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Eco-Efficiency Evaluation of Integrated Transportation Hub Using Super-Efficiency EBM Model and Tobit Regressive Analysis – Case Study in China

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ABSTRACT

The transportation industry is a key area for ecological civilisation construction and low-carbon development. As the core support of the national integrated transportation system, the ecological development level of integrated transportation hub (ITH) is crucial for enhancing the sustainable development capacity of the national integrated transportation. An eco-efficiency evaluation index system of ITH is established in this study and the eco-efficiencies of twenty international ITHs in China are comprehensively evaluated based on the super-efficient epsilon-based measure (EBM) model. Then the panel Tobit regression model is adopted to analyse the influencing factors of eco-efficiency. The results show that the average eco-efficiency of ITHs in China during 2011–2021 declines first and then rises, with a relatively high level overall but not efficient yet, and there is an obvious gradient distribution characteristic in all eco-efficiencies. Among them, Guangzhou ranks first, followed by Haikou, and Harbin ranks last. It is found that integrated transportation efficiency, urban green coverage, level of opening-up and economic development improve eco-efficiency significantly, while urbanisation rate, industrial structure and technology input have a negative impact. The results are consistent with the actual situation, verifying the practicality of models, and can be used to promote the sustainable development of integrated transportation.

KEYWORDS

integrated transportation hub; eco-efficiency; super-efficient EBM model; Tobit regression model.

1. INTRODUCTION

Currently, the global climate crisis caused by greenhouse gas emissions is becoming increasingly severe and has attracted widespread attention from the international community. Ecological transportation is a strong support and guarantee for the sustainable development of the economy and society, and also an important field for achieving "dual-carbon" strategic goals. Compared with traditional transportation, ecological transportation places more emphasis on the coordinated development of transportation, nature, society and economy. Therefore, the development of ecological transportation is an inevitable choice for China to respond to climate change and promote harmony between humans and nature within the framework of sustainable development. Over the years, China has been committed to building a green and low-carbon national integrated transportation system where transportation construction coexists with social environment. As the core foundation of the national integrated transportation system, the ecological development level of integrated transportation hub (ITH) directly affects the green development quality of the entire system, which is crucial to enhance the sustainable development capacity of national integrated transportation. So, what is the current situation and trend of ecological development in terms of China's ITHs? What are the effects of driving factors? These issues are worth exploring in depth. Therefore, timely assessment of the eco-efficiency and characteristics of China's ITHs under resource and environmental constraints, revealing the factors influencing on the eco-efficiency of ITHs, is of great significance for clarifying the problems in the sustainable development process of the current integrated transportation system and alleviating ecological pressure.

Transportation efficiency is the ratio between effective output and resource input in transportation activities, reflecting the operation status and development potential of the transportation system [1]. The level of transportation efficiency is not only related to whether resources and energy can be efficiently utilised but also to whether the entire transportation system can achieve sustainable development [2]. The study of transportation efficiency began in the 1970s, with researchers initially measuring and analysing the efficiency of urban public transportation [3]. Subsequently, the research scope expanded to include other modes of transportation such as railway [4], aviation [5], waterway [6] and highway [7]. In the 1980s, some countries, including the United States, France and the United Kingdom, began to focus on stock optimisation in transportation infrastructure construction, improving the integrated transportation system through the integration-substitution-expansion of single transportation modes [8]. Relevant studies mainly focused on policy adjustments and technology integration relating to the relationship between the "new" and the "old" [9, 10]. In 1991, the Intermodal Surface Transportation Efficiency Act (ISTEA) in the United States defined integrated transportation efficiency as "maximizing the benefits of transportation efficiency based on existing infrastructure to meet the needs of socio-economic development" [11]. Since then, integrated transportation and its efficiency issues have gradually attracted the attention of government departments and scholars in various countries. This marks a shift from single transportation mode to integrated planning layout. In the early research on integrated transportation efficiency, the focus was mostly on measuring urban integrated transportation [12]. Based on this, scholars further explored the efficiency of integrated transportation at the regional level [13, 14] or national level [15].

To meet the research needs of multi-level transportation efficiency issues, diversified measurement and evaluation methods have emerged, and related studies have shown two development trends. The first trend is that frontier efficiency analysis is mainly used as a measurement model, and the parameter frontier analysis method is gradually being replaced by non-parametric frontier analysis method. A few researchers have chosen stochastic frontier analysis (SFA) from the former to measure transportation efficiency [16]; the data envelopment analysis (DEA) in the latter is the most popular model, which is widely accepted due to its advantage in dealing with multiple inputs and outputs. So far, the study on measuring transportation efficiency using the traditional DEA method is quite mature [17–19]. In order to improve the accuracy and practicality of measurement results, more and more scholars have applied the DEA advanced models, such as multi-stage DEA model [20], slacks-based measure (SBM) model [21–23], epsilon-based measure (EBM) model [24], etc. The second trend is the multiple selection of input-output indicators for measurement. It has evolved from considering only desirable outputs to considering both desirable outputs and undesirable outputs, introducing transportation carbon emissions [25] or other social and environmental indicators [26] as undesirable outputs. Especially in recent years, with the increasing prominence of environmental issues and the integration of sustainable development concepts into various fields, the academic community has gradually focused on the sustainable development capabilities of transportation, and has begun to widely use models that take into account the undesirable factors to study the ecological efficiency, energy efficiency and carbon dioxide emission efficiency of integrated transportation in various countries. Leal et al. [27] conducted DEA analysis on the eco-efficiency of transportation sectors in Brazil. Egilmez et al. [28] assessed the efficiency of carbon emissions and energy consumption in transportation process of the manufacturing industry of the United States. Lyovin et al. [29] discussed the evaluation criteria for the energy efficiency of Russia's integrated transportation system. Ma et al. [30, 31] measured the green efficiency of integrated transportation of 30 provinces in China. Hussain et al. used the SBM model and windows analysis to estimate the sustainable transport efficiency of 35 OECD countries, indicating that socioeconomic factors have a remarkable impact on sustainable transport efficiency [32], and they also verified that transport-related climate change mitigation technology has a remarkable impact on efficiency levels [33]. Akbar et al. [34] employed the SBM model for bad output to assess the transport energy efficiency of 19 Belt and Road countries.

Generally, studies on the theory and methods of integrated transportation eco-efficiency have generally made substantial achievements, which can provide available references for the present paper. However, some deficiencies still exist for further research, such as the following aspects. (1) In terms of research level, existing literature only evaluates eco-efficiency of a country or region's integrated transportation sector at the macro level, but has not conducted research on cities at the micro level. In fact, different cities have differences in the ecological space organisation of integrated transportation. Especially for cities located at different hub positions, due to the significant personalised differences in their transportation characteristics, the ecological and environmental problems generated are also different. Therefore, when evaluating the eco-efficiency of different level hubs (i.e. cities), the corresponding indicator systems should be set up to identify the root causes of their respective problems and provide solutions according to the situation. (2) In terms of research methods, most literature uses the DEA method for quantitative measurement, but this method does not include relaxation variables in the measurement of inefficiency, and does not consider the "undesirable" output and overestimates the actual efficiency value. To improve measurement accuracy, many scholars have adopted the undesirable output SBM model based on relaxed variables to calculate efficiency values, but this model cannot handle situations where input and output variables have both radial and non-radial characteristics. The EBM model considers both desirable and undesirable output scenarios and is compatible with both radial and non-radial slack variables. Combining the model with the super-efficiency model can further distinguish effective decision-making units with the efficiency value of 1, which can accurately measure the level of eco-efficiency. However, there is currently no literature on using the super-efficient EBM model to measure the eco-efficiency of integrated transportation hubs, and there is even no research on analysing its spatiotemporal evolution patterns and influencing factors based on it.

