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Measuring environmental efficiency in transportation sector based on a meta-frontier SBM approach: focusing on the Yangtze River Economic Belt (YEB) and Beijing–Tianjin–Hebei (JingJinJi)

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Abstract

Purpose – The purpose of this study is to analyze the environmental efficiency level and trend of the transportation sector in the upper–mid–downstream of the Yangtze River Economic Belt and the JingJinJi region in China and assess the effectiveness of policies for protecting the low-carbon environment.

Design/methodology/approach – This study uses the meta-frontier slack-based measure (SBM) approach to evaluate environmental efficiency, which targets and classifies specific regions into regional groups. First, this study employs the SBM with the undesirable outputs to construct the environmental efficiency measurement models of the four regions under the meta-frontier and group frontiers, respectively. Then, this study uses the technology gap ratio to evaluate the gap between the group frontier and the meta-frontier.

Findings – The analysis reveals several key findings: (1) the JingJinJi region and the downstream of the YEB had achieved the overall optimal production technology in transportation than the other two regions; (2) significant technology gaps in environmental efficiency were observed among these four regions in China; and (3) the downstream region of the YEB exhibited the lowest levels of energy consumption and excessive CO_2 emissions.

Originality/value – To evaluate the differences in environmental efficiency resulting from regions and technological gaps in transportation, this study employs the meta-frontier model, which overcomes the limitation of traditional environmental efficiency methods. Furthermore, in the practical, the study provides the advantage of observing the disparities in transportation efficiency performed by the Yangtze River Economic Belt and the Beijing–Tianjin–Hebei regions.

Keywords Transportation environmental efficiency, Meta-frontier SBM, Yangtze River Economic Belt, Beijing–Tianjin–Hebei (JingJinJi)

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1. Introduction

Since adopting reform and opening-up policies, China has experienced rapid economic growth, becoming the world’s second-largest economy by GDP. However, achieving this feat

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necessitated adopting an unbalanced development strategy that focused on promoting economic growth in the eastern coastal region, where favorable geographical and economic development conditions exist. Despite this strategy's success in promoting economic growth, it has led to unintended side effects, such as wealth concentration in certain regions, and the initially expected spillover effect has not materialized. To address these issues, China has adopted more balanced and cooperative development strategies that promote regional development. Two representative examples of these strategies are the Yangtze River Economic Belt (YEB) Development Strategy and the Beijing–Tianjin–Hebei (JingJinJi) Region Coordinated Development Strategy.

The YEB leverages its unique geographical advantages to coordinate the development of China's eastern, central and western regions, as well as to promote the opening of coastal, river and border regions to the outside world. As a result, the YEB has become one of China's most economically intensive regions, exerting a significant influence on the global inland river economic belt. In November 2018, the State Council of China emphasized the importance of green development as the primary driving force for the coordinated development of all YEB regions, promoting high-quality development while avoiding excessive development. This underscores the country's commitment to promoting sustainable and environmentally friendly development in the YEB. The JingJinJi region, comprising Beijing (China's capital), Tianjin (the gateway to the metropolitan area) and Hebei Province (an economic hinterland for the metropolitan area), aims to extend its development to northern China through coordinated development strategies. Optimizing the allocation of resources in Beijing, Tianjin and Hebei promotes functional complementarity and industrial upgrading in the region, as well as economic development in the surrounding areas. As the third growth pole, this regional coordinated development has accelerated the national economy's growth. However, resource consumption and environmental pollution in the JingJinJi region remain significant obstacles to its joint development. Figure 1 displays the geographic distribution of provinces

Source(s): Figure created by authors

Figure 1. Geographic distribution of provinces and cities of the Yangtze River Economic Belt (YEB) and the Beijing–Tianjin–Hebei (JingJinJi) region

and cities in the YEB and the Beijing–Tianjin–Hebei (JingJinJi) region. The blue area on the map represents the JingJinJi region, while the red, green and yellow areas indicate the upstream, midstream and downstream regions of the YEB, respectively.

China has become the world's largest energy consumption (British Petroleum, 2022) and emitter of carbon dioxide country (World Bank Open Data, 2023), resulting in significant energy and environmental challenges in recent decades. In response, the country has pursued a "green and low-carbon development" path by implementing several new carbon and energy targets, particularly, in the transportation sector, based on 2010 emission levels (Na *et al.*, 2017). Despite the various policy measures implemented by the Chinese government, there remains substantial room for improvement in energy efficiency and carbon emissions (Feng and Wang, 2018; Wei *et al.*, 2021). Therefore, to address this issue, constructing a targeted efficiency assessment model for the Chinese energy–environment–transportation system and analyzing the problem can better serve as a basis for government decision-making, leading to improvements in energy consumption and carbon dioxide emissions. The YEB and the JingJinJi region have also implemented various policies to mitigate carbon dioxide emissions in the transportation sector.

Conducting an analysis to examine the variations in environmental transportation efficiency across regions can be instrumental in identifying the strengths and weaknesses of each region concerning its transportation planning. It can provide reference to governments and businesses for optimizing regional transportation systems, exploring multi-modal transportation and relevant policy-making. In addition, the evaluation could assist in formulating effective environmental protection measures to reduce the transportation industry's adverse effects on climate change.

Despite the transportation and environmental significance of the JingJinJi region and the YEB, there is a current dearth of comparative analysis concerning the environmental transportation efficiency across these four regions. Therefore, this study aims to analyze the environmental efficiency level and trend of the transportation sector in the upper-mid-downstream of the YEB and the JingJinJi region in China from 2004 to 2017 and assess the effectiveness of policies for protecting the low-carbon environment of the transportation sector. The study period covered 14 years, spanning from the 10th to the 13th of the Five-Year Plans in China, and during this period, several transportation-related carbon emission regulations and environmental protection policies were announced and implemented.

The paper is organized as follows. Section 2 reviews the literature on essential research viewpoints and approaches related to environmental efficiency. Section 3 proposes a slack-based measure (SBM) meta-frontier model to estimate the environmental efficiency of the YEB and JingJinJi region. Section 4 presents the empirical analysis based on this model. Finally, Section 5 provides conclusions and policy implications for China's sustainable transportation development.

2. Literature review

Environmental efficiency assessment is typically applied to measure the extent of synergy between the economy and the environment. In recent years, the data envelopment analysis (DEA) approach developed by Charnes *et al.* (1978) has gained significant prominence within the domain of energy and environmental efficiency research. For instance, the DEA was introduced to evaluate energy efficiency from the concept of disaggregate efficiency (Hu and Wang, 2006) and to analyze the energy and environmental efficiency of transportation sectors (Wei *et al.*, 2021). Furthermore, an SBM–DEA model was carried out to measure the environmental efficiency of the US transport sector (Park *et al.*, 2018), which showed that the state was supposed to substantially reduce carbon emissions to alleviate the environmental inefficiency issues. Some other research associated with transportation, such as passenger airlines, airports, global airlines, ports and railways (Merkert and Hensher, 2011; Lin and Hong, 2006; Scheraga, 2004; Liu and Hoon Lim, 2017; Song *et al.*, 2016), were found in the literature.

