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Transportation Efficiency Evaluation Considering the Environmental Impact for China's Freight Sector: A Parallel Data Envelopment Analysis

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Abstract: The freight sector is an important component of China's national economy. It is composed of multiple sub-sectors and has a complex internal structure. This internal structure can hide information on the freight sector's operational performance. Previous studies on transportation operational performance made measurements based on the whole transportation sector, and all of these studies ignored the impacts that the internal structure of the sub-sectors have on performance, which leaves a gap in the research. To illustrate this structure, this study proposes a parallel slacks-based measure model to measure transportation efficiency, which can represent the freight sector's operational performance. The efficiencies of transportation operations for the whole freight sector and its three sub-sectors are further measured, by treating the sub-sectors as parallel subunits. Then, the inefficiency sources from the sub-sectors can be identified by the proposed model. To detect the environmental impact on transportation operations, energy consumption and carbon dioxide emissions are also considered in the evaluation. On the basis of the proposed approach, an application of the Chinese freight sector from 2013 to 2017 is provided. The impacts of influential factors on transportation efficiency are also explored. The empirical findings can be illustrated as follows: (1) there exist significant disparities in regional transportation efficiencies in the freight sector and its sub-sectors; (2) the inefficient transportation performance of the Chinese freight sector mainly derives from the poor performance of the waterway sub-sector; and (3) freight volume and population density have positive impacts on the transportation efficiencies of the railway and highway sub-sectors. Finally, some policies for improving transportation efficiency are also provided.

Keywords: transportation efficiency; freight sector; parallel structure; slacks-based model; environmental impact

1. Introduction

China's policies for reform and opening-up have helped it to achieve a great amount of economic growth and social progress over the past four decades. These have stimulated the construction of infrastructure for China's transportation sector, which obtained an amazing expansion in scale [1]. The transportation scale expansion has simultaneously promoted the prosperity of the freight sector. China's national gross domestic product (GDP) increased by approximately 43.83 times from 1990 to 2017, and the freight turnover volume increased by 7.30 times in this period [2]. As an important component of the national economy, the freight sector has played a crucial role in current and future development in China.

The growing demands for commodities and the development of economic globalization can establish a strong long-term relationship between freight demand and economic growth [3]. Figure 1 shows the trends of variation in national GDP and freight turnover volume from 1990 to 2017 in China, which illustrates the close relationship between freight turnover volume and GDP growth. This close relationship suggests that GDP growth can increase freight demand, which is also mentioned in the work of [4]. Benefiting from the economic growth in China, China's freight demand and operational scale are expected to continue to increase.

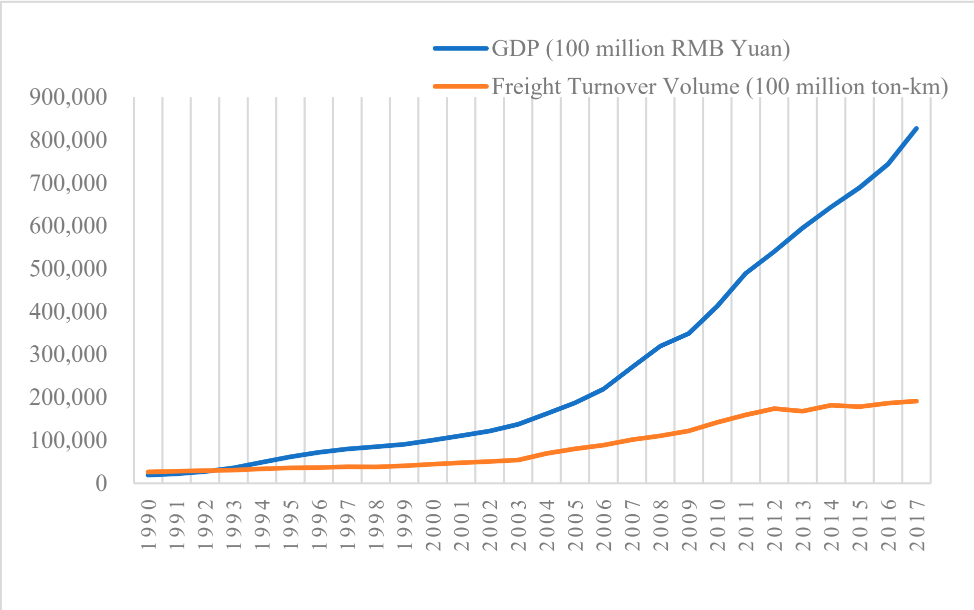

Figure 1. Relationship of gross domestic product (GDP) and freight turnover volume in China from 1990 to 2017.

Considering the growth of the freight sector's scale, the development of the freight sector has attracted much attention from China's central government in recent years. However, compared with developed countries, China's freight sector still has low operational performance [5]. To this end, the government has launched a series of policies to increase its operational performance, reduce cost, save energy, and abate pollution emissions from the freight system. For instance, solutions for optimizing the transportation sector's structure, strengthening the supervision and management measures in operations, and improving the technologies level to make energy savings are advocated in China's 12th 5-year-plan (2011–2015) for the transportation sector. To improve the performance of the Chinese transportation sector, especially for the freight sector, a comprehensive metric called 'transportation efficiency' should be developed. Transportation efficiency can be defined as the conversion ratio of a transportation system's output to its input resource [6], which can represent the transportation operational performance (called the 'transportation performance' for convenience) of the freight sector in this study. An effective transportation performance evaluation can help the government to propose appropriate policies to improve allocation of resources and operational processes. Thus, exploring the transportation efficiency of China's freight sector is essential.

From an environmental perspective, the enormous consumption of fossil fuel produces substantial carbon dioxide (CO_2), which consequently generates a greenhouse effect and induces natural hazards [7]. The freight sector also consumes a massive amount of energy in the transportation process. In 2014, the transportation sector accounted for nearly one-quarter of the world's energy-related CO_2 emissions and was the second-largest source of CO_2 emissions in the world [8]. While global energy consumption in the freight sector commonly accounts for about 40% of the transportation sector's total consumption, as well as its greenhouse gas (GHG) emissions [9]. Obviously, the freight sector is an important source of fossil fuel consumption and energy-related CO_2 emitter owing to the rapid expansion of freight scale and the increased energy consumption. More attention should be paid to the freight sector, as the sector is facing an increasing number of environmental issues. To achieve sustainable development, China committed that 45% carbon intensity will be reduced by 2020 over the 2005 level. Undoubtedly, the freight sector should undertake tasks of national energy conservation and emission reduction [10]. To reduce energy consumption and carbon emissions, the environmental impact should be taken into consideration in the evaluation of the freight sector's transportation efficiency.