In view of the above analysis, the purpose of the study is to analyse the eco-efficiency development characteristics and influencing factors of ITHs at the urban level, and explore the overall development level of a country's integrated transportation hubs, further providing decision-making support for achieving sustainable development of national integrated transportation system. Specifically, the research process is to first use the decision-making trial and evaluation laboratory (DEMATEL) method to construct an indicator system that conforms to the characteristics of ITH. Secondly, a super-efficient EBM model considering undesirable outputs is used to calculate the eco-efficiency of twenty international ITHs in China. Then, the kernel density estimation method and standard deviation ellipse method are used to analyse the spatiotemporal evolution characteristics of eco-efficiency. Finally, the panel Tobit model is used to reveal the main factors affecting the development of eco-efficiency.

The rest of the paper is organised as follows: Section 2 introduces the concept and connotation of ITH and establishes an evaluation index system for the eco-efficiency of ITH. Section 3 explains the evaluation and analysis methods. Section 4 is the empirical results and discussion. Section 5 provides the conclusions.

2. CONCEPTIONS AND EVALUATION SYSTEM

2.1 Definition of relevant concepts

The transportation industry, as the fundamental industry of the national economy, is crucial for the development of the entire national economy and society. From the development practice of transportation industry in various countries, the development of integrated transportation system is a new trend and direction for modern transportation industry [35], and also a new model for the development of transportation industry in various countries around the world [36, 37]. The integrated transportation hub is the main body of the construction and development of integrated transportation system, and the spatial carrier for efficient connection and integrated organisation of various transportation modes. It plays an important role in promoting the integration of various transportation modes, adjusting transportation structures and promoting the construction of modern industrial systems. Regarding the conception of ITHs, there is currently no clear definition in academic fields, so in this paper ITHs are defined as node cities serving for the regional or national transportation networks, which are passenger and cargo transfer centres for integrated development of various modes of transportation with connectivity. Three main contents of integrated development are the coordinated development among all modes of transportation, the integration of the transportation industry with other industries and the overall coordination between integrated transportation hub and transportation corridor. ITHs can be classified into three types of international, national and regional hubs according to service scope and target, and each type of hub processes distinct transportation characteristics and functions. International ITHs focus on global connectivity and radiation levels, expanding diverse transportation network by land, sea and air, and serving as the international gateway. International port and station serve as the main operation location of international ITHs. Different hubs can build various ports and stations based on their featured modes of transportation, including international railway hubs and stations, international shipping hubs (port hubs) and international aviation hubs.

With the rapid development of the economy, the scale of the integrated transportation system is constantly expanding, and the transportation network is also constantly improving. However, at the same time, the negative impact on resources, environment and other aspects is also becoming increasingly serious. The current complex and severe transportation problems indicate that the traditional demand-oriented integrated transportation development model is no longer able to meet the green development goals. Therefore, it is urgent to find ways to achieve sustainable transportation construction. More attention has been paid to ecological transportation, leading to a lively discussion among many scholars [38]. Ecological transportation is an eco-friendly transportation system that is planned, constructed and managed following the principles of natural ecology, economy, ecology and human ecology. It represents an advanced stage in the development of integrated transportation system [39]. Different from the focus of green transportation [40] and sustainable transportation [41], ecological transportation is an important branch of ecology [42], emphasising the importance of ecological environment. Ecological transportation takes a strong initiative in not only paying attention to the impact on the ecological environment but also being able to spontaneously balance the relationship with the ecosystem, and has the function of improving and optimising the ecological environment. The implementation of a sustainable integrated transportation system needs to fully consider the carrying capacity of resources and environment, and build a true ecological system based on the coordination of transportation infrastructure and ecological space. Thus, it is an inevitable trend for future integrated transportation systems to achieve ecological development. Also, the ITHs will inevitably evolve along the ecological direction as the constituent elements of the system.

Eco-efficiency is an important indicator for evaluating the development level of ecological transportation, which was first proposed by Schaltegger and Stum [43]. Subsequently, the World Organisation for Economic Co-operation and Development (OECD) further defined it as the efficiency of utilising ecological resources to meet human needs, striving to minimise its environmental impact while promoting economic development [44]. Eco-efficiency provides new ideas for quantitatively analysing the input and output of economic development and ecological environment conditions, and measuring the synergistic development relationship between economic society and ecological environment. Abide by this idea, this paper defines the eco-efficiency of ITH as the degree to which certain costs are invested in the operation of ITH to meet integrated transportation needs as well as reducing environmental damage and resource consumption, within the framework of ecological transportation development. That is to say, the larger the transportation output of an ITH under the same input is and the smaller the impact on the environment and resources is, the higher eco-efficiency of the ITH becomes.

2.2 Explanation of research objects

This paper is to conduct a comprehensive evaluation of the eco-efficiency of ITHs in China. A total of 100 cities in China have been selected for the ITHs, with 20 cities positioned as international ITHs and 80 cities positioned as national ITHs, all of which have begun to demonstrate excellent hub function. Considering the differences of economic development and transportation level between each hub, only 20 international ITHs are selected for exploration and analysis in the paper, because they cover most of China's provinces and cities that play an important role in international transportation and foreign trade. They have relatively mature transportation development history and can precisely reflect the overall development features of China's ITHs. Meanwhile, these cities are also the areas with the most comprehensive collection of relevant data. The twenty international ITHs are Beijing, Tianjin, Shanghai, Nanjing, Hangzhou, Guangzhou, Shenzhen, Chengdu, Chongqing, Shenyang, Dalian, Harbin, Qingdao, Xiamen, Zhengzhou, Wuhan, Haikou, Kunming, Xi'an and Urumqi.

Beijing, Shanghai, Guangzhou and Shenzhen have always held a leading position in the development of transportation hubs in China. Tianjin is the traffic throat of North China, with a transportation network extending in all directions. Nanjing and Hangzhou, located in Eastern China, are transportation centres in the Yangtze River Delta region. Chengdu, Chongqing and Kunming are important transportation portals in the southwest region, with unique geographical locations and transportation advantages. Shenyang, Dalian and Harbin are located in Northeast China and have built complete integrated transportation networks. Qingdao is a coastal city in Eastern China, where integrated transportation pattern of "sea, land, air and rail" is becoming increasingly perfected. Xiamen is an important sea-land-air hub port in the southeast region. Zhengzhou and Wuhan are traditional transportation hubs in Central China. Haikou is the centre of highway and railway network within Hainan Province in Southern China. Xi'an and Urumqi are the two most important transportation hubs in the northwest region, with complete railway, highway and aviation networks.