Concerning China's transportation environmental efficiency, the total-factor framework was one of the most favorable options for researchers. The total-factor DEA considers multiple input and output factors for a comprehensive evaluation of unit performance rather than focusing solely on a single input and output. For example, Zhou *et al.* (2013) applied output-oriented environmental DEA technology to analyze transportation environmental efficiency in China. Since the traditional DEA models with radial assumption adjust input or output variables at the equal ratio while projecting each DMU to the frontier line (Tone, 2001), a non-radial SBM–DEA model was extended to provide more comprehensive efficiency measures and the source of inefficiency by examining slack values (Chang *et al.*, 2013). For instance, Chen *et al.* (2019) employed non-radial DEA to evaluate the performance of the truck restriction policy in China, identifying excessive investment as a primary source of inefficiency from slack decomposition. In addition, to estimate the economic and environmental performances, many studies treated CO_2 emission as an undesirable output and captured the slack values of input and undesirable output as well as the shortfalls of desirable output. Zhou *et al.* (2014) performed an energy efficiency assessment of the regional transport sectors in China from 2003 to 2009. Not only that, Cui and Li (2014) designed a virtual frontier DEA to eliminate the effects of non-operational factors and strengthen the effectiveness of the ranking system. Na *et al.* (2017) measured China's container port environmental efficiency with CO_2 emissions using the inseparable input–output SBM method, which reflects the inseparable characteristics of inputs and outputs. Furthermore, Wang *et al.* (2020) employed a regression model to identify determinants of environmental efficiency in 18 Chinese ports, using estimated efficiency scores as dependent variables. However, traditional environmental efficiency methods in transportation studies did not account for the technology gap and regional heterogeneity, despite evident disparities in economic development and industrial structure across different regions (Wang *et al.*, 2013).

In order to address technology heterogeneity, O'Donnell *et al.* (2008) developed the meta-frontier concept. Unlike the traditional frontier, which is typically a generic standard applicable to all organizations or regions, the meta-frontier can accommodate the specific circumstances of different organizations or regions. In consideration of the energy consumption of regions, many meta-frontier DEA studies have evaluated energy efficiency and explored possible causes of inefficiency using technology gaps (Wang *et al.*, 2013; Lin and Zhao, 2016; Lin and Tian, 2017). Feng and Wang (2017) and Yao *et al.* (2015) considered energy efficiency and introduced carbon emission performance and reductions as analysis factors to provide relatively comprehensive policy implications. Concerning evaluating carbon emission performance, Wang *et al.* (2017) estimated China's provincial energy efficiencies based on the meta-frontier framework, classifying eight major economic regions. Li *et al.* (2020) measured CO_2 emission performance for Chinese port firms based on the meta-frontier model, which can consider the technology heterogeneity among enterprises. Specifically, they used a meta-frontier approach to divide port enterprises into two groups according to the firm size.

Given the research reviews above, we can find that the meta-frontier DEA approaches have been widely employed in environmental efficiency assessment, and the technology heterogeneity is a non-negligible factor. However, there is a lack of meta-frontier DEA research to estimate the transport sector's environmental efficiency in China. In this case, the difference in efficiency resulting from regional differences and technological gaps was hardly considered. Furthermore, from the description above, we know that transportation has become a significant development direction of Chinese cities in recent years, especially in

YEB and the JingJinJi region. However, Chinese policymakers currently lack information on the environmental performance of transportation levels, which brings potential risks in designing and implementing environmental protection policies. Hence, we selected the meta-frontier model to evaluate environmental efficiency, which targeted and classified specific regions into similar regional groups. In addition, we investigated the effect of carbon dioxide emissions on transportation environmental efficiency by setting each region's CO_2 emissions as undesirable output.

3. Methodology

The SBM approach introduced by Tone (2001) is a non-radial DEA model that directly shows the degree of the input excess and output shortage of decision-making units (DMUs) by utilizing slack variables (Wang *et al.*, 2017). Contrary to the radial DEA model that handles proportional changes of inputs/outputs, the SBM DEA model changes inputs or outputs using slacks (Tone, 2001). Additionally, the SBM DEA model is a non-oriented model, meaning that it does not need input- or output-oriented. However, the SBM DEA approach assumes that the production technology is the same among DMUs, which causes a biased evaluation of efficiency (Wang *et al.*, 2013; Zhang *et al.*, 2015a, b). Since unbalanced policy and development gaps among different regions in China have led to provincial differences in the production structure (Wang *et al.*, 2012), the meta-frontier approach has been widely employed in the literature. Similarly, this study adopted the method to construct frontiers for evaluating transportation efficiency and to identify technological gaps between different regions.

3.1 Production possibility set

We assumed there were N DMUs in the YEB and the JingJinJi region. In this research, all DMUs can be divided into H groups; and for each DMU M inputs were utilized to produce R desirable outputs and J undesirable outputs during the T production period.

Let $x \in R_+^m$, $y \in R_+^R$ and $b \in R_+^J$, representing the input, desirable output and undesirable output of the transportation sector, respectively, and defines the matrices $X = [x_1, \cdots, x_N] \in R^{M \times N}$, $Y = [y_1, \cdots, y_N] \in R^{R \times N}$ and $B = [b_1, \cdots, b_N] \in R^{J \times N}$, respectively. Let $X > 0, y^g > 0, y^b > 0$, and group h contains N^h DMUs. From the total factor theory, the production possibility set T^h under the group frontier of Group h is:

$$T^h = \{(x, y, b) : x\, can\, produce\, (y, b)\}$$

$$\begin{cases} \sum_{n=1}^{N} \lambda_n x_{mn} \leq x_m, & m = 1, \cdots, M \\ \sum_{n=1}^{N} \lambda_n y_{rn} \geq y_r, & r = 1, \cdots, R \\ \sum_{n=1}^{N} \lambda_n b_{jn} \leq b_j, & j = 1, \cdots, J \\ \lambda_n \geq 0, & n = 1, \cdots, N \end{cases} \tag{1}$$

The production possibility set under the meta-frontier can be employed as the envelope line of the production possibility set under the group frontier $T^{meta} = \{T^1 \cup T^2 \cup \cdots \cup T^H\}$, expressed as: $T^{meta} = \{(x, y, b) : x\, can\, produce\, (y, b)\}$

$$\begin{cases} \sum_{h=1}^{H}\sum_{n=1}^{N^h}\lambda_h^h x_{mn} \leq x_m, & m = 1,\cdots,M \\ \sum_{h=1}^{H}\sum_{n=1}^{N^h}\lambda_h^h y_{rn} \geq y_r, & r = 1,\cdots,R \\ \sum_{h=1}^{H}\sum_{n=1}^{N^h}\lambda_h^h b_{jn} \leq b_j, & j = 1,\cdots,J \\ \lambda_h^h \geq 0, n = 1,\cdots,N^h, & h = 1,\cdots,H \end{cases} \tag{2}$$

