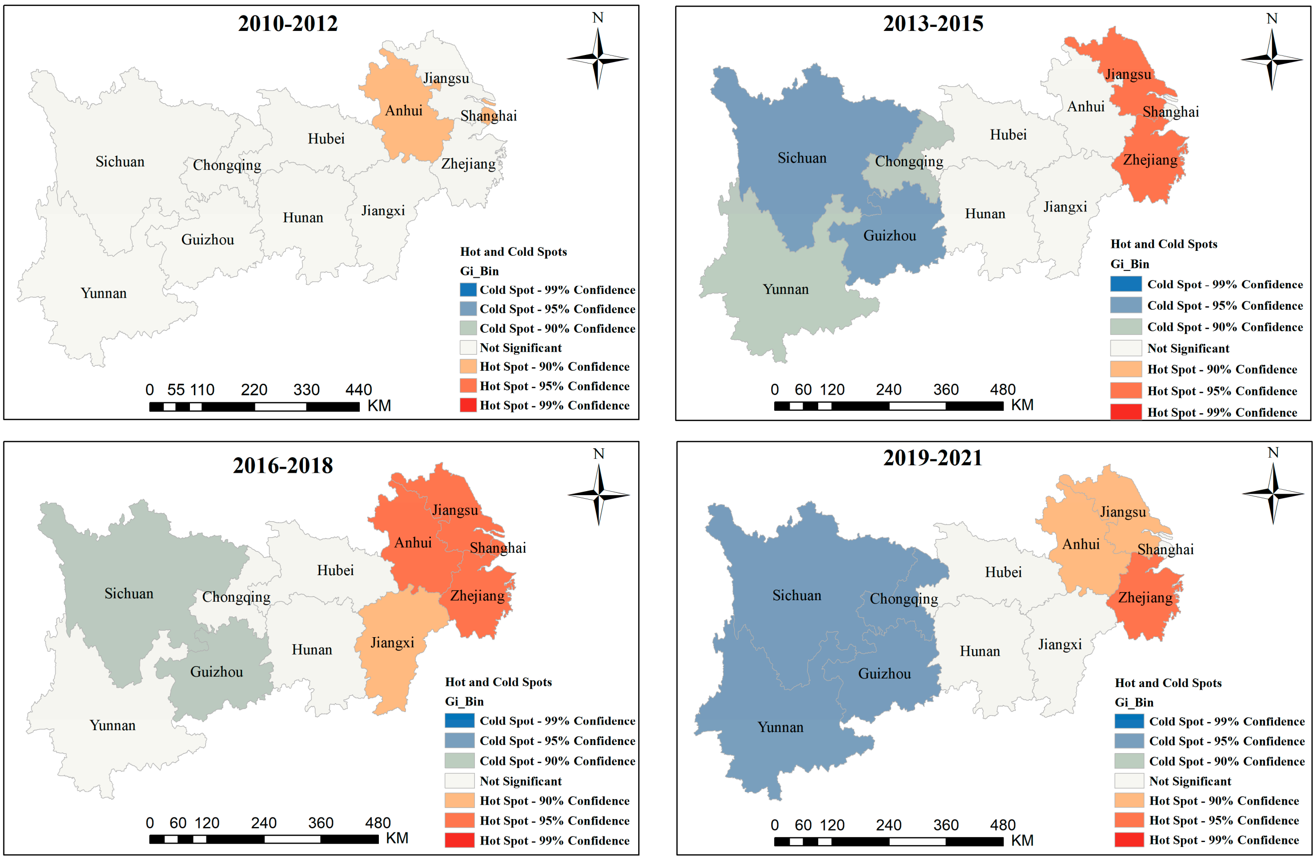

Figure 10. Evolution of the spatial distribution of cold and hot spots in transportation green efficiency in the YREB.

The upstream regions, characterized by challenging geographical conditions and a weak economic base, are situated in cold and sub-cold spots, whereas the hot spots are predominantly found in the more economically developed lower reaches of the Yangtze River with better transportation infrastructure. Specifically, the hot spots of GTE in the YREB consistently cluster in the lower reaches, with the middle reaches acting as transitional areas that develop in an east–west direction. This pronounced imbalance in spatial distribution is becoming increasingly apparent, indicating a growing disparity in transportation green efficiency within the YREB.

5. Conclusions and Policy Recommendations

Based on the calculation and analysis of transportation green efficiency in the YREB, this chapter proposes strategies and recommendations to enhance its green efficiency.