In the works of [11,12], the transportation sector is regarded as an integration industry in the performance evaluation, which is in ignorance of the production processes of internal sub-sectors. In practice, there exist multiple modes of transportation according to various means of transport, such as trains, trucks, ships, planes, and pipes, which can be defined as railway, highway, waterway, air, and pipe transportation, respectively. Transportation operations based on these transportation modes are defined as transportation sub-sectors in this study. This study focuses on the railway, highway, and waterway sub-sectors. The freight turnover volume of these three sub-sectors is 19.23 trillion ton-kilometers in China in 2017, which accounts for approximately 97.45% of the total national freight turnover volume [2]. Disparities in economic production, operational scale, and environmental performance of these sub-sectors can affect the overall transportation performance. However, this subdivision issue is not specifically discussed in the existing studies. It is difficult for these studies to provide accurate information on the sources of inefficiencies in the transportation sector in ignorance of the inner structure of the whole sector. Therefore, it is necessary to examine the transportation performance of the sub-sectors as well as that of the whole freight sector.

Furthermore, the regional disparity in China should also be considered in the performance evaluation. There are many provinces, autonomous regions, and municipalities within China, and each province has a different economic development status [13–15]. Significant regional disparities can exist based on the differences in natural resource endowment, modes of transportation, energy utilization structure, and economic development level, which may affect the operations of a regional freight sector. Hence, a reasonable transportation performance evaluation of the freight sector cannot ignore the regional disparities that occur in practice.

The main question of this research is to propose a new approach to evaluate transportation performance that can detect all of the related information of the sub-sectors. The information should be identified by an effective approach. The network slacks-based measure (SBM) data envelopment analysis (DEA) model [16], transformed into a parallel form in this study, is an appropriate choice of method to achieve this objective. Compared with the existing studies, the parallel SBM method has the advantage of being able to detect the inefficiencies in performance from the inner structure of the production process, and present a more detailed description of performance. On the basis of the proposed approach, the transportation performance of the whole freight sector and its sub-sectors is expected to be evaluated for China's regional freight transportation systems. This may help to improve the inefficiencies of operational performance of freight sub-sectors in practice.

The main contributions of this study can be summarized as follows. First, this study constructs a new analytical framework that decomposes the whole operational process of the freight sector into sub-sectors by adopting the parallel SBM method. This can be regarded as a first attempt for the application of China's freight sector. The environmental impact is also considered in the efficiency evaluation with the modeling including energy and CO_2 factors. Second, this paper investigates diverse sources of transportation inefficiency for China's regional sub-sectors, which provides a managerial insight to improve the performance of the freight sector in regional China.

The remaining part of this paper is organized as follows. In Section 2, related literature is reviewed. Section 3 introduces the proposed method of framework analysis. The proposed method is applied to explore the performance of the freight sector in China's provinces in Section 4. Conclusions are provided in Section 5.

2. Literature Review

This section provides a brief introduction to three streams of literature: transportation efficiency evaluation; the applications of DEA in the transportation sector; and the parallel DEA method.

There are several studies on performance evaluation in the transportation sector. Transportation efficiency, as a popular proxy of transportation performance, has several definitions in the literature [6,17–20]. It is defined in this study as the conversion ratio of a transportation system's output to its input resource [6]. Considering that a single-factor evaluation cannot reflect the nature of a transportation system [21,22], a comprehensive measure that considers all related factors should be proposed as an important start to an evaluation of transportation efficiency. As a multi-factor efficiency evaluation method, DEA is suitable for measuring transportation efficiency.

The DEA model was proposed by Charnes et al. in 1978 [23], and can be used to assess the relative efficiency of decision-making units (DMUs) through identifying an efficient frontier. For the merit of forbidding the imposition of any functional form on a total-factor efficiency evaluation [24], DEA is a widely accepted method for evaluating a transportation sector's efficiency [25–29]. On the basis of a DEA efficiency evaluation, the existing applications of transportation sectors can be divided into two main types: the evaluations with or without the consideration of undesirable outputs.

The first type refers to transportation efficiency estimation in transportation systems without the consideration of undesirable outputs. For example, Kerstens [30], Boame [31], and Karlaftis [32] use the DEA approach to assess the relative technical efficiency of the French, Canadian, and American urban transit systems, respectively. Yu and Lin [33] propose a multi-activity network DEA model to evaluate the efficiency of 20 selected European railways for the year 2002. Barros and Peypoch [34] employ a two-stage DEA model to estimate the operational efficiency of European airlines from 2000 to 2005. In this research direction, Chiu et al. [27] create a modified value-chains DEA model to evaluate the transportation efficiencies of 30 regions in China in 2006. Each of these studies performs an efficiency evaluation of a transportation system from a different perspective: technical efficiency, network DEA, two-stage DEA, and value-chains DEA. However, these studies ignore the undesirable outputs (e.g., air pollutants) of transportation activities.

The second type evaluates the efficiency of a transportation system with the consideration of undesirable outputs. The undesirable outputs may reflect the environmental impact by concomitant exhaust emissions, such as CO_2 and nitrogen oxide (NO_x). For example, McMullen and Noh [35] analyze the efficiency of 43 American bus transit agencies, while considering hazardous emissions (hydrocarbons, carbon monoxide (CO), and NO_x) for the year 2000. This study shows that once hazardous emissions are considered, some otherwise inefficient agencies may be identified as efficient. Wei et al. [28] employ a super-efficiency DEA method to measure the performance of urban transportation systems in 34 cities in China, taking NO_2 and noise level as the pollution indexes. Furthermore, numerous studies [12,15,36] indicate that energy and energy-related CO_2 can reflect the environmental impact on transportation efficiency. In terms of efficiency evaluations that consider the environmental impact in China, Chang et al. [11] take energy-related CO_2 as the pollution emission to evaluate the efficiency of the transportation sector in China's 30 provinces by proposing a non-radial DEA model with the slacks-based measure. Similarly, Song et al. [12] use the SBM model to estimate the changes in efficiency for the transportation sector in Chinese provinces during 2003–2012. Li et al. [15] employ the super-SBM DEA model to evaluate regional transportation efficiency in China with the consideration of CO_2 between 1995 and 2012, and analyze the factors that influence transportation efficiency. Some studies [29,36] investigate the performance of transportation systems in China, but do not distinguish the objects of transportation. For instance, Liu et al. [36] focus on land transportation, which combines passenger transportation with freight transportation, takes passenger turnover and freight turnover as desirable outputs, and takes energy-related CO_2 as an undesirable output. These studies mainly focus on the whole integrated transportation system, but do not distinguish transportation sub-sectors.