3.2 Meta-frontier SBM

In this research, the SBM with undesirable outputs was used to construct the efficiency measurement models under the meta-frontier and group frontiers, respectively. Meta-frontier DEA divides the DMUs into h(>1) groups and makes sub-production possibilities of groups, which can consider different production opportunities of DMUs in different industries, regions and/or countries. Based on Formulas (1) and (2), the group frontier SBM of Group *h* can be expressed as follows:

$$\rho^* = min\frac{1-\frac{1}{\mathrm{M}}\sum\limits_{m=1}^{M}\frac{s_{m0}^x}{x_{m0}}}{1+\frac{1}{\mathrm{R+J}}\left(\sum\limits_{r=1}^{R}\frac{s_{r0}^y}{y_{r0}}+\sum\limits_{j=1}^{J}\frac{s_{j0}^b}{b_{j0}}\right)}$$

$$S.T.$$

$$\begin{aligned} &\sum_{n=1}^{N^h}\lambda_n x_{mn} + s_{m0}^x = x_{m0} \\ &\sum_{n=1}^{N^h}\lambda_n y_{rn} - s_{r0}^y = y_{r0} \\ &\sum_{n=1}^{N^h}\lambda_n b_{jn} + s_{j0}^b = b_{j0} \\ &s_{m0}^x,\ s_{r0}^y, s_{j0}^b, \lambda_n \geq 0 \end{aligned} \tag{3}$$

The meta-frontier SBM of Group *h* can be expressed as follows:

$$\rho^{meta} = min\frac{1-\frac{1}{\mathrm{M}}\sum\limits_{m=1}^{M}\frac{s_{m0}^x}{x_{m0}}}{1+\frac{1}{\mathrm{R+J}}\left(\sum\limits_{r=1}^{R}\frac{s_{r0}^y}{y_{r0}}+\sum\limits_{j=1}^{J}\frac{s_{j0}^b}{b_{j0}}\right)}$$

$$S.T.$$

$$
\begin{aligned}
&\sum_{h=1}^{H}\sum_{n=1}^{N^h}\lambda_n^h x_{mn} + s_{m0}^x = x_{m0}\\
&\sum_{h=1}^{H}\sum_{n=1}^{N^h}\lambda_n^h y_{rn} - s_{r0}^y = y_{r0}\\
&\sum_{h=1}^{H}\sum_{n=1}^{N^h}\lambda_n^h b_{jn} + s_{j0}^b = b_{j0}\\
&s_{m0}^x,\ s_{r0}^y, s_{j0}^b, \lambda_n \geq 0
\end{aligned}
\tag{4}
$$

In equation (3) and (4), s_{m0}^x, s_{r0}^y and s_{j0}^b, respectively, represent the slack variables of input, "good" output and "bad" output. If $\rho = 1$ and $s_{m0}^x = s_{r0}^y = s_{j0}^b = 0$, the DMU is SBM-efficient (Tone, 2003).

3.3 Technical gap ratio

To evaluate the gap between the group frontier and the meta-frontier, the technology gap ratio (TGR_n^h) of environmental efficiency for DMU_n was constructed as shown in Eq. (5) (O'Donnell *et al.*, 2008).

$$TGR_n^h = \frac{MEE_n^h}{GEE_n^h} \tag{5}$$

In addition, the average technology gap ratio of the k^{th} group is calculated by Eq. (6).

$$TGR^k = \frac{\sum_{n=1}^{N_k} TGR_n^h}{N_k} \tag{6}$$

TGR can measure how close the technology within a certain group-frontier is to the meta-frontier technology level. As the meta-frontier is enveloped in the K group frontiers, $MEE \leq GEE$ always holds. Thus, the value of TGR is between 0 and 1. The closer the TGR is to 1, the smaller the technology heterogeneity of the production system, which means that the environmental efficiency of the group frontier is closer to that of the meta-frontier. On the other hand, if TGR is closer to 0, the technology heterogeneity is more significant, meaning a bigger gap between the environmental efficiency of the group frontier and meta-frontier.

4. Empirical analysis

In this section, we adopted the meta-frontier SBM approach to estimate the environmental efficiency of the JingJinJi region and the YEB from 2004 to 2017. First, we collected inputs, desirable and undesirable outputs data described in our framework, which consisted of 14 provinces and cities in the YEB and 3 in the JingJinJi region. The provinces and cities in the YEB were then divided into upper, mid and downstream parts. The upstream of the YEB comprises Sichuan, Chongqing, Yunnan and Guizhou Province. The midstream consists of Hubei, Hunan and Jiangxi Provinces, while the downstream comprises Shanghai, Zhejiang, Jiangsu and Anhui Provinces. The JingJinJi region comprises Beijing, Tianjin and Hebei provinces.

4.1 Data

We assumed that the production model involved four kinds of input, three kinds of desirable output and one undesirable output. The inputs considered net fixed assets and a total number of vehicles as the capital factors, total labor as the labor factor and energy consumption as the energy factor. Passenger and freight turnover volume, value-added of transport, storage and post stood for desirable outputs, and CO_2 emission represented the undesirable output. The labor, net fixed asset value and total number of vehicles were collected from the Chinese Logistics Statistical Yearbook and National Transportation Statistical Yearbook (2004–2018). Passenger and freight turnover volume and value-added transport, storage and postal data were collected from the National Statistical Yearbook, Chinese Logistics Statistical Yearbook and National Transportation Statistical Yearbook (2004–2018). The energy consumption data were sourced from the National Environment Statistical Yearbook (2004–2018).

According to the "China Energy Statistics Yearbook," the types of energy consumption in the transportation sector mainly include raw coal, clean coal, briquette, coke oven gas, kerosene, diesel, fuel oil, liquefied petroleum gas, natural gas, heat, electricity and other energy sources. This paper converted the energy consumption of the YEB and the JingJinJi region into standard coal based on the energy conversion coefficient in the "China Energy Statistical Yearbook." The specific calculation formula is as follows:

$$E = \sum C_i * e_i \tag{7}$$

C_i is the energy conversion coefficient of the i-th energy, and e_i is the consumption of the i-th energy.

The estimation approach of carbon dioxide is different from energy consumption since emission data is not disclosed in the yearbook. Thus, fossil energy consumption is employed to estimate carbon emissions in this paper. The calculation formula is shown as follows:

$$C = \sum_{i=1}^{n} C_i = \sum_{i=1}^{n} E_i * NCV_i * CEF_i * COF_i \tag{8}$$

In the formula above, E_i is the consumption of the i-th type of energy, NCV_i is the average low calorific value of the i-th type of energy, CEF_i is the carbon emission coefficient of the ith type of energy provided by IPCC, and COF_i is the carbon oxidation factor is 44/12, and the unit is 10,000 tons. The average low calorific value and carbon emission coefficient of each energy source are from the 2006 IPCC National Greenhouse Gas Inventory Guidelines.

Table 1 shows the descriptive statistics of input and desirable and undesirable output data. Table 2 shows the correlation matrices for inputs and outputs. All the correlation coefficients between the inputs and outputs are significantly positive except for Freight Turnover Volume and Passenger Turnover Volume. Correspondingly, as inputs were added, the output values also tended to increase, representing the "isotonicity" of the inputs and outputs in the DEA model (Mostafa, 2009). Therefore, employing the meta-frontier SBM approach for measuring environmental efficiency is feasible.

