

Spatial-temporal Analysis of Energy Efficiency of Different Transport Modes in China

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Abstract. This research employs stochastic frontier analysis (SFA) to investigate the development of transport energy efficiencies of railway, highway, water and civil aviation transport in different stages. In addition, total factor energy efficiency indicator (TFEE), technology efficiency change indicator (TECH) and frontier technology change indicator (TPCH) are introduced to further analyze the technology gaps among thirty studied provinces in China from 2000 to 2018. The results indicate that the transport energy efficiencies in China decrease from 2000 to 2010, which mainly caused by regional technological gaps. On the contrary, the transport energy efficiencies increase from 2011 to 2018 owing to the technological improvement. Furthermore, the energy efficiency of railway transport is the highest among four transport modes. The energy efficiency of highway transport is relatively low although highway transport takes a large proportion of all the intercity transports. Therefore, in order to make the development of transport more sustainable, it is necessary to narrow the technology gaps among the provinces and adjust the transport volume of different transport modes rationally.

Keywords: Stochastic Frontier Approach; Transport energy efficiency; Technological heterogeneities; Different transportation modes and sectors; Energy-savings strategy

1. Introduction

With the rapid growth of economy and population in China, people have more disposable incomes and more travel demands, which generates more frequent travels. In the meantime, the development of e-commerce also drives a rapid growth of express delivery demand, which significantly improves the freight transport volume in the last two decades. The sustained growth of transport demand in both people and freight would result in a sharp increase in transport energy consumption [1]. At the same time, pollutants coming from transport energy consumption have a negative influence on environmental conservation and sustainable development. The World Energy Council defines energy efficiency as the ratio of service output to energy consumption. The former expression refers to obtaining more output or better living quality with same or less energy, and the latter expression means the diminution of energy usage because of technological advances, lifestyle changes, and improved management.

Stochastic frontier approach (SFA) uses the production function to construct the technical efficiency of the invalidation rate term under the condition of production frontier and technical failure, and has a good reliability and comparability that have little influence from special points. Thus, this study uses SFA to investigate the development of energy efficiency of different transport modes in China from 2000 to 2018, with the energy efficiency and inefficiency under various modes of transportation. There are three main contributions in this research.

Many scholars focus on comprehensive researches of transport energy efficiency and economic sustainable development. According to existing researches, improving energy efficiency will facilitate alleviate energy shortages and achieve energy conservation and emission reduction [2]. These studies conduct empirical research on the transport sector or a certain mode of transportation to explore the impact of economic factors and policies on energy efficiency. Moreover, population, civil vehicle ownership, passenger and freight turnover are positively correlated with transport

energy consumption [3]. These research results show that optimize transport structure and improve energy efficiency can promote the reduction of transport energy consumption.

Energy efficiency calculations are able to be divided into two categories. One is single index, which only accepts energy as a single input and does not consider the contribution of other production factors to output. The single index is not comprehensive enough to consider the substitution effect of other inputs on energy. Another one is total factor energy efficiency, which considers various factors and substitution effect between different input factors. SFA and Data Envelopment Analysis (DEA) are able to calculate the utilization efficiency of input factors with multi-factor production function theory. Many literatures use DEA to empirically analyze energy efficiency and its interfering factors at provincial or industrial level [4]. Feng and Wang [5] use DEA with improved Malmquist index to consider the energy efficiency and conservation potential in combination with regional heterogeneity. DEA is established with four inputs and two outputs to evaluate renewable energy efficiency [6]. However, since the statistical error and other stochastic errors are not considered in DEA, it is easy to be affected by the quality of sample data.

In consideration of the statistical errors in macro data, SFA is suggested to solve this problem. At present, a few studies use SFA to discuss energy efficiency of many countries and regions. Zhou et al. [7] construct SFA method with Shephard distance function to analyze energy efficiency in economic system. In addition, there are some studies combined with relevant theories to construct SFA model. From the perspective of positive economics of 30 provinces in China, Ouyang et al. [8] use SFA to measure the changes of the economic factors and evaluate their impact on the energy efficiencies.

As mentioned above, scholars mainly focus on the energy efficiency of transport. Nevertheless, few studies consider the uneven production technology of various transportation modes in different regions. In China, the differences of economic development and resource endowment among different regions lead to technical heterogeneity. These heterogeneities lead to the different technological development of transport sector in different regions. The energy efficiency and saving potential of different modes of transportation in mainland of China are evaluated and analyzed by using the meta-frontier SFA, while considering the heterogeneity among different regions.