The abovementioned studies share one common sense that the transportation production process is regarded as a "black box" that ignores the internal production processes within the transportation sector. This kind of performance evaluation may not be rational if the internal independent sub-units within the unit are not considered [37,38]. The freight sector in China is composed of multiple independent sub-sectors. The transport activities of these sub-sectors are being operated simultaneously. Hence, the independent sub-sectors can collectively be treated as a parallel structure. In the actual transportation operational process, each sub-sector consumes different amounts of resources to achieve different freight turnover amounts. This can result in performance differences among sub-sectors. In this circumstance, the traditional method for evaluating transportation efficiency may bring about an unreasonable estimation without the consideration of performance differences in the independent parallel structure of the sub-sectors, which would influence policymakers to formulate specific policies. It is necessary to examine the transportation efficiency of the sub-sectors in addition to that of the whole freight sector, which leaves a gap in the research.

To solve the aforementioned issue, we may use the parallel DEA model, as it is suitable for the efficiency evaluation of a parallel-series system [39]. Kao [40] proposes the concept of parallel DEA model, which can account for the situation of individual components when measuring the efficiency of the whole system. If each DMU has production sub-processes, the system structure of this DMU can be regarded as a parallel structure. Following the work of [40], some scholars have further developed the parallel DEA method and applied it in various empirical studies. For example, Bi et al. [41] propose a parallel DEA model that can be used for resource allocation and target setting in a production system, and demonstrate the validity of their proposed method using Chinese industry data. Ma and Chen [39] provide a parallel DEA approach to estimate the operation and coordination efficiencies of the parallel two-stage system and apply it to an empirical study of Taiwanese non-life insurance companies. To the transportation sector, Wu et al. [42] divide a highway transportation system into two parallel transport subsystems (passenger transportation and freight transportation) and evaluate the energy and environmental efficiency of the whole system and the subsystems.

Several studies have concentrated on the efficiency estimation of the transportation sector in recent years. Most studies [11,12,15,36,43] estimate the efficiency of a transportation sector by a comprehensive evaluation that combines multiple transportation modes (e.g., highway, railway, and waterway sub-sectors). These evaluations neglect the internal independent transportation sub-sectors. Furthermore, the efficiency investigation of the freight sector to detect regional disparities is still scarce in the existing literature. Owing to the lack of efficiency evaluations considering transportation sub-sectors and regional disparities, the analysis of the freight sector is a valuable and significant research topic that should be further explored.

3. Methodology

This study proposes a parallel SBM model that considers the structure of internal sub-sectors to estimate the transportation efficiency for the freight sector. The conceptual structure, related variables, and models are illustrated in this section. To develop the proposed parallel SBM model, the following notations are listed in Table 1.

Table 1. Definition of notations.

Symbol	Description
X_K	transportation capacity of the freight sector
X_N	transportation route mileage of the freight sector
X_E	energy of the freight sector
Y_F	freight turnover volume of the freight sector
Y_C	CO_2 of the freight sector
X_K^i	transportation capacity of the railway, highway, and waterway sub-sectors, respectively (hereinafter referred to as the three sub-sectors)
X_N^i	transportation route mileage of the three sub-sectors, respectively
X_E^i	energy of the three sub-sectors, respectively
Y_F^i	freight turnover volume of the three sub-sectors, respectively
Y_C^i	CO_2 of the three sub-sectors, respectively
i	corresponding to the specific sub-sector i, (i = 1, 2, 3)
j	the jth decision-making unit
η_0^*	transportation efficiency of the freight sector in Model (1)
S_K^-	slack variable attached to transportation capacity of the freight sector
S_N^-	slack variable attached to transportation route mileage of the freight sector
S_E^-	slack variable attached to energy of the freight sector
S_F^+	slack variable attached to freight turnover volume of the freight sector
S_C^-	slack variable attached to CO_2 of the freight sector
λ_j	intensity variable representing the participation for each evaluated observation
ρ_0^*	transportation efficiency of the freight sector in Model (2)
s_K^{i-}	slack variable attached to transportation capacity of the three sub-sectors, respectively
s_N^{i-}	slack variable attached to transportation route mileage of the three sub-sectors, respectively
s_E^{i-}	slack variable attached to energy of the three sub-sectors, respectively
s_F^{i+}	slack variable attached to freight turnover volume of the three sub-sectors, respectively
s_C^{i-}	slack variable attached to CO_2 of the three sub-sectors, respectively
ω_i	the weights allocated to of the three sub-sectors, respectively
λ_j^i	intensity variables representing the participation for each evaluated observation corresponding of the three sub-sectors, respectively
ρ_1^*	transportation efficiency of the railway sub-sector in Model (2)
ρ_2^*	transportation efficiency of the highway sub-sector in Model (2)
ρ_3^*	transportation efficiency of the waterway sub-sector in Model (2)

3.1. Parallel Sub-Sectors and Variables

China's freight sector is composed of three main sub-sectors (i.e., the railway, highway, and waterway sub-sectors) that perform massive transportation tasks. Owing to the importance of these three sub-sectors, which together comprise most of the transportation operations, these three sub-sectors will be considered in our model. In this study, the freight sector in China is divided into three independent parallel sub-sectors. Figure 2 shows the structure.

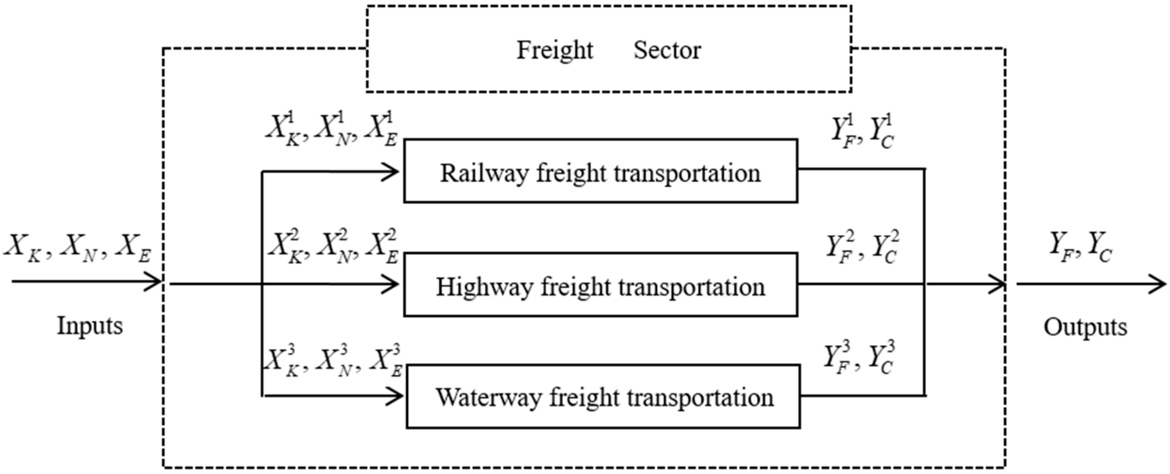

Figure 2. The freight sector in China with three parallel sub-sectors.