4.2 Results and analysis

We measured the transportation environmental efficiency of 14 provinces of YEB and JingJinJi region from 2004 to 2017. First, we estimated meta-frontier environmental efficiency using Formula (3) of all DMU without considering regional and technical heterogeneities. Second, we evaluated the group frontiers by considering regional and technological heterogeneities in the upper, mid and downstream YEB and the JingJinJi regions through Formula (4). Then, the TGR (technological gap ratio) was calculated through Formula (5). Lastly, we analyzed the causes of environmental inefficiency in each region through slack analysis and discussed ways to increase the environmental efficiency of transportation in YEB and JingJinJi region through CO_2 reduction analysis. The estimated results demonstrate some consistency with previous research concerning regional rankings in assessing environmental efficiency in the transportation sector (Jiang, 2022; Zhimin, 2019).

Table 1.
Descriptive statistics of input and output variables, 2004–2017

	Input variables				Output variables			
					Desirable outputs			Undesirable output
	Labor (10*4 persons)	Net fixed asset value (100 million yuan)	Total number of vehicles	Total energy consumption (10*4ton TOE)	Passenger turnover volume (billion person-km)	Freight turnover volume (billion ton-km)	Value added of transport, storage and post	Total carbon dioxide emissions (10*4tons)
Average	21.20	953.49	34.11	835.29	76.89	486.7931467	822.56	1786.64
S.D	11.47	800.85	24.38	455.82	45.39	482.3844819	580.48	976.59
Max	59.12	4492.62	144.02	2398.72	187.24	2499.871	3097.67	5182.35
Min	6.77	92.86	5.64	124.72	9.17	36.77	96.7	273.67

Source(s): Authors' own work

Table 2. Correlation matrix for inputs and outputs, 2004–2017

	Labor	NFAV	TNV	Energy consumption	Passenger -km	Freight ton-KM	Value added	CO_2 emissions
Labor	1.0000							
NFAV	0.5606*	1.0000						
TNV	0.3301*	0.6200*	1.0000					
Energy consumption	0.7038*	0.5750*	0.3271*	1.0000				
Passenger-KM	0.2501*	0.4413*	0.6424*	0.2731*	1.0000			
Freight ton-KM	0.3069*	0.2219*	0.3428*	0.6184*	0.1111	1.0000		
Value added	0.6117*	0.6842*	0.7165*	0.6113*	0.5753*	0.4963*	1.0000	
CO_2 emissions	0.6904*	0.5553*	0.3147*	0.9990*	0.2626*	0.6271*	0.5981*	1.0000

Note(s): * Correlation is significant at the 1% level (2-tailed)
Source(s): Authors' own work

4.2.1 Meta-frontier results. The environmental efficiency analysis based on the meta-frontier SBM approach showed that the average overall environmental efficiency in 14 regions was 0.5875. The average environmental efficiency in the YEB and the JingJinJi region was 0.5619 and 0.6394, respectively, indicating that the JingJinJi region was higher than the YEB. The midstream of YEB and JingJinJi region showed a similar efficiency level. In contrast, the upstream of YEB showed the lowest efficiency, and the efficiency gap with other regions was also relatively large.

The province-level analysis of the SBM frontier revealed that Tianjin exhibited the highest environmental efficiency among the regions from 2004 to 2011. This achievement might be ascribed to its reliance on waterway transportation. Conversely, from 2011 to 2017, Hebei emerged as the most efficient province. Notably, in 2011, Hebei initiated the adoption of new energy vehicles to replace diesel vehicles and actively promoted the growth of waterway transportation. In contrast, Yunnan, situated upstream of the YEB, obtained the lowest ranking among the 14 regions. This outcome could be attributed to various factors, including a heavy dependence on outdated transportation modes and inadequate attention to transitioning towards lower energy consumption. The results of transportation environmental efficiency for both the YEB and JingJinJi regions are presented in Table 3.

Figure 2 illustrates the four regions' average SBM frontier efficiency trend from 2004 to 2017. It seems the four regions' environmental efficiency has shown significant growth in 2010 since China announced its commitment to energy conservation and emissions reduction at the 2009 Copenhagen Climate Change Conference. The downstream of the YEB demonstrated the best performance from 2008. This could be related to well-executed transportation planning and environmental protection measures in the area. For example, Jiangsu Province took the lead in launching the construction of a green, circular and low-carbon transportation demonstration province, creating a number of green transportation cities, roads and ports. This played a positive role in promoting environmental efficiency to some extent.

4.2.2 Group frontier results. Table 4 demonstrates the results of group frontier analysis for four regions. The analysis results showed that the average efficiency of 14 regions from 2004 to 2017 was 0.8047. The upstream of the YEB had an average group frontiers efficiency of 0.7950 from 2004 to 2017, with Guizhou province demonstrating the highest efficiency at 0.9902 due to its lower transportation inputs. Meanwhile, Hunan province in the midstream of the YEB exhibited the highest transportation environmental efficiency level, averaging 0.9678, which can be attributed to its effective input conversion capabilities. The downstream region of the YEB had an average efficiency of 0.8570, with Shanghai having the highest

Table 3.
SBM meta-frontier environmental efficiency results of each region from 2004 to 2017

Region	Province	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Ave
UYREB	Chongqing	0.1397	0.1535	0.1686	0.194	0.2321	0.2337	0.2523	0.297	0.3036	0.2243	0.2537	0.2529	0.2647	0.2854	0.2325
	Guizhou	1	1	1	1	1	0.3422	0.3331	1	1	0.2536	0.2906	0.292	0.3141	1	0.7018
	Sichuan	0.1915	0.1995	0.1867	0.186	0.2474	0.1923	0.214	0.265	0.2841	0.2297	0.2415	0.2652	0.2615	0.284	0.2320
	Yunnan	0.1287	0.1065	0.1025	0.117	0.1159	0.1025	0.0965	0.1079	0.1167	0.1024	0.0965	0.0999	0.098	0.1027	0.1067
MYREB	Hunan	1	1	1	1	0.6579	0.4705	0.6278	1	1	0.7087	1	0.7142	0.875	1	0.8610
	Jiangxi	1	1	1	0.8093	1	0.6674	0.565	0.5763	0.6286	0.4961	0.4851	0.4582	0.5108	0.5721	0.6978
	Hubei	0.2535	0.2534	0.2363	0.2546	0.3615	0.3411	0.4172	0.5103	0.5525	0.4007	0.4591	0.4882	0.4692	0.5842	0.3987
DYREB	Anhui	1	0.9577	0.9113	0.7819	1	1	1	1	1	0.7739	1	0.5306	0.5215	0.5214	0.8570
	Jiangsu	0.3464	0.5418	0.7252	1	1	0.6795	0.772	1	1	1	0.908	0.8419	0.8734	1	0.8349
	Shanghai	0.3325	0.3681	0.3924	0.4798	0.4913	0.3315	1	1	1	0.4953	1	0.6693	0.7029	1	0.6617
	Zhenjiang	0.3238	0.3512	0.4428	0.5149	0.5562	0.5205	0.6413	0.6814	0.6369	0.5776	0.601	0.6284	0.8839	1	0.5971
JingJinJi	Beijing	0.1326	0.1155	0.116	0.1539	0.1408	0.1147	0.1556	0.1714	0.1398	0.1301	0.1289	0.1231	0.1228	0.1562	0.1358
	Tianjin	1	1	1	1	1	0.9078	1	1	0.7634	0.6162	0.6565	0.5884	0.6442	1	0.8698
	Hebei	1	0.7546	0.8028	0.918	1	0.8199	0.8232	1	1	0.8739	1	0.9342	0.8483	1	0.9125
UYREB	Ave	0.365	0.3649	0.3645	0.3743	0.3989	0.2177	0.224	0.4175	0.4261	0.2025	0.2206	0.2275	0.2346	0.418	0.3183
UYREB	Ave	0.7512	0.7511	0.7454	0.688	0.6731	0.493	0.5367	0.6955	0.727	0.5352	0.6481	0.5535	0.6183	0.7188	0.6525
UYREB	Ave	0.5007	0.5547	0.6179	0.6942	0.7619	0.6329	0.8533	0.9204	0.9092	0.7117	0.8773	0.6676	0.7454	0.8804	0.7377
UYREB	Ave	0.7109	0.6234	0.6396	0.6906	0.7136	0.6141	0.6596	0.7238	0.6344	0.5401	0.5951	0.5486	0.5384	0.7187	0.6394