5.1. Conclusion Summary

This study establishes an evaluation index system tailored for regional transportation's green efficiency and introduces the PCA model to optimize this system. Utilizing input–output index data from 2010 to 2021 for 11 provinces and cities in the YREB, the paper calculates and discusses the spatial–temporal characteristics of transport green efficiency in the region. The study's innovative aspects are threefold: first, it integrates government-level capital input into the evaluation framework for regional transport green efficiency, enriching the understanding of regional transport output to include capital output alongside traditional transport output. Second, it analyzes the distribution characteristics of the transport industry's green efficiency in the YREB at both regional and provincial spatial levels. Finally, through a spatial statistical analysis model, the study further explores the spatial correlation of transport green efficiency in the YREB. These findings offer valuable insights for local governments to implement targeted measures for improving regional GTE. Based on the above analysis, the main research results can be summarized as follows:

(1) In terms of energy consumption and carbon emissions, Hunan, Hubei, Zhejiang, Sichuan, and Shanghai fall into the category of high energy consumption and low emission regions. Anhui, Guizhou, Yunnan, Jiangxi, and Chongqing are classified as low energy consumption and low emission areas. Jiangsu Province stands out as a region with high energy consumption and carbon emissions. This is largely due to its location in the lower reaches of the Yangtze River, near coastal areas, and its thriving international trade, which has driven the growth of its industrial and manufacturing sectors, leading to high levels of energy consumption and carbon emissions. It is worth noting that none of the provinces or cities fall into the category of low energy consumption and high emissions. This may be attributed to the Chinese government's efforts over the past decade to implement proactive emission reduction policies and promote the development of the clean energy industry;

(2) In terms of the economic input and output effect of transportation, Jiangsu and Zhejiang are the regions with high investment and high output, while Yunnan and Sichuan are the regions with high investment and low output. The main reason is that the terrain is complex and the construction of transportation infrastructure lags behind;

(3) At the regional scale, the overall GTE of the YREB exhibits a U-shaped trend. Initially, between 2010 and 2015, there was a decline in GTE, followed by a gradual recovery. Moreover, there are notable disparities in GTE among the upper, middle, and lower reaches, with a pattern of strength in the east and weakness in the west, specifically, downstream region > midstream region > upstream region;

(4) At the provincial level, Shanghai and Anhui have the highest GTE in the YREB, whereas Sichuan, Guizhou, Yunnan, and other provinces in the upper reaches exhibit lower efficiency. During the period from 2010 to 2021, there was a notable increase in both government and social capital investments in Sichuan Province. Substantial disparities exist in the GTE among provinces and cities;

(5) From a spatial correlation perspective, the GTE in various regions of the YREB exhibits significant spatial dependence, indicating clear spatial clustering characteristics. Provinces and cities with higher green efficiency tend to be geographically adjacent, as do those with lower green efficiency. Chongqing, Sichuan, Guizhou, and Yunnan in

the upper YREB consistently maintain a low–low clustering state, suggesting a strong spatial autocorrelation among these regions. Conversely, Shanghai and Jiangsu in the lower YREB consistently exhibit high–high clustering, indicating their high green efficiency, which could serve as a model for other regions. The spatial distribution of cold and hot spots in the middle reaches of the YREB remains relatively stable, with upstream areas generally in cold spots or sub-cold spots and hot spots primarily concentrated in downstream areas.

These findings highlight significant opportunities for improving green transportation in the YREB. The pronounced imbalance in green transportation efficiency, which appears to be worsening, underscores the need for targeted policies and measures to foster high-quality sustainable development in the regional transport industry.

5.2. Policy Recommendations

Based on the research findings outlined above, to enhance the high-quality development of the transportation industry in the YREB, this paper proposes the following recommendations, building upon existing policies:

(1) Tailored transport development policies should be implemented based on local circumstances. In regions with high green transport efficiency, such as the lower reaches of the Yangtze River, the focus should be on enhancing green efficiency by optimizing transportation modes and adopting green technologies. In areas like the middle reaches of the Yangtze River where efficiency is lower, efforts should concentrate on elevating the level of green transportation and enhancing efficiency through the development of green transport facilities. In the upper reaches of the Yangtze River where efficiency is comparatively lower, the emphasis should be on transportation infrastructure construction, with a focus on reducing the cost of infrastructure through thoughtful design [37];