To evaluate the efficiency of transportation operations using the DEA method, several scholars have proposed various factors in relation to the efficiency measure. Wu et al. [42] argue that the main investment in transportation infrastructure is physical resources, which can be represented by transportation route mileage and transportation capacity. Transportation route mileage denotes the total length of all transportation routes. Transportation capacity denotes the total cargo tonnage of all means of transport; that is, the capability of freight transportation. These two factors have been widely used in efficiency evaluation in previous studies [29,42,44,45]. To accurately measure the input of fuel consumption in the transportation sector, Song et al. [29] and Cui and Li [46] both adopt energy as another input index, which is generally converted to the standard coal equivalent (SCE). In accordance with the previous literature and actual practice, this study chooses transportation route mileage, transportation capacity, and energy consumption as the inputs of transportation operations. With respect to the output of transportation operations, turnover volume is the most appropriate substitute [15,29,42,47]. Regarding the environmental impact of transport activities, energy-related CO_2 has been regarded as an undesirable output in efficiency evaluation [12,36,48–50]. Following these studies, CO_2 is adopted in this research. Moreover, energy consumption and CO_2 emissions are both factors that can represent the environmental impact. Consequently, this study selects five variables (three inputs and two outputs) to characterize the operation process in the freight sector.

As shown in Figure 2, the inputs of the freight sector are X_K (i.e., transportation capacity), X_N (i.e., transportation route mileage), and X_E (i.e., energy). Two outputs occur: one is the desirable output Y_F (i.e., freight turnover volume); and the other is the undesirable output Y_C (i.e., CO_2). Each sub-sector consumes X_K, X_N, and X_E to produce Y_F and Y_C. X_K^i, X_N^i, X_E^i, Y_F^i, and Y_C^i (i = 1, 2, 3) denote transportation capacity input, transportation route mileage input, the energy input, freight turnover volume output, and CO_2 output of the railway, highway, and waterway sub-sectors, respectively. i denotes the specific sub-sector i. Notably, the amount of input/output for the whole freight sector is equal to the sum of the three sub-sectors, except for the transportation route mileage, that is, $X_K = \sum_{i=1}^{3} X_K^i$, $X_E = \sum_{i=1}^{3} X_E^i$, $Y_F = \sum_{i=1}^{3} Y_F^i$, and $Y_C = \sum_{i=1}^{3} Y_C^i$. Owing to the differences in transportation route mileage among the three sub-sectors, the use of the sum of transportation route mileage in the efficiency evaluation is unreasonable. Therefore, we use the weight α to calculate the total transportation route mileage for the whole freight sector, that is, $X_N = \sum_{i=1}^{3} \alpha^i X_N^i$, where α is the ratio of freight turnover volume to transportation route mileage of each sub-sector, which represents the importance of each type of transportation route mileage in the freight sector. For example, the α values of the railway, highway, and waterway sub-sectors in 2013 are 0.2828, 0.0128, and 0.6312, respectively.

3.2. Evaluating the Transportation Efficiency of the Freight Sector

To evaluate the transportation efficiency of the freight sector, this study takes the sector within a province as one DMU, which is denoted as DMU_j (j = 1, 2, ... , n). In the literature, the radial measure and the non-radial measure are two widely used approaches in the efficiency evaluation using DEA. Compared with the radial model, the SBM model can effectively discriminate more sources of inefficiency in the measurement process by identifying each "input excess" and "output shortfall" to find the maximum slacks [51–53]. Thanks to this merit, the SBM model is widely accepted in the efficiency evaluation literature; examples are the works of [54,55]. Therefore, the SBM model is adopted to measure transportation efficiency in this study.

First, we propose a transportation efficiency measure for the whole freight sector without the consideration of internal sub-sectors as follows:

$$
\begin{aligned}
\eta_0 = \quad & \min \frac{1-\frac{1}{3}\left(\frac{S_K^-}{X_K}+\frac{S_N^-}{X_N}+\frac{S_E^-}{X_E}\right)}{1+\frac{1}{2}\left(\frac{S_F^+}{Y_F}+\frac{S_C^-}{Y_C}\right)} \\
\text{s.t.} \quad & \sum_{j=1}^{n} \lambda_j X_{Kj} + S_K^- = X_K, \\
& \sum_{j=1}^{n} \lambda_j X_{Nj} + S_N^- = X_N, \\
& \sum_{j=1}^{n} \lambda_j X_{Ej} + S_E^- = X_E, \\
& \sum_{j=1}^{n} \lambda_j Y_{Fj} - S_F^+ = Y_F, \\
& \sum_{j=1}^{n} \lambda_j Y_{Cj} + S_C^- = Y_C, \\
& \sum_{j=1}^{n} \lambda_j = 1, \\
& \lambda_j, S_K^-, S_N^-, S_E^-, S_F^+, S_C^- \geq 0,\ j = 1, 2, \cdots, n.
\end{aligned}
\tag{1}
$$

In Model (1), η_0 is denoted as the transportation efficiency of the freight sector; S_K^-, S_N^-, S_E^-, S_F^+, and S_C^- are slack variables attached to transportation capacity, transportation route mileage, energy, freight turnover volume, and related CO_2 emissions, respectively. λ_j is denoted as intensity variable representing the participation of each evaluated observation.

3.3. The Proposed Parallel Slacks-Based Measure Approach

Model (1) measures the efficiency of the freight sector without the consideration of internal sub-sectors. Thus, the inefficiencies from internal processes cannot be discriminated. In practice, an inefficient freight transportation system might be inefficient in any sub-sector. Hence, an effective evaluation method is required.