Source(s): Authors' own work

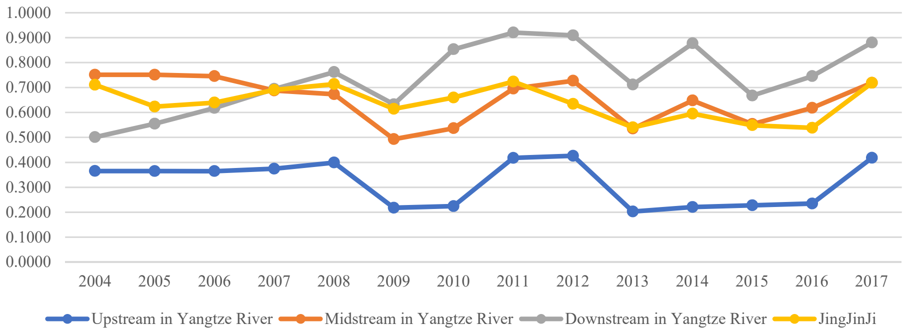
efficiency of 0.9355. Shanghai's remarkable efficiency can be attributed to its steadfast commitment to expanding the scale of its high-speed rail and road network. Additionally, in 2015, it took the lead in implementing higher emission standards for motor vehicles, resulting in a significant reduction in the growth rate of energy consumption in the transportation industry. However, Beijing, China's capital, had very low environmental efficiency, with an average of 0.1621 over the 14-year period. This inefficiency can be attributed, in part, to its relatively lower scale efficiency in the initial stages.

4.2.3 Technological gap ratio. Investigating the gap between the efficiency values of group frontiers and meta-frontier and comparing the environmental technology gap ratio between different regions, the TGRs of the transportation environment in the YEB and the JingJinJi region were calculated and displayed in Table 5. It was found that the JingJinJi region and downstream of the YEB achieved the potential optimal production technology in transportation. It is evident that the JingJinJi region and downstream of YEB had the most advanced production technology and were China's most economically developed regions.

In Figure 3, the JingJinJi region had the highest TGR during the period of 2004–2009 and 2014–2016, while downstream of YEB had the highest TGR from 2010 to 2013 and 2017. This was consistent with the fact that the JingJinJi and downstream of YEB had been playing the leading character in the economy, technology and environmental governance. As an example, Jiangsu province has demonstrated a strong commitment to advancing multi-modal transportation, particularly in developing rail-water transportation since the 11th Five-Plan in 2011. In parallel, the region has implemented policies aimed at energy conservation and environmental sustainability, such as promoting swap trailer transport and the adoption of natural gas vehicles. The YEB region showed an increasing TGR trend since 2015, while the JingJinJi region showed a decreasing trend. Judging from this trend, the technological gap in these regions was reduced due to the effects of eco-friendly and low-carbon transportation-related policies implemented in the YEB regions since 2015.

4.2.4 Environmental efficiency increase and CO_2 reduction potential. In this section, we calculated the degree and excessive input, shortfall output and excessive undesirable level in the transportation environment efficiency of the YEB and the JingJinJi region. The slack value showed excessive input and output and a shortfall compared to the optimal efficiency for each input and output. Based on the results of the group frontier in the four regions, the slack analysis of inputs and outputs explored which parts should be adjusted to move to the efficient frontiers. Table 6 shows the input and output slacks of four regions.

The JingJinJi region ranked third in the transportation environmental efficiency among the four regions. The input of labor factor was highest and urgent to adjust. In the case of output factors, it was found that passenger and freight turnover in the JingJinJi region was



Source(s): Authors' own work

Figure 2. Environmental efficiency trend of Yangtze River economic region and JingJinJi region from 2004 to 2017

Table 4.
Group frontier environmental efficiency results of each region from 2004 to 2017

Region	Province	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Ave
UYREB	Chongqing	0.6039	0.6339	0.6761	0.7262	0.8248	0.8327	0.8622	1	1	1	1	0.8783	1	1	0.8599
	Guizhou	1	1	1	1	1	0.9361	0.9269	1	1	1	1	1	1	1	0.9902
	Sichuan	1	1	1	1	1	0.7532	0.837	1	1	1	0.8755	1	1	1	0.9618
	Yunnan	0.496	0.3918	0.3918	0.4265	0.4006	0.3561	0.3306	0.3672	0.4068	0.3323	0.3075	0.3177	0.3082	0.318	0.3679
MYREB	Hunan	1	1	1	1	1	0.736	0.8761	1	1	1	1	0.9374	1	1	0.9678
	Jiangxi	1	1	1	1	1	0.8722	0.8886	1	1	1	0.845	0.7738	0.8754	1	0.9468
	Hubei	0.4927	0.4797	0.4654	0.4762	0.5686	0.5648	0.6506	0.7133	1	0.7573	1	1	0.8774	1	0.7176
DYREB	Anhui	1	1	1	0.9332	1	1	1	1	1	1	1	0.6702	0.676	0.6818	0.9258
	Jiangsu	0.4441	0.6289	0.8035	1	1	0.7626	0.8311	1	1	1	1	0.8419	0.8737	1	0.8704
	Shanghai	1	1	1	1	1	0.7229	1	1	1	0.5887	1	0.7853	1	1	0.9355
	Zhenjiang	0.4407	0.4731	0.5676	0.6267	0.6597	0.6121	0.7186	0.7704	0.7239	0.6951	0.7219	0.7692	0.9687	1	0.6963
JingJinJi	Beijing	0.1527	0.1179	0.1183	0.1599	0.1466	0.1307	0.1934	0.2025	0.1652	0.1395	0.1452	0.1422	0.1623	0.2926	0.1621
	Tianjin	1	1	1	1	1	1	1	1	0.7705	1	0.6568	0.5888	0.6443	1	0.9043
	Hebei	1	0.7546	0.8028	0.918	1	0.8199	0.8232	1	1	0.8739	1	0.9342	0.8483	1	0.9125
UYREB	Ave	0.775	0.7564	0.767	0.7882	0.8064	0.7195	0.7392	0.8418	0.8517	0.8331	0.7958	0.799	0.8271	0.8295	0.7950
UYREB	Ave	0.8309	0.8266	0.8218	0.8254	0.8562	0.7243	0.8051	0.9044	1	0.9191	0.9483	0.9037	0.9176	1	0.8774
UYREB	Ave	0.7212	0.7755	0.8428	0.89	0.9149	0.7744	0.8874	0.9426	0.931	0.821	0.9305	0.7667	0.8796	0.9205	0.8570
UYREB	Ave	0.7176	0.6242	0.6404	0.6926	0.7155	0.6502	0.6722	0.7342	0.6452	0.6711	0.6007	0.5551	0.5516	0.7642	0.6596