(2) Pay attention to scientific and technological research and development, especially in the field of intelligent transportation technology, because advanced technology and equipment can ease traffic congestion and exhaust emissions. Therefore, we can rely on the existing technology and talent advantages of Shanghai Songjiang G60 Science and Technology Innovation Corridor to promote the research, development, and promotion of green transportation technology, promote the sharing of resources and technology, and promote cooperative innovation [38]. On the other hand, through joint research and development and the integration of scientific research resources between universities and high-tech enterprises, the cost of research and development can be reduced, the efficiency of research and development and the technical level can be improved, the transformation and application of green and other related scientific and technological achievements can be accelerated, and the implementation and promotion of green transportation technology can be promoted [39];

(3) It is necessary to adjust the energy structure of all provinces and cities in the YREB to improve energy efficiency. In regions with high energy consumption and emissions, such as Jiangsu Province, promoting energy structure adjustment and industrial transformation and upgrading is crucial. This includes developing and utilizing clean energy, optimizing industrial structures, and replacing fossil energy with cleaner alternatives. These measures can help to clean up the energy structure, thereby improving the region's GTE. For regions with high energy consumption and low emissions, like Hunan, Hubei, and Zhejiang, maintaining a low-energy consumption development mode is important [40]. Additionally, these regions should strengthen green transportation construction, increase the use of public transportation, promote energy-saving and environmentally friendly vehicles, and reduce transportation energy consumption. Regions with low energy consumption and emissions, such as Anhui, Guizhou, Yunnan, Jiangxi, and Chongqing, should focus on infrastructure construction, improving energy utilization efficiency, promoting green transportation development, and enhancing the overall GTE in the YREB;

(4) Optimize the investment structure of the transportation industry in the YREB. For regions with high investment and high output, such as Jiangsu and Zhejiang provinces, maintaining investment intensity and optimizing the investment structure is key. This includes increasing investment in green transportation projects. In regions with high investment and low output, such as Yunnan and Sichuan, there should be a focus on increasing investment and optimizing the investment structure. This involves prioritizing green transportation projects to improve investment efficiency;
(5) Enhance inter-regional cooperation within the YREB and facilitate the coordinated development of the green transportation industry. The research indicates that the transport industry's efficiency in one province impacts surrounding provinces. Therefore, considering the unequal development of the transport industry and significant differences in transport efficiency, the YREB should promote inter-provincial cooperation. Leveraging the spatial correlation characteristics of transport green efficiency should harness the positive influence of high-efficiency transport, encouraging provinces and cities with high transport green efficiency to share their experiences and technologies with those with lower efficiency. This will drive the green development of the transport industry in the surrounding areas;
(6) Establish and enhance the assessment mechanism for the green and sustainable development of the transport industry in the YREB. Utilizing the evaluation indicators for GTE in the region, third-party professional institutions should conduct regular assessments and inspections, rewarding provinces and cities that demonstrate improvement. For regions with lagging efficiency, interviews should be conducted and improvement plans developed. Additionally, the supervision system should be strengthened given the YREB's involvement in 11 provinces and cities. Improving monitoring capabilities and clarifying administrative supervision channels for all provinces and cities will ensure the fairness and effectiveness of supervision, facilitating its implementation.

Policymakers should also be aware of the challenges they may face in implementing these policies. On the one hand, while implementing differentiated transportation development policies tailored to local conditions may benefit most regions, it may also harm the interests of some economically and transportationally developed areas in the short term. Building an integrated transportation network often requires these areas to make more contributions and bear more responsibilities, which could be an obstacle to promoting cooperation among regions within the YREB. Furthermore, promoting the improvement in transportation and green efficiency in the YREB requires a large amount of funding, the sources of which are still uncertain. Finally, the YREB involves multiple administrative regions and stimulating the enthusiasm of each administrative region remains a major challenge. Therefore, policymakers need to adjust and optimize relevant policies more in line with the actual situation.