As shown in Figure 2, the freight sector is modeled as a parallel production system with three independent sub-sectors. Following the works of [40,56], the efficiency measure of freight operations with the parallel structure can be measured by the following programming:

$$
\begin{aligned}
&\rho_0 = \min \frac{\sum_{i=1}^{3} \omega_i \left[1-\frac{1}{3}\left(\frac{s_K^{i-}}{X_K^i}+\frac{s_N^{i-}}{X_N^i}+\frac{s_E^{i-}}{X_E^i}\right)\right]}{\sum_{i=1}^{3} \omega_i \left[\left(1+\frac{1}{2}\left(\frac{s_F^{i+}}{Y_F^i}+\frac{s_C^{i-}}{Y_C^i}\right)\right)\right]} \\
&\text{s.t.} \\
&\left.\begin{aligned}
&\sum_{j=1}^{n} \lambda_j^1 X_{Kj}^1 + s_K^{1-} = X_K^1, \\
&\sum_{j=1}^{n} \lambda_j^1 X_{Nj}^1 + s_N^{1-} = X_N^1, \\
&\sum_{j=1}^{n} \lambda_j^1 X_{Ej}^1 + s_E^{1-} = X_E^1, \\
&\sum_{j=1}^{n} \lambda_j^1 Y_{Fj}^1 - s_F^{1+} = Y_F^1, \\
&\sum_{j=1}^{n} \lambda_j^1 Y_{Cj}^1 + s_C^{1-} = Y_C^1, \\
&\sum_{j=1}^{n} \lambda_j^1 = 1,
\end{aligned}\right\}\text{Railway freight transportation} \\
&\left.\begin{aligned}
&\sum_{j=1}^{n} \lambda_j^2 X_{Kj}^2 + s_K^{2-} = X_K^2, \\
&\sum_{j=1}^{n} \lambda_j^2 X_{Nj}^2 + s_N^{2-} = X_N^2, \\
&\sum_{j=1}^{n} \lambda_j^2 X_{Ej}^2 + s_E^{2-} = X_E^2, \\
&\sum_{j=1}^{n} \lambda_j^2 Y_{Fj}^2 - s_F^{2+} = Y_F^2, \\
&\sum_{j=1}^{n} \lambda_j^2 Y_{Cj}^2 + s_C^{2-} = Y_C^2, \\
&\sum_{j=1}^{n} \lambda_j^2 = 1,
\end{aligned}\right\}\text{Highway freight transportation} \\
&\left.\begin{aligned}
&\sum_{j=1}^{n} \lambda_j^3 X_{Kj}^3 + s_K^{3-} = X_K^3, \\
&\sum_{j=1}^{n} \lambda_j^3 X_{Nj}^3 + s_N^{3-} = X_N^3, \\
&\sum_{j=1}^{n} \lambda_j^3 X_{Ej}^3 + s_E^{3-} = X_E^3, \\
&\sum_{j=1}^{n} \lambda_j^3 Y_{Fj}^3 - s_F^{3+} = Y_F^3, \\
&\sum_{j=1}^{n} \lambda_j^3 Y_{Cj}^3 + s_C^{3-} = Y_C^3, \\
&\sum_{j=1}^{n} \lambda_j^3 = 1,
\end{aligned}\right\}\text{Waterway freight transportation} \\
&s_K^{i-}, s_N^{i-}, s_E^{i-}, s_F^{i+}, s_C^{i-} \geq 0,\ i = 1,2,3, \\
&\lambda_j^i \geq 0,\ j = 1,2,\cdots,n.
\end{aligned}
\tag{2}
$$

In Model (2), ρ_0 denotes the overall transportation efficiency of the freight sector, which is in the range of [0, 1]; s_K^{i-}, s_N^{i-}, s_E^{i-}, s_F^{i+}, and s_C^{i-} are slack variables that refer to transportation capacity, transportation route mileage, energy, freight turnover volume, and CO_2 emissions for the three sub-sectors, respectively, which represent input's excess and output's shortfall; $\omega_i (i = 1, 2, 3)$ are the weights allocated to the three sub-sectors, which are provided exogenously and meet the following constraint: $\sum_{i=1}^{3} \omega_i = 1$; and $\lambda_j^i (i = 1, 2, 3)$ are the intensity variables representing the participation of each evaluated observation. If $\rho_0^* = 1$ and all the optimal slacks are equal to zero, the DMU would be ranked as efficient; otherwise, it is inefficient. If a DMU's efficiency value ρ_0^* is greater than the ones of other DMUs, then this DMU performs better in the transportation operational process than other DMUs.

It is worth noting that the overall transportation efficiency obtained from Model (2) for the freight sector can be further decomposed into the efficiencies of three sub-sectors, that is, ρ_1, ρ_2, and ρ_3, respectively. They are shown in Formula (3).

$$\begin{aligned}
\rho_1 &= \min \frac{1-\frac{1}{3}\left(\frac{s_K^{1-}}{X_K^1}+\frac{s_N^{1-}}{X_N^1}+\frac{s_E^{1-}}{X_E^1}\right)}{1+\frac{1}{2}\left(\frac{s_F^{1+}}{Y_F^1}+\frac{s_C^{1-}}{Y_C^1}\right)} \\
\rho_2 &= \min \frac{1-\frac{1}{3}\left(\frac{s_K^{2-}}{X_K^2}+\frac{s_N^{2-}}{X_N^2}+\frac{s_E^{2-}}{X_E^2}\right)}{1+\frac{1}{2}\left(\frac{s_F^{2+}}{Y_F^2}+\frac{s_C^{2-}}{Y_C^2}\right)} \\
\rho_3 &= \min \frac{1-\frac{1}{3}\left(\frac{s_K^{3-}}{X_K^3}+\frac{s_N^{3-}}{X_N^3}+\frac{s_E^{3-}}{X_E^3}\right)}{1+\frac{1}{2}\left(\frac{s_F^{3+}}{Y_F^3}+\frac{s_C^{3-}}{Y_C^3}\right)}
\end{aligned} \quad . \tag{3}$$

Notably, the transportation efficiency measures for the railway, highway, and waterway sub-sectors are in target function in Model (2), which should be optimized to obtain the overall transportation efficiency ρ_0. By solving Model (2), all sub-sectors' efficiencies (i.e., ρ_1, ρ_2, and ρ_3) can be obtained.

4. Empirical Study

In this section, the proposed DEA approach is applied to estimate the transportation efficiency for China's freight sector and three sub-sectors from 2013 to 2017. The factors that influence the transportation efficiency of the freight sector are also examined.

4.1. Observed Regions and Data Source

There are 31 provinces, autonomous regions, and municipalities in mainland China. These provincial regions can be classified into three major areas [57], which are described in Table 2. Because of a lack of data on the waterway sub-sector in Beijing, Inner Mongolia, Ningxia, Qinghai, Xinjiang, and Tibet, these six regions are not taken into account in this study.