The remainders of this study are organized as follows. Section 2 collects the data and makes descriptive statistics. The SFA model is established in Section 3. Section 4 discusses the regression results and gives policy recommendations. The main findings are concluded and relative policy recommendations are provided in Section 5.

2. Data and descriptive statistics

This research selects thirty provinces in China as the studied provinces. Tibet is not taken into consideration because of the lack of the data. 2000 to 2018 is chosen as studied period. Data of transport volume, traffic mileage, labor, transportation gross output, energy and capital are collected to regress and calculate transport energy efficiency. The main descriptive statistics of these variables are presented in Table 1.

Table 1 Descriptive statistics of studied variables

Index	Unit	Transport modes	Mean value	Standard deviation	Minimum value	Maximum value
Transport volume (T)	108 people	Total	5.9733	0.2393	3.2208	7.6529
		Railway	1.1494	0.3212	0.0653	3.4121
		Highway	4.5524	0.2294	0.3151	10.5249
		Water	0.1223	0.8862	0.0002	0.4497
		Civil aviation	0.2549	0.7227	0.0165	1.2913
	108 tons	Total	16.8799	0.5610	10.1531	19.6897

		Railway	1.3417	0.3693	0.9592	1.9823
		Highway	13.1817	0.2712	9.6633	17.5875
		Water	2.9272	0.6016	1.2192	5.0818
		Civil aviation	0.0025	0.0018	0.0011	0.0519
Traffic mileage (M)	104 miles	Railway	0.4363	0.1691	0.0502	1.2832
		Highway	15.8283	0.2336	1.3163	33.1625
		Water	0.5012	0.3778	0.0102	2.4436
		Civil aviation	10.0988	0.4545	3.9122	25.9962
Labor (L)	104 people	Total	29.5974	5.3705	3.9102	85.8739
Energy (E)	104 tons	Total	1385.9333	523.0014	243.6108	2784.2650
Total output of provincial transport sector (Y)	100 million Yuan RMB	Total	984.3621	356.2101	435.8131	1562.3452
Energy efficiency (λ)	104 yuan per ton	Total	1.2756	0.1126	1.7901	0.5611

Due to the lack of the data, Y is calculated according to the perpetual inventory method [9], as shown in Eq. (1).

$$Y_t = I_t + (1 - \delta_t)Y_{t-1} \quad (1)$$

Where Y_t and Y_{t-1} are the investment in period t and $t-1$. I_t and δ_t represent investment and depreciation ratio of fixed assets over the period t respectively.

λ usually refers to the ratio of effective output to energy input in the production process. The output value of unit energy consumption, which is calculated through Eq. (2), is used as an index to measure the efficiency of energy consumption in this research.

$$\lambda = \frac{f}{e} \quad (2)$$

Where f presents the total output of transport, and e represents the total energy consumption of transport.

Geographical proximity is an appropriate division standard for regional grouping. Therefore, this study divides the studied provinces into eastern regions, central regions and western regions, as shown in Fig. 1. Different patterns represent different regions. Heterogeneities exist among the three regions in China. For instance, provinces in eastern regions, which located on the eastern coast of China, have relatively better economic foundation, rapider development in science and technology, and more enormous investment in infrastructure compared with provinces in central region or western region.



Fig. 1. Studied provinces and regions in China

3. Modeling work

In this study, global meta-frontier SFA approach is proposed to consider the heterogeneities of production technology among decision making units (DMU) when estimating energy efficiency.

Suppose there are k DMU and g groups. The technology of the units within a group are considered identical, whereas technologies among groups are different [10]. Therefore, each set of DMU forms a group boundary. All group boundaries form the meta-frontier. The procedure to determine the model by solving Eq. (3) and Eq. (4).

$$\lambda = f(T, M, L, E, Y; \beta | CRS) \exp(v_i) \exp(-u_i), \quad i = 1, \dots, k_g \quad (3)$$

$$f = \beta T^{\beta_1} M^{\beta_2} L^{\beta_3} E^{\beta_4} Y^{\beta_5} \quad (4)$$

$$\lambda = f(T, M, L, E, Y; \beta | CRS) \exp(v_i) \exp(-u_i), \quad i = 1, \dots, k_g \quad (3)$$

$$f = \beta T^{\beta_1} M^{\beta_2} L^{\beta_3} E^{\beta_4} Y^{\beta_5} \quad (4)$$

Where λ represents transport energy efficiency. (T, M, L, E, Y) denotes transport volume, mileage, labor, energy and investment respectively. CRS stands for constant returns to scale, k_g is the number in group g of DMU in the equation $\sum_{g=1}^G K_g = K$, v_i and u_i are error terms. v_i denotes random error term expressing statistical error, while u_i is non-negative error term which used to express technical inefficiency.