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References

1. Chen, J.; Liu, Z.; Mao, K. High-quality Development in the Chinese Path to Modernization: History, Achievements, and Prospects. *East China Econ. Manag.* **2023**, *37*, 1–16.
2. Zhao, C.; Jia, R.; Dong, K. How does smart transportation technology promote green total factor productivity? The case of China. *Res. Transp. Econ.* **2023**, *101*, 101353. [CrossRef]
3. Comprehensive Three-Dimensional Transportation Corridor Plan for the Yangtze River Economic Belt (2014–2020). *China Transp. Rev.* **2014**, 14–25.
4. Takayabu, H. CO_2 mitigation potentials in manufacturing sectors of 26 countries. *Energy Econ.* **2020**, *86*, 104634. [CrossRef]
5. Ma, Q.-F.; Jia, P.; Kuang, H.-B. Spatial Characteristics of Comprehensive Transportation Green Efficiency in China. *J. Transp. Syst. Eng. Inf. Technol.* **2022**, *22*, 300–308.
6. Ma, Q.; Jia, P.; Kuang, H. Green efficiency changes of comprehensive transportation in China: Technological change or technical efficiency change? *J. Clean. Prod.* **2021**, *304*, 127115. [CrossRef]
7. Lv, Y.; Fan, T.; Zhang, J. Spatiotemporal Characteristics and Influencing Factors of China's Transport Sector Carbon Emissions Efficiency. *Ecol. Econ.* **2023**, *39*, 13–22.
8. Ding, T.; Naiyu, Z. Spatial Relationship between Railway Transport Efficiency and Economic Development in the Yangtze River Economic Belt. *Railw. Transp. Econ.* **2023**, *45*, 63–67+122.
9. Zhou, Q.; Liang, X.; Huang, J.-S.; Wang, H.-P.; Mao, B.-H. Carbon Emission Efficiency and Influencing Factors Analysis of Urban Rail Transits. *J. Transp. Syst. Eng. Inf. Technol.* **2023**, *23*, 30–38, 85.
10. Cao, B.R.; Deng, L.J. Influencing Factors of Logistics Industry Growth Efficiency in Yangtze River Economic Belt. *Econ. Geogr.* **2019**, *39*, 148–157.
11. Yuan, C.W.; Zhang, S.; Jiao, P.; Wu, D. Temporal and spatial variation and influencing factors research on total factor efficiency for transportation carbon emissions in China. *Resour. Sci.* **2017**, *39*, 687–697.
12. Beltrán-Esteve, M.; Picazo-Tadeo, A.J. Assessing environmental performance trends in the transport industry: Eco-innovation or catching-up? *Energy Econ.* **2015**, *51*, 570–580. [CrossRef]
13. Zheng, Y.; Ba, W.-T.; Xiao, Y.-J. Dynamic Efficiency Measure in Yangtze River Delta Port Cluster Considering Carbon Emissions. *J. Transp. Syst. Eng. Inf. Technol.* **2023**, *23*, 34–46.
14. Jiang, H.; Ding, J. Port efficiency of eight cities along the Yangtze River in Jiangsu Province based on DEA game cross-effciency-SDM model. *J. Chongqing Jiaotong Univ. (Nat. Sci.)* **2022**, *41*, 56–61.
15. Wei, F.; Zhang, X.; Chu, J.; Yang, F.; Yuan, Z. Energy and environmental efficiency of China's transportation sectors considering CO_2 emission uncertainty. *Transp. Res. Part D Transp. Environ.* **2021**, *97*, 102955. [CrossRef]
16. Song, Y.; Li, J.; Wang, J.; Yang, G.; Chen, Z. Eco-efficiency of Chinese transportation industry: A DEA approach with non-discretionary input. *Socio-Econ. Plan. Sci.* **2022**, *84*, 101383. [CrossRef]
17. Kiani Mavi, R.; Fathi, A.; Farzipoor Saen, R.; Kiani Mavi, N. Eco-innovation in transportation industry: A double frontier common weights analysis with ideal point method for Malmquist productivity index. *Resour. Conserv. Recycl.* **2019**, *147*, 39–48. [CrossRef]
18. Li, F.; Ye, S.; Chevallier, J.; Zhang, J.; Kou, G. Provincial energy and environmental efficiency analysis of Chinese transportation industry with the fixed-sum carbon emission constraint. *Comput. Ind. Eng.* **2023**, *182*, 109393. [CrossRef]
19. Rehman, F.U.; Islam, M.M.; Miao, Q. Environmental sustainability via green transportation: A case of the top 10 energy transition nations. *Transp. Policy* **2023**, *137*, 32–44. [CrossRef]
20. Tone, K. A Slacks-Based Measure of Efficiency in Data Envelopment Analysis. *Eur. J. Oper. Res.* **2001**, *130*, 498–509.
21. Wang, Y. Research on the Spatiotemporal Characteristics and the Influencing Factors of Integrated Transportation Efficiency in Yangtze River Economic Belt. Master's Thesis, Wuhan University of Technology, Wuhan, China, 2021.
22. Li, H.; Calder, C.A.; Cressie, N. Beyond Moran's I: Testing for spatial dependence based on the spatial autoregressive model. *Geogr. Anal.* **2007**, *39*, 357–375. [CrossRef]
23. Duan, X.; Cen, Y.-Q.; Lu, A.-Q. DEA Model-Based Efficiency Analysis for Road Transport of China's 31 Provinces. *J. Transp. Syst. Eng. Inf. Technol.* **2011**, *11*, 25–29.
24. Chang, Y.; Zhang, N.; Danao, D.; Zhang, N. Environmental efficiency analysis of transportation system in China: A non-radial DEA approach. *Energy Policy* **2013**, *58*, 277–283. [CrossRef]
25. Cui, Q.; Li, Y. The evaluation of transportation energy efficiency: An application of three-stage virtual frontier DEA. *Transp. Res. Part D Transp. Environ.* **2014**, *29*, 1–11. [CrossRef]
26. Song, J.-N.; Wu, Q.-Q.; Sun, Q.-P.; Bao, X.; Du, K. SBM-undesirable Model-based Efficiency Evaluation for Integrated Transportation. *J. Transp. Syst. Eng. Inf. Technol.* **2015**, *15*, 32–38.
27. Song, M.; Zhang, G.; Zeng, W.; Liu, J.; Fang, K. Railway transportation and environmental efficiency in China. *Transp. Res. Part D Transp. Environ.* **2016**, *48*, 488–498. [CrossRef]
28. Zhang, H.; You, J. An Empirical Study of Transport Efficiency of Urban Rail Transit Based on Data Envelopment Analysis and Tobit Model. *J. Tongji Univ. (Nat. Sci.)* **2018**, *46*, 1306–1311.
29. Qipeng, S.; Xiaozhuang, G.; Wenjing, J.; Chao, W. Study on Efficiency Evaluation and Spatio-Temporal Evolution of Freight Transport in China. *J. Ind. Technol. Econ.* **2018**, *37*, 53–61.
30. He, Q.; Han, J.; Guan, D.; Mi, Z.; Zhao, H.; Zhang, Q. The comprehensive environmental efficiency of socioeconomic sectors in China: An analysis based on a non-separable bad output SBM. *J. Clean. Prod.* **2018**, *176*, 1091–1110. [CrossRef]