Table 2. Regions within China's areas.

Area	Regions
East	Beijing, Tianjin, Shanghai, Liaoning, Hebei, Shandong, Jiangsu, Zhejiang, Fujian, Guangdong, Hainan
Center	Heilongjiang, Jilin, Inner Mongolia, Henan, Shanxi, Anhui, Hubei, Hunan, Jiangxi, Guangxi
West	Gansu, Guizhou, Ningxia, Qinghai, Shaanxi, Tibet, Yunnan, Xinjiang, Sichuan, Chongqing

This study uses three inputs (i.e., transportation capacity, transportation route mileage, and freight turnover volume) and two outputs (i.e., freight turnover volume and CO_2) in the efficiency evaluation. Data on transportation capacity, transportation route mileage, and freight turnover volume are collected from the China Statistical Yearbook 2014–2018. Notably, all of the national freight business of the railway sub-sector is coordinated and operated by China Railway Corporation, which consists of 18 railway administrations [58]. The statistical yearbooks contain only an aggregate data value of railway transportation capacity. Thus, we allocate the railway transportation capacity proportionately to the freight turnover of each region in this study. The energy data are calculated based on the unit energy consumption of freight turnover volume in each sub-sector, which derives from the Ministry of Transport of the People's Republic of China. However, there are no official statistics on the CO_2 emissions of China's provincial freight sector. Hence, this study estimates the energy-related CO_2 emissions based on energy consumption and carbon emission coefficients. The carbon emission coefficients for fossil fuels can be obtained from the Intergovernmental Panel on Climate Change guidelines [59], which are also applied in the works of [60,61]. Table 3 shows the descriptive statistics for all variables.

Table 3. Descriptive statistics. SCE, standard coal equivalent.

Year	Sectors	Variables	Max	Min	Mean	Std. Dev.
2013	Railway freight transportation	Transportation capacity (10^4 tons)	670.14	2.08	152.24	142.29
		Transportation route mileage (km)	6255.50	465.00	3329.80	1481.80
		Energy (10^4 tons of SCE)	192.21	0.60	43.66	40.81
		Freight turnover volume (10^4 ton-km)	4233.63	13.13	961.78	898.92
		CO_2 (10^4 tons)	447.24	1.39	101.60	94.96
	Highway freight transportation	Transportation capacity (10^4 tons)	1150.54	23.55	348.45	265.80
		Transportation route mileage (km)	301,816.00	12,633.00	153,104.64	72,185.88
		Energy (10^4 tons of SCE)	1249.80	14.33	395.10	345.52
		Freight turnover volume (10^4 ton-km)	6577.89	75.42	2079.48	1818.54
		CO_2 (10^4 tons)	2699.16	30.95	853.29	746.22
	Waterway freight transportation	Transportation capacity (10^4 tons)	4313.20	0.15	924.62	1172.61
		Transportation route mileage (km)	24,333.00	88.00	4919.08	5408.97
		Energy (10^4 tons of SCE)	444.90	0.00	78.43	110.74
		Freight turnover volume (10^4 ton-km)	13,965.47	0.01	2461.93	3476.00
		CO_2 (10^4 tons)	960.85	0.00	169.39	239.15
2015	Railway freight transportation	Transportation capacity (10^4 tons)	754.59	2.24	164.95	160.34
		Transportation route mileage (km)	6958.10	465.10	3891.95	1624.25
		Energy (10^4 tons of SCE)	170.02	0.50	37.17	36.13
		Freight turnover volume (10^4 ton-km)	3633.01	10.79	794.17	771.94
		CO_2 (10^4 tons)	398.42	1.18	87.10	84.66
	Highway freight transportation	Transportation capacity (10^4 tons)	1283.78	23.35	381.44	290.93
		Transportation route mileage (km)	315,582.00	13,195.00	160,583.72	75,317.63
		Energy (10^4 tons of SCE)	1296.08	14.95	407.43	325.17
		Freight turnover volume (10^4 ton-km)	6821.48	78.66	2144.35	1711.44
		CO_2 (10^4 tons)	2799.11	32.28	879.91	702.27
	Waterway freight transportation	Transportation capacity (10^4 tons)	4379.65	0.15	1039.01	1329.21
		Transportation route mileage (km)	24,389.00	88.00	4964.96	5422.43
		Energy (10^4 tons of SCE)	538.97	0.00	84.18	126.06
		Freight turnover volume (10^4 ton-km)	19,195.54	0.05	2998.02	4489.65
		CO_2 (10^4 tons)	1163.99	0.00	181.80	272.25
2017	Railway freight transportation	Transportation capacity (10^4 tons)	823.88	1.94	172.24	175.13
		Transportation route mileage (km)	7162.02	465.10	4103.89	1647.12
		Energy (10^4 tons of SCE)	185.25	0.44	38.73	39.38
		Freight turnover volume (10^4 ton-km)	4278.36	10.08	894.44	909.44
		CO_2 (10^4 tons)	435.75	1.03	91.10	92.63
	Highway freight transportation	Transportation capacity (10^4 tons)	1408.35	27.08	437.36	343.03
		Transportation route mileage (km)	329,950.47	13,321.99	166,467.31	78,604.23
		Energy (10^4 tons of SCE)	1421.88	14.15	444.11	350.93
		Freight turnover volume (10^4 ton-km)	7899.32	78.61	2467.27	1949.64
		CO_2 (10^4 tons)	3070.79	30.56	959.13	757.90
	Waterway freight transportation	Transportation capacity (10^4 tons)	4626.63	0.13	1025.43	1320.74
		Transportation route mileage (km)	24,383.36	88.48	4963.90	5419.70
		Energy (10^4 tons of SCE)	586.60	0.00	91.30	156.09
		Freight turnover volume (10^4 ton-km)	24,690.72	0.06	3843.03	6570.01
		CO_2 (10^4 tons)	1266.87	0.00	197.18	337.11

4.2. Transportation Efficiency Estimation

In the transportation efficiency evaluation, the freight sector's efficiency and the three sub-sectors' efficiencies are measured by the proposed Model (2). Model (1) is used to measure transportation efficiency without the consideration of internal parallel sub-sectors. To detect the impact of the inner structure of the sub-sectors, we can make a comparison between the results of Model (1) and (2).