Source(s): Authors' own work

Table 5. Technological gap ratio of environmental efficiency for each region from 2004 to 2017

Region	Province	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Ave
UYREB	Chongqing	0.2313	0.2422	0.2494	0.2671	0.2814	0.2807	0.2926	0.297	0.3036	0.2243	0.2537	0.2879	0.2647	0.2854	0.2687
	Guizhou	1	1	1	1	1	0.3656	0.3594	1	1	0.2536	0.2906	0.292	0.3141	1	0.7054
	Sichuan	0.1915	0.1995	0.1867	0.186	0.2474	0.2553	0.2557	0.265	0.2841	0.2297	0.2758	0.2652	0.2615	0.284	0.242
	Yunnan	0.2595	0.2718	0.2616	0.2743	0.2893	0.2878	0.2919	0.2938	0.2869	0.3082	0.3138	0.3144	0.318	0.323	0.2925
MYREB	Hunan	1	1	1	1	0.6579	0.6393	0.7166	1	1	0.7087	1	0.7619	0.875	1	0.8828
	Jiangxi	1	1	1	0.8093	1	0.7652	0.6358	0.5763	0.6286	0.4961	0.5741	0.5921	0.5835	0.5721	0.7309
	Hubei	0.5145	0.5282	0.5077	0.5346	0.6358	0.6039	0.6413	0.7154	0.5525	0.5291	0.4591	0.4882	0.5348	0.5842	0.5592
DYREB	Anhui	1	0.9577	0.9113	0.8379	1	1	1	1	1	0.7739	1	0.7917	0.7714	0.7647	0.9149
	Jiangsu	0.78	0.8615	0.9026	1	1	0.891	0.9289	1	1	1	0.908	1	0.9997	1	0.948
	Shanghai	0.3325	0.3681	0.3924	0.4798	0.4913	0.4586	1	1	1	0.8413	1	0.8523	0.7029	1	0.7085
	Zhenjiang	0.7347	0.7423	0.7801	0.8216	0.8431	0.8504	0.8924	0.8845	0.8798	0.831	0.8325	0.817	0.9125	1	0.8444
JingJinJi	Beijing	0.8684	0.9796	0.9806	0.9625	0.9604	0.8776	0.8046	0.8464	0.8462	0.9326	0.8877	0.8657	0.7566	0.5338	0.8645
	Tianjin	1	1	1	1	1	0.9078	1	1	0.9908	0.6162	0.9995	0.9993	0.9998	1	0.9652
	Hebei	1	0.7546	0.8028	0.918	1	0.8941	0.9572	1	1	1	1	1	1	1	0.9519
UYREB	Ave	0.4206	0.4284	0.4244	0.4319	0.4545	0.2974	0.2999	0.464	0.4687	0.254	0.2835	0.2899	0.2896	0.4731	0.3771
UYREB	Ave	0.8382	0.8427	0.8359	0.7813	0.7646	0.6695	0.6646	0.7639	0.727	0.578	0.6777	0.6141	0.6644	0.7188	0.7243
UYREB	Ave	0.7118	0.7324	0.7466	0.7848	0.8336	0.8	0.9553	0.9711	0.97	0.8616	0.9351	0.8653	0.8466	0.9412	0.8540
UYREB	Ave	0.9561	0.9114	0.9278	0.9602	0.9868	0.8932	0.9206	0.9488	0.9457	0.8496	0.9624	0.955	0.9188	0.8446	0.9272

Source(s): Authors' own work

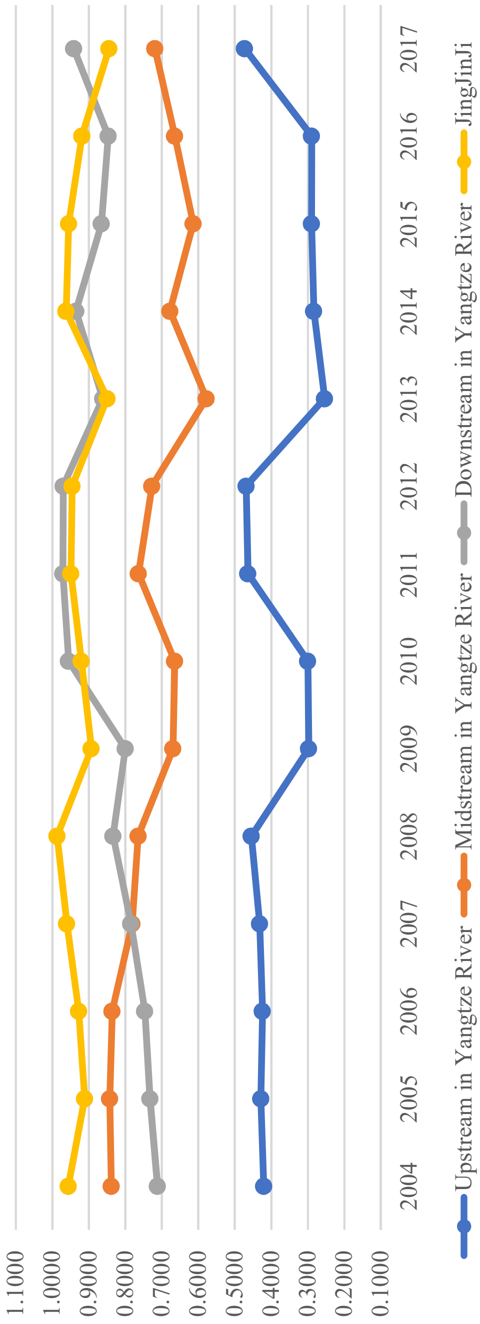


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Figure 3.
Technical gap ratio of Yangtze River economic region and JingJinJi region from 2004 to 2017

Table 6.
Inputs and outputs slacks of four regions

		Input slacks				Output slacks			
Region	Efficiency score	Labor	Net fixed asset value	Total number of vehicles	Total energy consumption	Passenger turnover volume	Freight turnover volume	Value-added	Total carbon dioxide emissions
Average upstream YTZ river	0.7950	−20318.89	−221.09	−7.5	−114.76	13.73	6.99	36.29	−2460622.29
Average mid-stream YTZ	0.8774	−22304.41	−74.74	−0.88	−129.36	21.76	173.53	7.93	−2907205.75
Average down stream YTZ	0.8570	−25825.4	−178.09	−2.1	−73.05	92.31	604.66	0.65	−1495177.62
Average JingJinJi	0.6596	−94418.53	−180.16	−1.42	−141.67	14.19	3196.42	2.34	−2942350.62

Source(s): Authors' own work

insufficient. The additional 4667.43 (unit) ton-km, which was more than 2.6 times higher than the downstream of the YEB, could move to the efficiency frontier. Due to these causes, the JingJinJi region received low environmental efficiency than other regions.