Due to the relatively advanced development of integrated transportation in the above listed twenty hubs, it is feasible to better understand and learn from the overall eco-efficiency status of ITHs in China by analysing the eco-efficiency of each hub.

2.3 Establishment of evaluation index system

By comparing and analysing the existing literature about ecological transportation [45] and integrated transportation efficiency [13] evaluation index systems, and considering the characteristics of international ITH, a preliminary selection of fifteen evaluation indicators has been made from three aspects of economy, social and transportation (as seen in *Table 1*). Furthermore, the DEMATEL method is applied to identify key indicators. The DEMATEL method uses graph theory and matrix tools to analyse the logical relationships and direct influence relationships between the elements in the system [46]. It calculates the influence degree of each factor on other factors and the affected degree of it by other factors, as well as the centrality and causality of each factor, to finally identify the main factors in the system. MATLAB software is used in this paper to code the calculation for the direct influence matrix of evaluation indicators, and the results are shown in *Table 1*.

Centrality represents the position of a factor in the indicator system and the degree of its impact, which is obtained by adding the influence degree value of the factor to the affected degree value. The greater the centrality is, the more significant the role of the factor on eco-efficiency development of ITHs is. Causality represents the influenced degree of a factor on other factors, which is obtained by subtracting the affected degree value of the factor from the influence degree value. If the value of causality is greater than 0, it indicates that the factor has a significant impact on other factors and can be classified as a causal factor. If the degree of causality is less than 0, it indicates that the factor is greatly affected by other factors, and it can be classified as an outcome factor [46].

To visually compare the centrality and causality of factors, it is necessary to construct a centrality-causality quadrant diagram (as shown in *Figure 1*). This quadrant chart is divided into four quadrants with an average centrality value of 3.3 and a causal value of 0 as the centre, and with centrality and causality as the two dividing lines. Among them, the factors in the first quadrant have high centrality and high causality, so they can be taken as causal factors. The factors in the second quadrant have high causality but low centrality,

Table 1 – Calculation results of preliminary evaluation indicators using DEMATEL method

Evaluation aspect	Preliminary evaluation indicators	Affected degree	Influence degree	Centrality	Causality
Economy level	Urban GDP(F_1)	1.110	2.457	3.567	1.347
Social effect	Proportion of environmental governance investment(F_2)	1.663	0.851	2.514	-0.812
	Urban green coverage (F_3)	1.887	2.275	4.162	0.388
	Integrated transportation passenger mileage (F_4)	1.667	2.846	4.513	1.179
	Integrated transportation freight mileage (F_5)	1.499	2.875	4.374	1.376
	CO_2 emissions from transportation(F_6)	2.326	1.964	4.290	-0.362
	PM2.5 (F_7)	2.446	1.875	4.321	-0.571
	Transportation energy consumption (F_8)	2.555	2.645	5.200	0.090
Transportation capacity	Total freight volume of integrated transportation (F9)	2.805	1.919	4.724	-0.886
	Total passenger volume of integrated transportation (F_{10})	2.503	1.968	4.471	-0.535
	Number of international transportation corridors (F_{11})	0.955	0.759	1.714	-0.196
	Rationality of integrated transportation network structure (F_{12})	0.626	0.251	0.877	-0.375
	Coverage of smart transportation (F_{13})	0.328	0.567	0.895	0.239
	Proportion of green transportation facilities (F_{14})	1.147	0.464	1.611	-0.683
	Level of integrated transportation management (F_{15})	0.994	0.644	1.638	-0.350

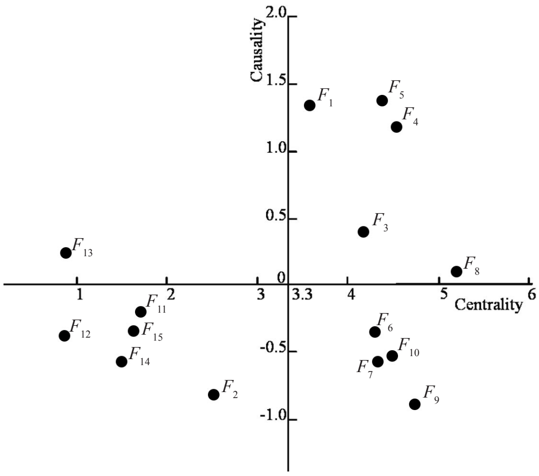

Figure 1 – Centrality and causality of all indicators

showing that their importance is slightly less. The centrality and causality of factors in the third quadrant are both low, so they can be considered relatively unimportant. The factors in the fourth quadrant have high centrality and low causality, so they can be taken as outcome factors. Therefore, there is a tendency to choose indicators from the first and fourth quadrants.

It can be observed in *Figure 1* that five indicators of F_1, F_3, F_4, F_5 and F_8 are located in the first quadrant with high centrality and high causality, which are the main factors affecting eco-efficiency of ITHs and can

Table 2 – Evaluation indicator system for the eco-efficiency of ITHs in China

Types of indicators	Indicator variable	Unit
Input indicators	Urban GDP (F_1)	108 yuan
	Urban green coverage (F_3)	percentage
	Integrated transportation passenger mileage (F_4)	km
	Integrated transportation freight mileage (F_5)	km
	Transportation energy consumption (F_8)	MT
Desired output indicators	Total freight volume of integrated transportation (F_9)	MT
	Total passenger volume of integrated transportation (F_{10})	10^4 persons
Undesired output indicators	CO_2 emissions from transportation (F_6)	MT
	PM2.5 (F_7)	μm

be used as input indicators. Four indicators of F_6, F_7, F_9 and F_{10} are located in the fourth quadrant with high centrality and low causality. They are outcome factors that reflect the results of eco-efficiency and can be used as output indicators. Therefore, nine input and output indicators are ultimately selected in the paper to measure the eco-efficiency of ITHs and establish an evaluation indicator system (as shown in *Table 2*).

3. METHODS

3.1 Data description

The study area covers twenty ITHs in China from 2011 to 2021. Regarding the data source of indicators in *Table 2*, the data for each hub are mainly taken from "China Statistical Yearbook", "China Urban Statistical Yearbook", "China Energy Statistical Yearbook", as well as statistical bulletins on national economic and social development and relevant official websites of each city. For the four indicators of integrated transportation passenger and freight mileage, as well as total passenger and freight volume of integrated transportation, because there is no water transportation in some hubs, the corresponding indicator data of roads, railways and aviation are chosen for unifying the measurement calibre, and finally converted to the total volume of integrated transportation. The data of urban CO_2 emissions is sourced from the China Carbon Accounting Database, and based on the proportion of CO_2 emissions from urban transportation industry accounting for approximately 10% of urban CO_2 emissions [47], thus transportation CO_2 emissions of each city are calculated. Descriptive statistics of the data are presented in *Table 3*.