31. Song, M.; Chen, Y. The Impact of Comprehensive Transportation Efficiency on Economic Growth in Urban Agglomerations: A Comparative Study Based on the Yangtze River Delta and Guangdong-Hong Kong-Macao Greater Bay Area. *Urban. Probl.* **2019**, *45-53.1*.
32. Liu, J.; Yuan, C.; Li, X. The Environmental Assessment on Chinese Logistics Enterprises Based on Non-Radial DEA. *Energies* **2019**, *12*, 4760. [CrossRef]
33. Jia, P.; Hu, Y.; Yuan, S.; Kuang, H.B. A research on the comprehensive transportation efficiency and its spatial relevancy in China's provinces. *Sci. Res. Manag.* **2020**, *41*, 219–229.
34. Zhang, Y.; Jiang, L.; Shi, W. Exploring the growth-adjusted energy-emission efficiency of transportation industry in China. *Energy Econ.* **2020**, *90*, 104873. [CrossRef]
35. Zhang, S.-Q.; Wang, J.-W.; Zheng, W.-L. Spatio-temporal difference of transportation carbon emission and its influencing factors in China. *Acta Sci. Circumstantiae* **2017**, *37*, 4787–4797.
36. Feng, X. Analysis of Green Transportation Efficiency and Influencing Factors in the Yangtze River Economic Belt. Master's Thesis, Chongqing Jiaotong University, Chongqing, China, 2023.
37. Hah, K.J.; Pan, S.Y.; Lee, I.; Kim, H.; You, Z.; Zheng, J.M. Construction of the Three Gorges Dam and Prospect of Shipping on Chuan Jiang. *China Ship Surv.* **2001**.
38. Shah, K.J.; Pan, S.Y.; Lee, I.; Kim, H.; You, Z.; Zheng, J.M.; Chiang, P.C. Green transportation for sustainability: Review of current barriers, strategies, and innovative technologies. *J. Clean. Prod.* **2021**, *326*, 129392. [CrossRef]
39. Lu, M.; Xie, R.; Chen, P.; Zou, Y.; Tang, J. Green Transportation and Logistics Performance: An Improved Composite Index. *Sustainability* **2019**, *11*, 2976. [CrossRef]
40. Zhang, H.; Ke, J. An Intelligent Scheduling System and Hybrid Optimization Algorithm for Ship Locks of the Three Gorges Hub on the Yangtze River. *Mech. Syst. Signal Process.* **2024**, *208*, 110974. [CrossRef]