The three regions of the YEB showed different input and output slacks by region. In the midstream of the YEB region with the second highest efficiency, the excessive input level of factors was relatively small among the four. Although the excess emission of CO_2 showed the lowest level among the four regions, the freight turnover volume is relatively insufficient compared to the downstream of YEB.

The downstream of the YEB demonstrates the highest efficiency score among the four regions, indicating superior transportation environmental efficiency. It exhibits a notable advantage over other regions regarding freight turnover volume. However, despite this achievement, substantial opportunities for enhancing energy efficiency and curtailing CO_2 emissions remain unexplored. Conversely, upstream of the YEB records the lowest efficiency score, with considerable inputs failing to yield proportional outputs. This discrepancy may be ascribed to its geographical configuration, insufficient infrastructure and relatively lower technological advancement.

5. Conclusions and policy implications

Under the YEB Development Strategy and the Beijing–Tianjin–Hebei (JingJinJi) Region Coordinated Development Strategy, the YEB and the JingJinJi region are under pressure to reduce carbon dioxide in the transportation sector and introduce various environmental policies. This paper investigated the environmental efficiency of the transportation sector in the YEB and the JingJinJi region with CO_2 emissions from four perspectives. Based on the analysis results, we proposed policy suggestions to increase transportation environmental efficiency.

First, in light of low environmental efficiency and excessive CO_2 emissions in the analysis, the upstream of the YEB needs to tailor a low-carbon transportation development strategy based on their specific economic development levels. Specifically, measures such as reducing the massive use of low-quality fuel, addressing overloaded transportation and non-optimal route planning are urgently needed to be implemented. Integral to this strategy is the introduction of a government-driven clean fuel subsidy program. This policy could provide economic incentives, reduce operational costs, offset additional expenses associated with low-carbon fuels, stimulate market demand (Dahle *et al.*, 2021), integrate environmental responsibility and foster technological innovation (Hepburn *et al.*, 2018). In addition, as the mountainous terrain is a prominent feature of the upper Yangtze River region, the relatively longer transportation distances and the complexity of the terrain may result in the instability of fuel demand. Thus, the layout and transportation route optimization of green energy sites should be given priority consideration.

Second, the midstream of YEB, as a transportation hub in central China, should focus on implementing low-carbon transportation policies since energy consumption and excessive CO_2 emissions were found to be the highest in the midstream of the YEB. For example, the region could effectively promote the multi-modal transportation of water-rail and rail-road to reduce CO_2 emissions caused by the transportation sector (Heinold and Meisel, 2018). The establishment of cooperative alliances, taking into account the eco-label preferences of logistics service providers, can facilitate the advancement of intermodal transport (Zhang *et al.*, 2022). This cooperative approach fosters synergistic initiatives aimed at enhancing the sustainability and efficiency of transportation in the midstream YEB, aligning with the imperative to reduce the ecological footprint.

Third, the JingJinJi region should engage proactively in the coordinated development strategy. Specifically, Beijing needs to specialize in its functions to eliminate inefficiencies and transfer transportation-related functions to Hebei province and Tianjin because it had low environmental efficiency, with an average of 0.1621 over the 14-year period. In this regard, it is crucial for the JingJinJi region to establish cross-regional logistics centers and comprehensive transportation hubs. This would maintain stable volumes of passenger and freight through inter-regional links while simultaneously promoting economic and environmental efficiency of the transportation sector through the application of cutting-edge technologies related to the Fourth Industrial Revolution (Zhao and Xie, 2022).

The contributions of this study are twofold. First, this study employs the meta-frontier model to assess environmental efficiency in the transportation sector, considering the technology gap and heterogeneity of the regions. It contributes positively to the comparative analysis of transportation efficiency across multiple regions. Second, the study provides the advantage of observing the disparities in transportation efficiency performed by the Yangtze River Economic Belt and the Beijing–Tianjin–Hebei regions.

In conclusion, this research underscores the importance of sustainable and low-carbon transportation in the YEB and the JingJinJi region. By leveraging the insights gained from the analysis and adopting the policy suggestions proposed, both regions can pave the way for a more environmentally friendly and efficient transportation sector, contributing to the overall goal of achieving sustainable development and reducing carbon emissions in China.

References

British Petroleum (2022), “Statistical review of world energy 2022”, available at: https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html (accessed 12 October 2023).

Chang, Y.T., Zhang, N., Danao, D. and Zhang, N. (2013), “Environmental efficiency analysis of transportation system in China: a non-radial DEA approach”, *Energy Policy*, Vol. 58, pp. 277-283, doi: 10.1016/j.enpol.2013.03.011.

Charnes, A., Cooper, W.W. and Rhodes, E. (1978), “Measuring the efficiency of decision making units”, *European Journal of Operational Research*, Vol. 2 No. 6, pp. 429-444, doi: 10.1016/0377-2217(78)90138-8.

Chen, X., Wu, G. and Li, D. (2019), “Efficiency measure on the truck restriction policy in China: a non-radial data envelopment model”, *Transportation Research Part A: Policy and Practice*, Vol. 129, pp. 140-154.

Cui, Q. and Li, Y. (2014), “The evaluation of transportation energy efficiency: an application of three-stage virtual Frontier DEA”, *Transportation Research Part D: Transport and Environment*, Vol. 29, pp. 1-11, doi: 10.1016/j.trd.2014.03.007.

Dahlke, S., Sterling, J. and Meehan, C. (2021), “Chapter 12 - policy and market drivers for advancing clean energy”, in Azad, A.K. (Ed.), *Advances in Clean Energy Technologies*, Academic Press, pp. 451-485, doi: 10.1016/B978-0-12-821221-9.00012-8.

Feng, C. and Wang, M. (2017), “Analysis of energy efficiency and energy savings potential in China’s provincial industrial sectors”, *Journal of Cleaner Production*, Vol. 164, pp. 1531-1541, doi: 10.1016/j.jclepro.2017.07.081.

Feng, C. and Wang, M. (2018), “Analysis of energy efficiency in China’s transportation sector”, *Renewable and Sustainable Energy Reviews*, Vol. 94, pp. 565-575, doi: 10.1016/j.rser.2018.06.037.

Heinold, A. and Meisel, F. (2018), “Emission rates of intermodal rail/road and road-only transportation in Europe: a comprehensive simulation study”, *Transportation Research Part D: Transport and Environment*, Vol. 65, pp. 421-437, doi: 10.1016/j.trd.2018.09.003.

Hepburn, C., Pless, J. and Popp, D. (2018), “Policy brief—encouraging innovation that protects environmental systems: five policy proposals”, *Review of Environmental Economics and Policy*, Vol. 12 No. 1, pp. 154-169, doi: 10.1093/reep/rex024.

Hu, J.L. and Wang, S.C. (2006), "Total-factor energy efficiency of regions in China", *Energy Policy*, Vol. 34 No. 17, pp. 3206-3217, doi: 10.1016/j.enpol.2005.06.015.

Jiang, X. (2022), *Based on DEA Model to Analysis Transportation System Efficiency in China*, Hubei University, Wuhan.

Li, Y., Li, J., Gong, Y., Wei, F. and Huang, Q. (2020), "CO2 emission performance evaluation of Chinese port enterprises: a modified meta-frontier non-radial directional distance function approach", *Transportation Research Part D: Transport and Environment*, Vol. 89, 102605, doi: 10.1016/j.trd.2020.102605.