Table 3 – Descriptive statistics of the independent variables

Variables	N*	Min.	Max.	Mean	Std. dev.
F_1	220	761.76	43214.85	11620.11	8668.11
F_3	220	32.5	58.33	41.46	3.62
F_4	220	42.17	1151.68	327.01	250.49
F_5	220	82.18	4289.12	650.64	651.02
F_8	220	123.63	2618.69	565.15	466.67
F_9	220	8156	155211.9	41727.77	30215.35
F_{10}	220	3030	185011	27922.58	30298.47
F_6	220	40.95	2076.34	805.02	516.11
F_7	220	12	95.35	40.62	15.82

** N represents the sample size of each variable, which is the result of multiplying the number of research periods (11 years) and the number of research subjects (20 cities).*

3.2 Super-efficient EBM model

The traditional DEA model is a radial model, which conducts the improvement of ineffective decision-making units (DMUs) based on the assumption that inputs or outputs proportionally change. However, when there is excessive inputs or insufficient outputs, that is, there is nonzero slack in inputs or outputs, the radial DEA model neglects to improve the slack, resulting in biased calculation results. In order to overcome the above explained problems, Tone [48] proposed the SBM model in 2001. This model improves the non-radial variation between inputs and outputs, by adding non-radial slack variables to avoid the assumption of proportional change, and incorporates undesirable output into the model, making the calculation results more appropriate. However, the SBM model misses the original proportion information of projection values on the efficiency frontier during the calculation process, which may cause distortion in results. Moreover, this method cannot handle situations with both radial and non-radial characteristics.

The relationship between inputs and outputs in the production process of the transportation industry is relatively complex. On the one hand, inputs such as transportation capital and labour may not necessarily vary proportionally with outputs in reality, indicating a non-radial relationship between inputs and outputs. On the other hand, there is a radial relationship between transportation energy input and carbon output, that is, consuming a certain proportion of energy will produce the same proportion of undesirable outputs such as CO_2. Therefore, the paper incorporates undesirable outputs into the calculation framework and uses the EBM model proposed by Tone et al. [49] to calculate the eco-efficiency of ITHs. The EBM model can effectively reflect the proportion information between objective values and actual values, and simultaneously handle the radial and non-radial slack changes between inputs and outputs, enhancing the relative comparability of DMUs. At present, it is gradually applied to efficiency measurement issues in various fields [50, 51]. It has been widely applied in studies on ecological efficiency, energy efficiency and other related areas. However, the conventional EBM model may encounter situations where the efficiency values of multiple DMUs are equal to 1, hence the super-efficiency EBM model is adopted to conduct further analysis of the differences between efficient evaluation units [52], in order to improve the evaluation accuracy.

The EBM model comprehensively evaluates efficiency values from three aspects, i.e. inputs, desirable outputs and undesirable outputs. Therefore, three constraint conditions are established accordingly to ensure that by increasing or reducing slack variables, the actual level of inputs, desirable outputs and undesirable outputs can reach the level of those on the optimal frontier (i.e. the efficient level), that is, obtaining the maximum desirable outputs and the minimum undesirable outputs with the least inputs. The slack variable represents the difference between the current efficiency value and the efficiency value at the optimal frontier of a DMU. Among them, the current efficiency value is obtained by linearly combining all inputs (or desirable outputs, undesirable outputs); the optimal frontier efficiency value is the inputs (or desirable outputs, undesirable outputs) at the efficient level. The introduction of slack variables into the objective function can solve the inefficiency problem caused by the variable slackness, compared to the efficiency at the optimal frontier.

$$\rho^* = \min \frac{\theta - \varepsilon_x \sum_{i=1}^{m} \frac{w_i^- s_i^-}{x_{ik}}}{\varphi + \varepsilon_y \sum_{r=1}^{n} \frac{w_r^+ s_r^+}{y_{nk}} + \varepsilon_b \sum_{p=1}^{q} \frac{w_p^{b-} s_p^{b-}}{b_{pk}}}$$

$$\begin{aligned} &\text{s.t.} \\ &\sum_{j=1, j \neq j_0}^{k} \lambda_j X + s_i^- = \theta x_{ik} \, (i = 1,2,3,\ldots,m) \\ &\sum_{j=1, j \neq j_0}^{k} \lambda_j Y - s_i^- = \varphi y_{rk} \, (r = 1,2,3,\ldots,n) \\ &\sum_{p=1}^{n} \lambda_j B + s_p^{b-} = \varphi b_{pk} \, (p = 1,2,3,\ldots,q) \\ &\lambda_i \geq 0, \;\; s_i^-, s_r^+, s_p^{b-} \geq 0 \end{aligned} \tag{1}$$

Suppose there are t DMUs expressed as DMU_k (k=1,2,...,t). Each DMU_k has m types of inputs x_{ik} (i=1,2,...,m), n types of desirable outputs y_{rk} (r=1,2,...,n) and q types of undesirable outputs b_{pk} (p=1,2,...,q). So, the vectors for the inputs, desirable outputs and undesirable outputs can be represented as

$X=[x_1,x_2,...,x_t]\in R^{q\times t}$, $Y=[y_1,y_2,...,y_t]\in R^{q\times t}$, and $B=[b_1,b_2,...,b_t]\in R^{q\times t}$, respectively. The super-efficiency EBM model with undesirable outputs is expressed by *Equation 1*, where ρ^* is the value of eco-efficiency; φ is the output expansion ratio; θ is the planning parameter of the radial part; ε_x, ε_y, ε_b are key parameters of the non-radial part and $0\leq\varepsilon\leq 1$; s_i^- s_r^+ and s_p^{b-} are respectively the slack variables of inputs, desirable outputs and undesirable outputs; w_i^-, w_r^+, w_p^{b-} represent the weights of inputs, desirable outputs and undesirable outputs respectively and $\sum w=1(w\geq 0)$; λ_j represents the linear combination coefficient.

The judgment criteria of efficiency status are as follows. If the value of ρ^* is less than 1, it indicates that DMU_k is in an inefficient state; if the value of ρ^* is greater than or equal to 1, it indicates that DMU_k has reached an efficient state, and the larger the value of ρ^* is, the higher the level of eco-efficiency is.

3.3 Panel Tobit regressive model

Due to the truncated nature of the calculated eco-efficiency values, the dependent variable is limited and exhibits a discrete distribution. In order to avoid estimation bias, the panel Tobit regressive model [53] is selected to analyse the factors influencing eco-efficiency of ITH. The model expression is as follows:

$$Y_{it}=\alpha_i+\beta_1 x_{1it}+\beta_2 x_{2it}+\beta_3 x_{3it}+\cdots+\beta_n x_{nit}+\varepsilon_{it} \tag{2}$$

where Y_{it} represents the eco-efficiency of the ith hub in the tth year (i=1,2,3,…,20; t=1,2,3,…,11); $x_1,x_2,\dots,x_n$ represent influencing factors; $\beta_1,\beta_1,\dots,\beta_n$ represent the coefficients of influencing factors, reflecting the influence level of each influencing factor on the eco-efficiency of ITH; α_i represents the intercept term, which accounts for the baseline level of eco-efficiency of each ITH; ε_{it} represents the random error term, which captures the unobserved factors or measurement errors that affect the eco-efficiency of the ITH in the ith hub and the tth year.