To employ Model (2), the weights of three sub-sectors should be known in advance. Note that the industry structure proportion (ISP) is a suitable index for measuring different sub-sectors' weights [38]. In this study, the transportation sector structure proportion (TSSP) is defined as the ratio of the freight turnover volume of one sub-sector to the total freight turnover volume. The average TSSP values of the railway, highway, and waterway sub-sectors from 2013 to 2017 are 0.1445, 0.3270, and 0.5038, respectively. Thus, the weights for the three sub-sectors are determined based on the corresponding average TSSP values (i.e., ω_1 = 0.1445/(0.1445 + 0.3270 + 0.5038) = 0.1481, ω_2 = 0.3353, and ω_3 = 0.5166). The transportation efficiency results estimated in Models (1) and (2) are shown in Table 4. Note that we only choose three years of results to provide a simple illustration.

Here, we take the year 2013 as an illustrative example. Regarding the results from Model (1), the transportation efficiencies of Tianjin, Liaoning, Shanghai, Hainan, and Guizhou are rated as efficient in 2013. Nevertheless, four regions (i.e., Tianjin, Hebei, Shanghai, and Hainan) are rated as efficient in Model (2). These results imply that the proposed parallel DEA model can affect the results of transportation efficiency. For example, the transportation efficiency value of Hebei is 0.5967 in Model (1), while it is evaluated as efficient in Model (2). In contrast, Liaoning and Guizhou's freight sectors are evaluated as efficient in Model (1), while they are deemed to be inefficient (with transportation efficiency values of 0.8846 and 0.5714, respectively) in Model (2) for the inefficient sub-sectors (i.e., 0.8063, 0.7414, and 1.0000 and 0.8524, 0.6277, and 0.4544, respectively). The transportation inefficiency in one region can be derived from the transportation operations of the sub-sectors. For this reason, we can reasonably identify sources of inefficiency from the sub-sectors in Model (2). Taken together, the results indicate that the efficiency evaluation results of the freight sector may provide more information on transportation performance when using the parallel DEA model. Additionally, Pearson's correlation coefficient for the results of Model (1) and those of Model (2) is tested. The coefficient value is 0.700 at the 1% significance level. We find a general consistent correlation between the efficiencies of the two models, and a tiny difference that is derived from considering the internal structure of the freight sector. This also suggests that more information can be obtained from our proposed approach.

To reflect the difference in performance among the areas, dynamic trends of the mean transportation efficiencies of the whole freight sector and the three sub-sectors from Model (2) are shown in Figure 3. It can be found that the transportation efficiencies of the freight sector and the waterway sub-sector have insignificant fluctuations and slightly increasing trends during the study period. The efficiencies of the highway sub-sector increase for all areas from 2014 to 2017, and the gaps among the three areas are slightly narrowed. In contrast, the change in efficiencies of the railway sub-sector shows a declining trend. This indicates that there exists a great amount of competition between the highway sub-sector and the railway sub-sector. It is also observed that the average transportation efficiencies of the east area are always the highest for the overall freight sector and its sub-sectors. This indicates that the developed regions in the east area have invested more resources into the freight sector, which have brought about advanced management and technical advantages, to contribute to improving transportation efficiency. It is noteworthy that, to the overall freight sector and the highway sub-sector, the center area has a higher average efficiency than the west area, while the west area performs better than the center area in the railway sub-sector and the waterway sub-sector. This suggests that the western regions probably make more effective use of the resources in the railway and waterway sub-sectors.

To analyze the regional and sector disparities in transportation efficiencies, the mean efficiencies of all regions from 2013 to 2017 from Model (2) are provided in Table 5.

Table 4. Transportation efficiency results [a].

Year	2013					2015					2017				
Region	η_0	ρ_0	ρ_1	ρ_2	ρ_3	η_0	ρ_0	ρ_1	ρ_2	ρ_3	η_0	ρ_0	ρ_1	ρ_2	ρ_3
Tianjin	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Hebei	0.5967	1.0000	1.0000	1.0000	1.0000	0.4734	0.9894	1.0000	1.0000	0.9794	0.3953	1.0000	1.0000	1.0000	1.0000
Shanxi	0.5507	0.8403	0.9768	0.5341	1.0000	0.4110	0.8562	0.9319	0.6013	1.0000	0.3640	0.8637	0.9318	0.6235	1.0000
Liaoning	1.0000	0.8846	0.8063	0.7414	1.0000	1.0000	0.9239	0.7755	0.8723	1.0000	0.7310	0.9332	0.7858	0.8953	1.0000
Jilin	0.7085	0.5809	0.7466	0.6563	0.4844	0.4164	0.6088	0.7293	0.7140	0.5059	0.5051	0.6389	0.7428	0.7626	0.5289
Heilongjiang	0.4707	0.4788	0.7541	0.5129	0.3777	0.3169	0.4913	0.7387	0.5567	0.3780	0.3414	0.4932	0.7499	0.5593	0.3767
Shanghai	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Jiangsu	0.3809	0.5058	0.7730	0.5493	0.4009	0.2849	0.5325	0.7725	0.6542	0.3847	0.2500	0.5400	0.7712	0.6696	0.3897
Zhejiang	0.5281	0.5594	0.7842	0.6222	0.4541	0.4898	0.6098	0.7622	0.7597	0.4688	0.3876	0.6212	0.7637	0.8187	0.4522
Anhui	0.4048	0.6678	0.8069	1.0000	0.4122	0.2920	0.6583	0.7938	1.0000	0.3977	0.2423	0.6570	0.7892	1.0000	0.3965
Fujian	0.5887	0.5822	0.7410	0.6265	0.5079	0.5765	0.6326	0.7315	0.7296	0.5413	0.5316	0.6575	0.7343	0.7654	0.5654
Jiangxi	0.5263	0.5688	0.7857	0.7467	0.3912	0.4759	0.6401	0.7615	0.9644	0.3948	0.4369	0.6535	0.7626	1.0000	0.3974
Shandong	0.3692	0.6042	0.8491	0.6704	0.4910	0.3034	0.6579	0.8122	0.8729	0.4742	0.2546	0.6384	0.8101	0.8377	0.4598
Henan	0.4741	0.6045	0.8912	0.6522	0.4915	0.3527	0.6336	0.8789	0.7764	0.4706	0.2954	0.6512	0.8822	0.8458	0.4587
Hubei	0.4867	0.5647	0.7965	0.6656	0.4328	0.4547	0.6389	0.8007	0.8392	0.4624	0.4055	0.6490	0.7993	0.8459	0.4782
Hunan	0.5186	0.5692	0.7976	0.7136	0.4100	0.4268	0.6562	0.7865	1.0000	0.3958	0.3899	0.6513	0.7844	1.0000	0.3868
Guangdong	0.4204	0.5442	0.7395	0.6342	0.4298	0.5051	0.6601	0.7324	0.7659	0.5707	1.0000	0.8974	0.7337	0.8117	1.0000
Guangxi	0.4469	0.5768	0.7814	0.7334	0.4165	0.3578	0.6233	0.7624	0.8865	0.4125	0.3232	0.6429	0.7637	0.9401	0.4154
Hainan	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9729	0.8173	1.0000	1.0000	1.0000	0.9185	0.8190	1.0000	0.8941
Chongqing	0.5121	0.5573	0.7920	0.5992	0.4628	0.4122	0.5783	0.7814	0.6697	0.4607	0.3986	0.5881	0.7762	0.6796	0.4747
Sichuan	0.4743	0.5002	0.7977	0.5241	0.3993	0.3726	0.5264	0.7838	0.6054	0.4013	0.3406	0.5245	0.7769	0.5870	0.4116
Guizhou	1.0000	0.5714	0.8524	0.6277	0.4544	0.4850	0.6133	0.8161	0.7308	0.4790	1.0000	0.6299	0.8029	0.7976	0.4715
Yunnan	0.5244	0.5090	0.7782	0.5249	0.4214	0.3848	0.5322	0.7801	0.5982	0.4183	0.4326	0.5422	0.7665	0.6308	0.4204
Shaanxi	0.7376	0.6214	0.8465	0.6564	0.5342	0.5343	0.6690	0.8779	0.7902	0.5304	0.5150	0.6920	0.8670	0.8417	0.5448
Gansu	0.8226	0.8705	0.9795	0.6229	1.0000	0.5169	0.8962	0.8967	0.7362	1.0000	0.5370	0.9012	0.8518	0.7708	1.0000
Mean	0.6217	0.6705	0.8431	0.7046	0.5989	0.5137	0.7040	0.8209	0.8049	0.6051	0.5231	0.7194	0.8186	0.8273	0.6209