Lin, L.C. and Hong, C.H. (2006), "Operational performance evaluation of international major airports: an application of data envelopment analysis", *Journal of Air Transport Management*, Vol. 12 No. 6, pp. 342-351, doi: 10.1016/j.jairtraman.2006.08.002.

Lin, B. and Tian, P. (2017), "Energy conservation in China's light industry sector: evidence from inter-factor and inter-fuel substitution", *Journal of Cleaner Production*, Vol. 152, pp. 125-133, doi: 10.1016/j.jclepro.2017.03.099.

Lin, B. and Zhao, H. (2016), "Technology gap and regional energy efficiency in China's textile industry: a non-parametric meta-frontier approach", *Journal of Cleaner Production*, Vol. 137, pp. 21-28, doi: 10.1016/j.jclepro.2016.07.055.

Liu, Q. and Hoon Lim, S. (2017), "Toxic air pollution and container port efficiency in the USA", *Maritime Economics and Logistics*, Vol. 19 No. 1, pp. 94-105, doi: 10.1057/mel.2015.29.

Merkert, R. and Hensher, D.A. (2011), "The impact of strategic management and fleet planning on airline efficiency–A random effects Tobit model based on DEA efficiency scores", *Transportation Research Part A: Policy and Practice*, Vol. 45 No. 7, pp. 686-695, doi: 10.1016/j.tra.2011.04.015.

Mostafa, M.M. (2009), "Modeling the efficiency of top Arab banks: a DEA–neural network approach", *Expert Systems with Applications*, Vol. 36 No. 1, pp. 309-320, doi: 10.1016/j.eswa.2007.09.001.

Na, J.H., Choi, A.Y., Ji, J. and Zhang, D. (2017), "Environmental efficiency analysis of Chinese container ports with CO2 emissions: an inseparable input-output SBM model", *Journal of Transport Geography*, Vol. 65, pp. 13-24, doi: 10.1016/j.jtrangeo.2017.10.001.

O'Donnell, C.J., Rao, D.S. and Battese, G.E. (2008), "Metafrontier frameworks for the study of firm-level efficiencies and technology ratios", *Empirical Economics*, Vol. 34 No. 2, pp. 231-255, doi: 10.1007/s00181-007-0119-4.

Park, Y.S., Lim, S.H., Egilmez, G. and Szmerekovsky, J. (2018), "Environmental efficiency assessment of US transport sector: a slack-based data envelopment analysis approach", *Transportation Research Part D: Transport and Environment*, Vol. 61, pp. 152-164, doi: 10.1016/j.trd.2016.09.009.

Scheraga, C.A. (2004), "The relationship between operational efficiency and customer service: a global study of thirty-eight large international airlines", *Transportation Journal*, Vol. 43 No. 3, pp. 48-58.

Song, M., Zhang, G., Zeng, W., Liu, J. and Fang, K. (2016), "Railway transportation and environmental efficiency in China", *Transportation Research Part D: Transport and Environment*, Vol. 48, pp. 488-498, doi: 10.1016/j.trd.2015.07.003.

Tone, K. (2001), "A slacks-based measure of efficiency in data envelopment analysis", *European Journal of Operational Research*, Vol. 130 No. 3, pp. 498-509, doi: 10.1016/s0377-2217(99)00407-5.

Tone, K. (2003), "Dealing with undesirable outputs in DEA: a slacks-based measure SBM approach", GRIPS Research Report Series, 2003.

Wang, Z., Yin, F., Zhang, Y. and Zhang, X. (2012), "An empirical research on the influencing factors of regional CO2 emissions: evidence from Beijing city, China", *Applied Energy*, Vol. 100, pp. 277-284.

Wang, Q., Zhao, Z., Zhou, P. and Zhou, D. (2013), "Energy efficiency and production technology heterogeneity in China: a meta-frontier DEA approach", *Economic Modelling*, Vol. 35, pp. 283-289, doi: 10.1016/j.econmod.2013.07.017.

Wang, P., Zhu, B., Tao, X. and Xie, R. (2017), "Measuring regional energy efficiencies in China: a meta-frontier SBM-Undesirable approach", *Natural Hazards*, Vol. 85 No. 2, pp. 793-809, doi: 10.1007/s11069-016-2605-5.

Wang, L., Zhou, Z., Yang, Y. and Wu, J. (2020), "Green efficiency evaluation and improvement of Chinese ports: a cross-efficiency model", *Transportation Research Part D: Transport and Environment*, Vol. 88, 102590, doi: 10.1016/j.trd.2020.102590.

Wei, F., Zhang, X., Chu, J., Yang, F. and Yuan, Z. (2021), "Energy and environmental efficiency of China's transportation sectors considering CO2 emission uncertainty", *Transportation Research Part D: Transport and Environment*, Vol. 97, 102955, doi: 10.1016/j.trd.2021.102955.

World Bank Open Data (2023), "World Bank open data", available at: https://data.worldbank.org

Yao, X., Zhou, H., Zhang, A. and Li, A. (2015), "Regional energy efficiency, carbon emission performance and technology gaps in China: a meta-frontier non-radial directional distance function analysis", *Energy Policy*, Vol. 84, pp. 142-154, doi: 10.1016/j.enpol.2015.05.001.

Zhang, N., Kong, F. and Yu, Y. (2015a), "Measuring ecological total-factor energy efficiency incorporating regional heterogeneities in China", *Ecological Indicators*, Vol. 51, pp. 165-172, doi: 10.1016/j.ecolind.2014.07.041.

Zhang, N., Zhou, P. and Kung, C.C. (2015b), "Total-factor carbon emission performance of the Chinese transportation industry: a bootstrapped non-radial Malmquist index analysis", *Renewable and Sustainable Energy Reviews*, Vol. 41, pp. 584-593, doi: 10.1016/j.rser.2014.08.076.

Zhang, Y., Heinold, A., Meisel, F., Negenborn, R.R. and Atasoy, B. (2022), "Collaborative planning for intermodal transport with eco-label preferences", *Transportation Research Part D: Transport and Environment*, Vol. 112, 103470, doi: 10.1016/j.trd.2022.103470.

Zhao, S. and Xie, C. (2022), "Spatial difference of China's regional logistics development and construction of information network platform based on artificial intelligence technology under the background of new economy", *Frontiers in Psychology*, Vol. 13, 871538, doi: 10.3389/fpsyg.2022.871538.

Zhimin, P. (2019), *Research on Total Factor Productivity in China's Transportation Industry under the Constraints of Resource and Environment*, Chang'an University.

Zhou, Y., Xing, X., Fang, K., Liang, D. and Xu, C. (2013), "Environmental efficiency analysis of power industry in China based on an entropy SBM model", *Energy Policy*, Vol. 57, pp. 68-75, doi: 10.1016/j.enpol.2012.09.060.

Zhou, G., Chung, W. and Zhang, Y. (2014), "Measuring energy efficiency performance of China's transport sector: a data envelopment analysis approach", *Expert Systems with Applications*, Vol. 41 No. 2, pp. 709-722, doi: 10.1016/j.eswa.2013.07.095.

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