4. RESULTS AND DISCUSSION

4.1 Measurement of eco-efficiency

MAXDEA Ultra9 Software is applied to measure the specific results of the eco-efficiency of each ITH in *Equation 1*, and accordingly the average eco-efficiency value of all ITHs from 2011 to 2021 is ranked from high to low (as shown in *Table 4*).

According to *Table 4*, the average eco-efficiency value of all ITHs from 2011 to 2021 is 0.964, indicating a relatively high level of ecological development of China's ITHs, but without reaching an optimal level. The average values of eco-efficiency of each hub ranged from 0.5 to 1.4, and that of nine hubs, including Guangzhou, Haikou, Beijing, Shenzhen, Shanghai, Chongqing, Kunming, Chengdu and Wuhan, have greater than 1, illustrating that these hubs have achieved an ideal input-output ratio in terms of transportation resources. On the other hand, Tianjin, Hangzhou, Nanjing, Dalian and Harbin have relatively lower levels, indicating that there is redundancy or insufficiency in the input and output of transportation resources, requiring the adjustments to ensure efficient utilisation of resources in these hubs.

Generally, the eco-efficiency of China's ITHs has showed a trend of initially decreasing and then increasing over the 11-year period. The average eco-efficiency went down year by year from 2012 to 2016 and decreased to the minimum of 0.837 in 2016. The reason is that since 2012, China has stepped into a new stage of accelerating the construction of a modern integrated transportation system, with significant advancements in transportation infrastructure such as railway, highway and civil aviation. However, this construction process inevitably led to increased consumption of natural resources and pollution of ecological environment, resulting in a significant decline in eco-efficiency. The eco-efficiency value fluctuated and increased from 2017 to 2021, reaching the maximum of 1.043 in 2021. The reason is that the Ministry of Transport of China formulated the strategy of green, circular and low-carbon development for the first time in 2013 and subsequently introduced a series of regulations, policies and standards aimed at promoting green development in the transportation industry comprehensively and nationwide. All hubs actively carried out energy-saving and

Table 4 – The eco-efficiency measurement results of ITHs in China

Hub	Year											Aver.*
	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	
Guangzhou	1.065	1.335	1.324	1.482	1.743	1.918	1.348	1.337	1.436	1.173	1.059	1.384
Haikou	1.025	0.995	0.841	1.286	1.240	1.455	1.476	1.467	1.376	1.639	1.967	1.342
Beijing	1.032	0.998	1.011	1.002	0.997	0.994	1.550	1.465	1.522	1.535	1.766	1.261
Shenzhen	1.139	1.139	1.146	1.125	1.049	1.200	1.252	1.383	1.264	1.239	1.153	1.190
Shanghai	1.172	1.135	1.981	1.066	1.007	0.990	1.079	1.114	1.147	1.184	1.039	1.174
Chongqing	1.660	1.402	1.424	1.136	1.258	0.672	1.032	1.025	1.010	0.907	0.742	1.115
Kunming	1.209	1.144	1.033	1.047	1.055	1.041	1.108	1.094	1.068	1.100	1.151	1.095
Chengdu	1.021	0.991	1.132	1.155	1.109	1.038	1.029	1.094	0.856	1.093	1.107	1.057
Wuhan	1.226	0.975	1.135	1.203	0.761	0.704	1.023	0.923	1.000	1.034	1.100	1.008
Xiamen	0.829	0.883	0.795	1.012	0.679	0.999	1.205	1.204	1.262	1.039	1.033	0.995
Xi'an	0.994	1.035	1.027	1.024	0.771	0.673	0.710	0.757	0.756	1.404	1.271	0.947
Urumqi	1.118	1.101	0.799	0.722	0.668	0.523	0.994	1.016	1.003	0.672	1.005	0.875
Qingdao	1.837	1.799	0.452	0.585	0.612	0.469	0.703	0.564	0.555	1.016	0.695	0.844
Zhengzhou	1.087	1.089	1.035	0.592	0.529	0.569	0.712	0.772	0.712	1.019	1.035	0.832
Shenyang	0.777	0.838	0.776	0.865	0.774	0.770	0.831	0.795	0.718	0.998	0.836	0.816
Tianjin	0.838	0.747	0.860	0.797	0.778	0.708	0.694	0.807	0.706	0.751	0.940	0.784
Hangzhou	1.005	1.175	0.817	0.657	0.608	0.706	0.557	0.510	0.566	0.735	0.615	0.723
Nanjing	0.722	0.704	0.748	0.567	0.529	0.525	0.566	0.604	0.726	0.993	0.989	0.698
Dalian	0.439	0.431	0.449	0.469	0.462	0.395	0.633	0.752	0.771	0.669	0.826	0.572
Harbin	0.898	0.879	0.625	0.447	0.442	0.386	0.529	0.502	0.506	0.493	0.540	0.568
Aver.*	1.055	1.040	0.971	0.912	0.854	0.837	0.952	0.959	0.948	1.035	1.043	0.964

** Aver. indicates the average value.*

emission reduction activities in transportation and achieved phased results in the following years, leading to an improvement in the eco-efficiency of hubs. Therefore, the calculated results of the model are consistent with the actual situation and the conclusion is reliable.

4.2 Analysis of eco-efficiency spatiotemporal evolution

Kernel density estimation is a non-parametric estimation method that transforms data of random variables into the form of a density curve. It can visually display overall information such as the number, position, height and curve tail of peaks [54]. A three-dimensional kernel density diagram is mapped by MATLAB to intuitively demonstrate the temporal characteristics of eco-efficiency of all ITHs (see *Figure 2*).

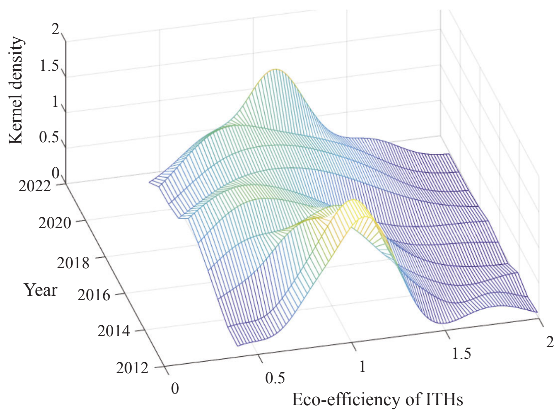

Figure 2 – Three-dimensional eco-efficiency kernel density curve of ITHs in China

In 2011–2021, the eco-efficiency kernel density curve of China's ITHs shifted leftward and then rightward, indicating that the overall eco-efficiency of China's ITHs showed a trend of first decreasing then increasing. The kernel density curve shows a single-peak distribution with no polarisation phenomenon among all eco-efficiencies. Taking 2017 as the dividing point, the height of the peak has declined and the peak width has become larger before 2017, representing that the eco-efficiency differences among the ITHs have become larger. After 2017, the peak height rose and the width narrowed, showing that the degree of difference in eco-efficiency has decreased and the spatial imbalance has improved. In recent years, due to resource competition among hubs with similar development levels, there is an obvious gradient feature in the eco-efficiency of China's ITHs. By observing the tail performance of each year, it can be seen that there is a clear rightward tail, indicating that the number of hubs with high eco-efficiency values is gradually increasing. Therefore, the eco-efficiency of China's ITHs exhibits an obvious "buckets effect" and the focus of future improvement should lie in the hubs with low eco-efficiency.