Taking Cobb-Douglas function as the production function of the model, Eq. (3) is able to be transformed into linear form, as shown in Eq. (5) and (6).

$$\ln \lambda_i^{meta} = \beta_0 + \beta_1 \ln T + \beta_2 \ln M + \beta_3 \ln L + \beta_4 \ln E + \beta_5 \ln Y + v_i + u_i, \quad i = 1, \dots, k_g \quad (5)$$

$$\ln \lambda_i^g = \beta_0 + \beta_1 \ln T + \beta_2 \ln M + \beta_3 \ln L + \beta_4 \ln E + \beta_5 \ln Y + v_i + u_i, \quad i = 1, \dots, k_g \quad (6)$$

Where λ_i^{meta} and λ_i^g are the meta-frontier and group frontier transport energy efficiency respectively.

Energy efficiency (EE) of a transportation mode or a region is calculated through Eq. (7).

$$EE_i = \exp(-u_i) = \frac{\lambda_i}{f(T, M, L, E, Y; \beta | CRS) \exp(v_i)} \quad (7)$$

Three indicators are introduced to further measure the energy efficient of transport. Technology efficiency change (TECH) is the change indicator of technical efficiency, which describes the influence of the production unit approach or distance to the production front on the total factor energy efficiency (TFEE) change under the given technical conditions and factor input. The value

can be calculated in Eq. (8) and Eq. (9).

$$TECH_i^{t,t+1} = TE_{i,t+1} / TE_{it} \quad (8)$$

$$TE_{it} = \frac{\lambda_{it}^g}{\lambda_{it}^{meta}} \exp(-u_{it}) \quad (9)$$

Where TE_{it} represents the technical efficiency of province i in year t .

Frontier technology change indicator (TPCH) describes the influence of the outward or inward movement of the frontier on TFEE change of the unit under the given factor input. Its value is able to be derived from the partial derivative of t by production function. TPCH can be obtained in Eq. (10).

$$TPCH_i^{t,t+1} = \exp \left[\frac{1}{2} \left(\frac{\partial \ln \lambda_{i,t+1}}{\partial (t+1)} + \frac{\partial \ln \lambda_{it}}{\partial t} \right) \right] \quad (10)$$

On the basis of transport energy efficiency and combining Malmquist productivity indicator, TFEE between t and $t+1$ period can be measured through Eq. (11) by multiplying TECH and TPCH.

$$TFEE_i^{t,t+1} = TECH_i^{t,t+1} \times TPCH_i^{t,t+1} \quad (11)$$

4. Scenario analysis

4.1 Energy efficiency changes of transport in different stages

The initial phase unfolds with the implementation of the tenth "Five-Year Plan" (FYP) and the subsequent eleventh FYP, marking a momentous epoch characterized by the explosive growth of China's transportation sector. During this phase, the energy efficiency of the transportation industry experiences a decline, primarily attributable to the swift expansion of the transportation system and a prevailing disregard for energy conservation measures. In contrast, the second stage comprises the twelfth FYP and the opening three years of the thirteenth FYP, signaling a notable shift in the dynamics. Here, the energy efficiency of the transportation sector experiences a notable upswing, driven by a deliberate emphasis on enhancing transportation infrastructure and a dedicated focus on energy conservation policies. This transformation underscores a comprehensive commitment to fostering a more sustainable and efficient transport landscape.

To lend greater weight to the empirical findings, the presentation of data in Table 2 has been artfully structured to offer a multifaceted perspective, delving into both regional and provincial groupings. This nuanced approach enhances the credibility of the results. Notably, there is a discernible upward trajectory in the Total Factor Energy Efficiency (TFEE) from the inaugural stage to the subsequent one. This upswing is a testament to China's steadfast commitment to prioritizing energy conservation within the realm of transportation. A pivotal juncture occurred in 2011 when China embarked on a transformative journey, instigating a series of visionary policies and guidelines aimed at bolstering energy conservation efforts. However, the first stage, encompassing the tenth and eleventh FYPs, reveals a notable paradox. During this period, energy efficiencies within the transport sector exhibited a perplexing decline. This decline can be attributed predominantly to the rampant expansion of transport infrastructure, which occurred at an unprecedented pace. This unbalanced, breakneck development inadvertently detracted from the sector's overall energy efficiency, underscoring the vital importance of harmonious and balanced growth.