The standard deviation ellipse method is one of the classical methods for analysing the directional characteristics of spatial distribution. The size of the ellipse reflects the concentration level of the overall spatial pattern and the inclination angle (long axis) reflects the dominant direction of the pattern [55]. The standard deviation ellipse method is used in this study to analyse the spatial distribution pattern and transfer characteristics of eco-efficiency of China's ITHs. The spatial transfer map of eco-efficiency is shown as *Figure 3*.

The relevant data of ellipses were obtained through ARCGIS Software and attributes of standard deviation ellipses are listed in *Table 5*.

As shown in *Figure 3*, the spatial distribution of eco-efficiency of China's ITHs exhibited an overall Northeast-Southwest pattern from 2011 to 2021, with a tendency to shift towards the Northeast, which means that hubs located in Eastern and Northern China are well ecological developed. The gradually increasing rotation angle of the ellipse tended to be stable, showing that this spatial pattern has become relatively stable. The fluctuation in the transfer distance of the centre of gravity is significant, with the largest distance observed during the period of 2014–2017, indicating an imbalance in the regional development of eco-efficiency,

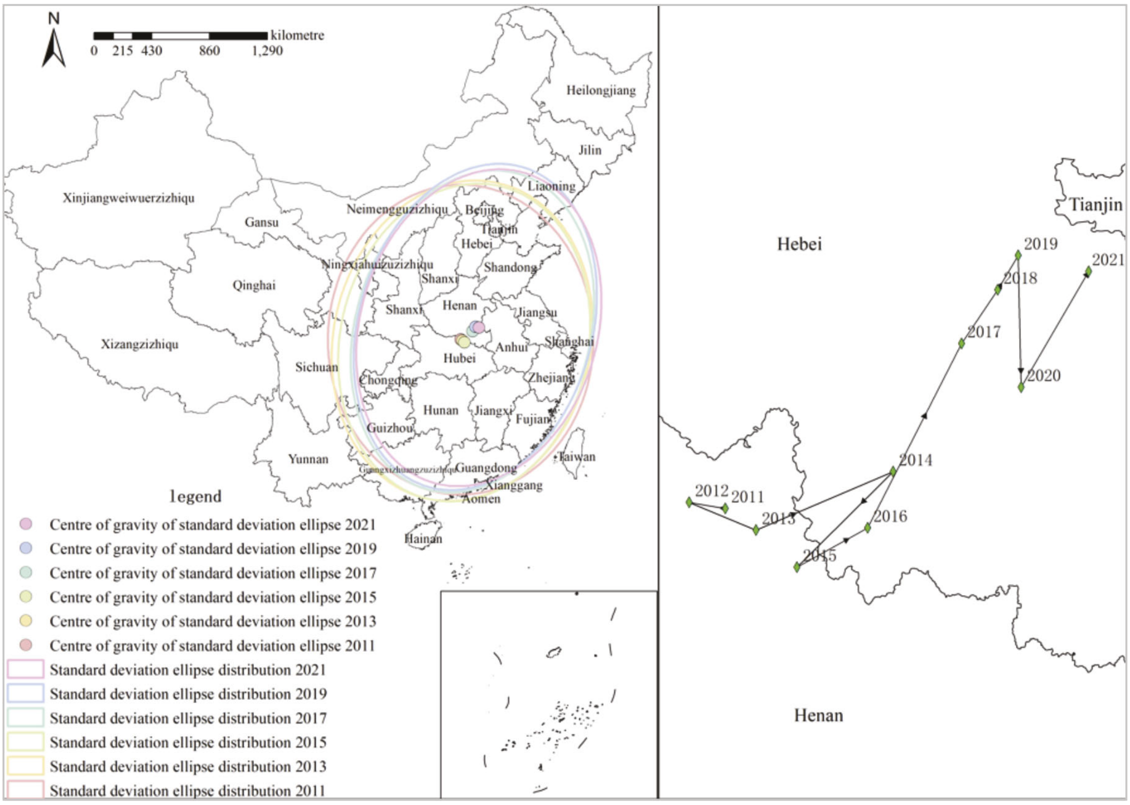

Figure 3 – Spatial transfer map of eco-efficiency of ITHs in China

Table 5 – Attributes of standard deviation ellipse

Year	Ellipse area [104 km^2]	Longitude* [°]	Latitude* [°]	Ellipse major axis [km]	Ellipse minor axis [km]	Ellipse rotation angle [°]	Transfer distance* [km]
2011	369.9039	111.3603	31.1331	1150.718	986.291	0.20936	-
2014	342.1459	112.1245	31.2164	1187.122	929.917	14.99596	64.236564
2017	329.2441	112.4914	31.6387	1220.279	871.039	15.51283	79.829243
2020	341.4745	112.6727	31.4636	1196.619	920.751	11.79006	47.353777
2021	327.1732	113.0201	31.8271	1199.695	880.507	15.64858	52.083501

** Longitude, latitude and transfer distance refer to those of centre of gravity in the ellipse.*

with significant differences in the east-west direction. The gradual decreasing of ellipse's area reflects that the spatial distribution of eco-efficiency is shifting from dispersion to concentration, showing a tendency to gather in the eastern and northern regions. The implementation of China's green and low-carbon development strategy in transportation has accelerated the change in eco-efficiency, with a clearer direction but more serious gradient phenomenon, hence attention should also be paid to the coordinated development among ITHs.

4.3 Analysis of factors influencing eco-efficiency

After investigating the current status and spatial imbalance of eco-efficiency of China's ITHs, further analysis of influencing factors is necessary to propose specific measures to improve the eco-efficiency level. Drawing on relevant research achievements, this study defines the eco-efficiency value of each ITH as the dependent variable and selects influencing factors from the perspectives of hub economy development, environmental protection and transportation development. Seven indicators are chosen as independent variables (as shown in *Table 6*).

Table 6 – Indicator system for factors influencing eco-efficiency of ITHs in China

Aspect	Independent variables	Variable interpretation	Unit
Economy development	Economic development level (X_1)	Per capita GDP	10^4 yuan
	Level of opening-up (X_2)	Total imports and exports	10^4 yuan
Environmental protection	Urban green coverage (X_3)	Urban Greenland area/urban area	%
	Level of environmental protection input (X_4)	Environmental protection fiscal expenditure/urban GDP	%
	Density of transportation carbon emissions (X_5)	Carbon emissions from transportation/total passenger and freight turnover	t/km
Transportation development	Level of scientific and technological input (X_6)	Science and technology fiscal expenditure/urban GDP	Percentage
	Integrated transportation efficiency (X_7)	Total passenger and freight turnover/urban GDP	km/10^4 yuan

We use a panel dataset of 1,540 observations from twenty ITHs in China during 2011–2021. The data is sourced from "China Statistical Yearbook", "China Urban Statistical Yearbook" and the official websites of each city. Among them, carbon emissions from transportation are estimated to account for approximately 10% of urban carbon emissions based on previous studies [56]. Descriptive statistics of the data are presented in *Table 7*.

Before conducting the Tobit regression analysis, it is necessary to test for multicollinearity among the selected independent variables. We use the variance inflation factor (VIF) to test for collinearity. General experience suggests that, if VIF < 10, it indicates the absence of multicollinearity among the independent variables [57]. The results of the multicollinearity test by STATA 16.0 Software are shown in *Table 8*.

Table 7 – Descriptive statistics of the independent variables

Variables	N*	Min.	Max.	Mean	Std. dev.
X_1	220	10.2176	12.1224	11.3041	0.3996
X_2	220	0.0040	43.9000	6.8897	6.3979
X_3	220	0.3250	0.5833	0.4146	0.0374
X_4	220	1.0099	6.1278	3.5621	1.0866
X_5	220	0.0356	2.5403	0.6282	0.5763
X_6	220	0.1883	6.6915	3.6359	1.3853
X_7	220	0.0263	1.7453	0.3433	0.3722

** N represents the sample size of each variable, which is the result of multiplying the number of research periods (11 years) and the number of research subjects (20 cities). The total of observations is the product of the sample size of each variable multiplied by the number of variables (7 variables).*

Table 8 – Results of VIF test

Variables	VIF	1/VIF
X_1	4.67	0.2143
X_2	3.23	0.3095
X_3	2.28	0.4390
X_4	1.55	0.6448
X_5	4.19	0.2388
X_6	1.03	0.9669
X_7	3.72	0.2689
Mean VIF	2.95	-

The mean value of VIF is 2.95, with a maximum value of 4.67. The VIF values of each independent variable are all below 5, with a mean value below 3, therefore it can be concluded that there is no multicollinearity, and the Tobit regression results can be used for analysis. STATA 16.0 Software is utilised in this paper to calculate *Equation 2* and perform LR test. The calculation results are shown in *Table 9*.

Table 9 – Results of Tobit regression

Variables	Coef.	Std. errs.	T	P>|z|
X_1	0.3578	0.1129	3.17	0.002***
X_2	0.4011	0.0167	2.40	0.016**
X_3	1.1217	0.6818	-4.43	0.100*
X_4	0.4812	0.0383	1.26	0.209
X_5	-1.1866	0.0796	-0.24	0.814
X_6	-0.1709	0.0383	1.65	0.000***
X_7	1.1655	0.0894	1.85	0.064*
_cons	-3.1721	1.1908	-2.66	0.008***
/sigma_u	0.1918	0.0421	4.56	0.000
/sigma_e	0.2205	0.0118	18.63	0.000
LR test of sigma_u=0:chibar2(01)=45.90			*Prob≥chibar2=0.000*	

, ** and * represent significance at the 10%, 5% and 1% level, respectively.*

The result that *Prob≥Chibar2*=0.000 has proved overall significance of regression model, and the well-fitting effect of regression coefficients. Among the seven independent variables, five of them have passed the significance test. The specific analysis of the influence of each variable on eco-efficiency of ITH is as follows.

The regression coefficient of economic development level is 0.3578, passing the significance test at the 1% level, which indicates a positive correlation with eco-efficiency, and thus the economic development of China's ITHs can promote the improvement of eco-efficiency. Eco-efficiency is the ratio of output to input and the optimal result should be to achieve more output with as little input as possible. In this sense hubs have effectively invested economic factors, that means the continuous investing in factors can also generate corresponding levels of benefits in ecological development, thereby advancing eco-efficiency. For this reason, ITHs should further expand effective investment in transportation, gather advantageous resources and efforts, promote efficient and green transportation modes and improve the efficiency and sustainable development quality of hub services with smaller investments, in order to enhance hub function.

The regression coefficient of level of opening-up is 0.4011, passing the significance test at the 5% level, which indicates a positive correlation with eco-efficiency. Transportation is crucial for a country's opening-up and cooperation with the outside world. In recent years, China has continuously increased its opening-up efforts and actively promoted international exchanges and cooperation in the field of transportation. Significant progress has been made in the joint construction of global sustainable transportation, participation in green transportation cooperation projects and the construction of multimodal cross-border transportation corridors. Taking advantage of this opportunity, various localities are going all out to promote the construction of low-carbon ITHs. By upgrading integrated hub systems and optimizing the combination of various transportation modes, the eco-environmental quality of ITHs has been significantly improved, greatly enhancing the level of hub's eco-efficiency.

The regression coefficient of urban green coverage is 1.1217, showing a positive correlation with eco-efficiency at a significance level of 10%. Practice has proved that good urban green level, especially road green level, can effectively improve the ecological environment and considerably contribute on the reduction of vehicle exhaust emissions for air purification. With the increasing attention to urban greening in China, ITHs are continuously enlarging local green area, gradually perfecting the ecosystem, which basically meets the development requirements of road construction. In the future, the expansion of green space will continue to be an important way to enhance eco-efficiency. It is worth noting that due to the current land shortage of urban road in most hubs, the effective utilisation of urban green rate should be implemented to achieve a balance between ITH construction and ecological environment.

Level of environmental protection input has a promoting effect on eco-efficiency, but it does not pass the significance test. Environmental protection and low-carbonisation of transportation vehicles are the most concerning issues around the world. The reason for failing to pass the test is that the current investment in transportation environmental protection falls behind the accumulation speed of transportation pollutants, and various input factors have not yet been fully utilised during the continual improvement on the layout of ITH. Owing to the potential and lagging characteristics of the promoting effect, hubs need to continue to make persistent efforts for environmental protection investment in transportation to steadily enhance the level of transportation eco-environmental protection in the future.

Densitsy of transportation carbon emissions shows a negative inhibitory effect on the eco-efficiency of ITHs, but the effect has not yet been shown. Density of transportation carbon emissions in the paper refers to the ratio of transportation carbon emissions to total passenger and freight turnover, which is the carbon emissions generated from the completion of unit turnover by ITH, reflecting the carbon emission efficiency of ITH. The reasons may lie in the following two aspects. China's ITHs are currently in a period of rapid development with the continuous expansion of transportation facilities, which has stimulated a significant increase in transportation demand. This is reflected in the fact that the growth rate of transportation volume is higher than that of carbon emissions. Therefore, the carbon emission density is relatively low and its effect on eco-efficiency is not significant enough. Meanwhile, in recent years, China's transportation industry has achieved significant results in green and low-carbon development, with a continuous decrease in carbon emissions per unit of GDP, which has to some extent weakened the negative impact of carbon emissions on eco-efficiency. In the future, ITHs should further improve their transportation organisation efficiencies through optimisation of transportation demand structure, strengthening of low-carbon transportation technology and adjustment of transportation energy structure, ensuring that carbon emissions do not lead to a significant decrease in eco-efficiency.