Table 2 TFEE, TECH and TPCH obtained according to regional division

Regions	Accumulated TFEE and its decomposition from 2000 to 2010			Accumulated TFEE and its decomposition from 2011 to 2018		
	TFEE	TECH	TPCH	TFEE	TECH	TPCH

East	0.9660	1.2792	0.7555	1.1569	1.1455	1.0413
Central	0.7944	1.3076	0.6074	0.9964	1.1958	0.8836
West	0.9217	1.3944	0.6593	1.1913	1.2606	0.9449
China	0.9040	1.3290	0.6808	1.1267	1.2011	0.9639

Because of the various economic and social development status in different provinces, the concrete reasons for the decline of transport energy efficiencies in different provinces are different. There also exist commonalities for the transport energy efficiencies among the studied provinces. In the first stage, the main reason for the decline in the transport energy efficiencies is the expansion of provincial technology gap, while in the second stage, the transport energy efficiencies of central provinces and western provinces still decline due to the low technology level and the widening of technology gap.

4.2 Strategies for improving energy efficiency in transport

Combining the current situation of inefficiency in the transport is essential for managers putting forward countermeasures for greater energy efficiency. The EE indices of four modes of transportation in 2018 are calculated in Table 3. Energy efficiency varies greatly among different regions. In addition, energy efficiencies of different modes of transportation varies. It shows that there exist significant development imbalances among three regions, and transport in the eastern region has the highest energy efficiency. The change of energy efficiency has a positive influence on energy consumption.

Table 3 EE indices of transport in 2018 according to regional division

Regions	Accumulated EE in freight traffic				Accumulated EE in passenger traffic			
	Railway	Highway	Water	Civil aviation	Railway	Highway	Water	Civil aviation
East	1.0297	0.2865	0.4841	1.1355	0.7987	0.5414	0.2889	0.6973
Central	1.0651	0.1952	0.5480	0.6499	0.8262	0.3689	0.3270	0.3990
West	0.9551	0.1396	0.3400	0.7970	0.7408	0.2638	0.2029	0.4894
China	1.0118	0.2083	0.4483	0.8819	0.7848	0.3936	0.2675	0.5415

The optimization of freight transport promotes the decrease of transportation energy consumption. The promotion of low energy intermodal mode, especially the development of water and railway transportation, makes the freight transportation develop towards a better situation. Meanwhile, the rapid growth of civil aviation freight transportation and the low proportion of railway transportation affect the energy saving effect. In the past few years, the overall energy consumption of highway transport shows a downward trend. The rapid development of railway transport plays an important part in the decline of energy consumption of passenger transport. With the opening and operation of new railway lines and the transformation of the original lines, the proportion of railway transport volume in passenger transport gradually increases. Furthermore, the energy efficiency of civil aviation transport increases, but the increase of energy consumption caused by the growth of civil aviation transport volume has no significant impact on total energy consumption.

In summary, each province should put forward the corresponding measures to improve transport energy efficiency in view of their own problems. Provinces in central regions and western regions with relatively backward development level should focus on the implementation of strategies improving transport energy efficiency to tap efficiency potential. As for the inefficiency of a certain mode of transport, managers should concentrate on improving the technical level of transport mode, such as eliminating old vehicles and using new energy-saving vehicles. Reducing energy consumption of existing vehicles and speeding up the improvement of motor vehicle fuel economy standard system are also valid ways to improve energy efficiency. In addition, provinces in the eastern regions can take advantage of their geographical advantages to develop better water transport. It is suggested to improve the current traffic management system and establish a unified

comprehensive transport management organization. The railway, highway, water and civil aviation transport ought to be integrated and regarded as a whole system to develop an energy-saving transport system.

5. Conclusions

This research adopts SFA to investigate the transport energy efficiency changes of each transport sector. Taking thirty provinces in China from 2000 to 2018 as studied objects, three indicators are introduced to study the transport energy efficiency and inefficiency level under various modes of transportation. The transport energy efficiencies according to regional division and provincial division in different periods are investigated respectively. In addition, this research also discovers the differences of energy efficiencies among railway, highway, water and civil aviation.

The regression results indicate the energy efficiency of transport in China decreases from 2000 to 2010, and increases from 2011 to 2018. Moreover, among the four transportation modes, the transport energy efficiency of railway and civil aviation is relatively higher. The energy consumption of civil aviation is relatively less. Highway transport occupies a larger proportion of all the intercity transports than civil aviation transport, but its energy efficiency is low. Although the volume of railway transport is larger than that of highway transport, the energy efficiency of railway transport is relatively high. Therefore, narrowing interregional technology gap and rationally adjusting transport volume of different transportation modes would be essential to support transport sustainable development in China. Although the heterogeneities of various modes of transportation are considered in this study, the factors considered for different transportation modes are limited by the unavailability of data. Considering the development of big data, more factors can be considered to discuss the energy efficiency of the transport sector in future study.

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