The regression coefficient of the level of scientific and technological input is -0.1709, representing an inhibitory effect on eco-efficiency at a significance level of 1%, which implies that more scientific and technological inputs do not necessarily lead to the higher eco-efficiency. The pursuit for investment scale but neglection of transformation and application of achievements will bring out inefficient investment reversely and hinder the application of modern technology and innovation of the emerging technology, resulting in the obstacles to eco-efficiency improvement. The current transformation rate of scientific and technological achievements in the transportation field of China is relatively low and the mismatch between scientific research achievements and market demand is one of the most important reasons. ITHs should accordingly seek out own transportation demand based on the development orientation of each hub, conduct the targeted investment and R&D in science and technology, pay attention to the matching between initial investment and output application, and ultimately form a virtuous interactive system for the transformation of technological achievements, providing a strong support for eco-efficiency improvement.

The regression coefficient of integrated transportation efficiency is 1.1655, showing a positive correlation with eco-efficiency at a significance level of 10%. Transportation efficiency reflects the effective utilisation of transportation resources. Over the years, China has regarded promoting green and low-carbon transformation as a strategic task for sustainable transportation development, continuously promoting the conservation, intensification and recycling of transportation resources. Especially with the construction of national integrated transportation system, ITHs have made significant progress in constructing green transportation infrastructure, optimising transportation structure and integrating transportation resource elements, and those lead to the growth of eco-efficiency level.

Based on the above stated findings, we can offer the following policy recommendations. ITHs are usually economically developed and have abundant transportation resources, with a high degree of agglomeration of various factors. In the process of promoting eco-hub construction, ITHs should guide more investment of various funds for transportation resources that meet ecological requirements, ensure that eco-hub development matches capital investment to maximise urban eco-efficiency. As an important node of national integrated transportation system, ITHs may generate more transportation pollution than that of general regions and the situation is also more complex. Therefore, it is necessary to strengthen the top-level design of eco-hub and establish integrated transportation planning from macro to specific levels in the view of ecology, that is, ITHs should actively participate in global cooperation and exchanges in the field of sustainable transportation and jointly build green and low-carbon transnational transportation corridors; should take the approaches of sharing green technologies, cross-regional intelligent transportation and establishing cooperation mechanisms to improve transportation resource utilisation; and should promote the coordinated development between hub construction and hub ecosystem, continuously increase investment in environmental protection input of transportation, and improve the transformation of transportation scientific and technological achievements guided by actual market demand. As a result, the function of ITH is strengthened at the international, intercity and hub levels, for the purpose of creating an ecological integrated transportation system by maximising and optimising the utilisation of limited space and transportation resources.

5. CONCLUSIONS

This paper proposes an evaluation method for the eco-efficiency of ITH based on super-efficiency EBM model, analyses factors influencing eco-efficiency through panel Tobit regressive model, and all the results are consistent with the actual situation. The following conclusions were drawn:

1) In 2011–2021, the average eco-efficiency levels of each international ITH ranged from 0.573 to 1.395, and half of hubs' values were greater than 1. The average eco-efficiency of all international ITHs in China was 0.974, indicating that China's ITHs developed well as a whole, but have not reached an efficient state yet. Due to the earlier acceleration of transportation infrastructure construction and gradual implementation of low-carbon transportation strategies later, the overall eco-efficiency average of ITHs in China declined first and then increased over the 11-year period. There was no polarisation phenomenon,

but the gradient distribution characteristics were obvious among ITHs. Among them, Guangzhou ranks first, followed by Haikou and Harbin ranks last.

2) The application of Tobit model to analyse factors influencing eco-efficiency of ITH reveals that the economic development level, urban green coverage, level of opening-up and integrated transportation efficiency had a significant positive impact on eco-efficiency. Among them, the greatest impact on eco-efficiency arose from integrated transportation efficiency, followed by urban green coverage, level of opening-up and economic development level. Level of scientific and technological input has an obvious negative impact on eco-efficiency of ITH, which currently hinders the ecological development of ITH. Level of environmental protection input and transportation carbon emission efficiency did not show a significant impact on eco-efficiency.
3) The limitation of the study is that the lack of some original data may affect calculation accuracy. For example, individual indicators data, such as freight mileage of railway transportation, was missing in some years, so the paper used the grey prediction model to predict and supplement data with characteristic of time series. The data on transportation carbon dioxide emissions cannot be directly obtained from relevant departments, so the paper used a proportional method approximately to estimate the data by multiplying the total urban carbon dioxide emissions by the proportion of transportation carbon dioxide emissions. These data processing processes may result in certain errors of calculation. Another limitation is the quantitative analysis on how each factor affects the eco-efficiency of ITH. Although the Tobit model has analysed the regression relationship between them, it cannot explore the dynamic impact mechanism of each factor on eco-efficiency and there is insufficient research on the impact trend. Therefore, further research should focus on studying the dynamic correlation mechanism between changes in various influencing factors and eco-efficiency. In addition, further cluster analysis or potential category analysis can also be conducted on ITHs according to the main factor indicators affecting eco-efficiency, in order to identity the indicator standards and their development laws that different categories of hubs should follow with the goal of achieving integrated transportation's ecological development, and then provide more specific improvement suggestions on corresponding indicators. Especially in tracking the impact by the introduction and promotion of relevant policies on the overall eco-efficiency of all hubs and that of each category of hubs, the regression model proposed in this study can be verified and supplemented.

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基于超效率EBM模型和Tobit回归分析的综合交通枢纽生态效率评价——以中国为例

摘要：

交通运输业是生态文明建设和低碳发展的关键领域。作为国家综合交通体系的核心支撑，综合交通枢纽的生态发展水平对提高国家综合交通的可持续发展能力至关重要。本研究建立了综合交通枢纽的生态效率评价指标体系，并基于超效率EBM模型对中国20个国际综合交通枢纽的生态效率进行评价，最后采用面板Tobit回归模型分析了生态效率的影响因素。研究结果表明，2011-2021年中国综合交通枢纽的平均生态效率先下降后上升，整体水平较高但尚未达到有效水平，各枢纽之间生态效率存在明显的梯度分布特征。其中，广州排名第一，海口排名第二，哈尔滨排名最后。综合交通效率、城市绿地覆盖率、对外开放水平和经济发展能够显著提高生态效率，而城市化率、产业结构和技术投入对生态效率产生负面影响。研究结果与实际相符，验证了模型的实用性，研究结论可用于促进综合交通可持续发展。

关键词：

综合交通枢纽；生态效率；超效率EBM模型；Tobit回归模型。