[a] η_0 is the transportation efficiency of the freight sector obtained from Model (1); ρ_0, ρ_1, ρ_2, and ρ_3 are the transportation efficiencies of the freight sector and its three sub-sectors obtained from Model (2), respectively.

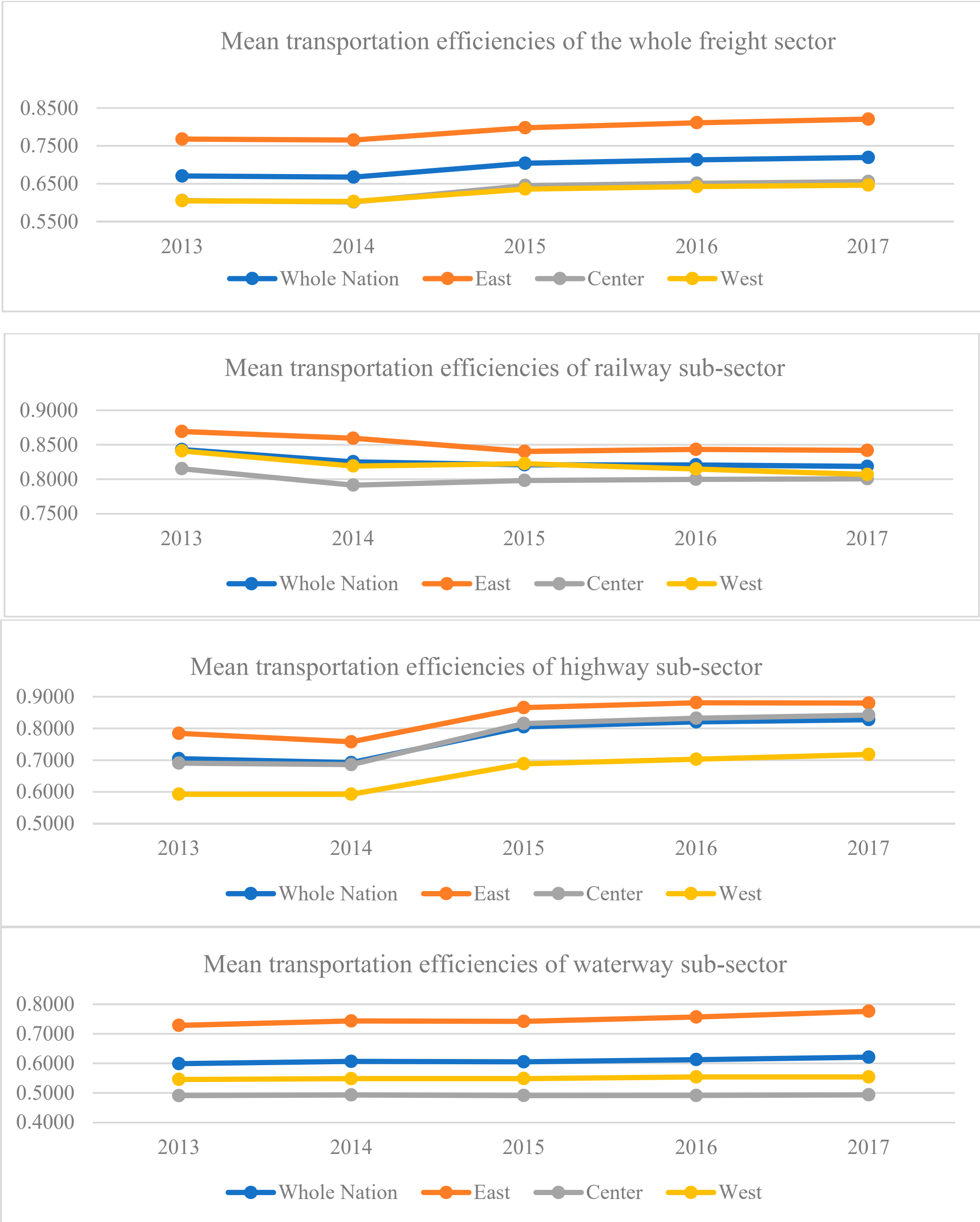

Figure 3. Dynamic trends of mean transportation efficiencies of the freight sector and its three sub-sectors.

As shown in Table 5, the average efficiencies of the railway, highway, and waterway sub-sectors are 0.8257, 0.7699, and 0.6087, respectively. This reveals that the disparities exist in the transportation efficiencies among sub-sectors. Overall, the railway sub-sector performs the best, while the waterway sub-sector performs the worst. It can be inferred that the inefficiency in the Chinese freight sector mainly derives from the lower performance of the waterway sub-sector.

Regarding the overall freight sector, only Tianjin and Shanghai are observed to be efficient. Hebei, Shanxi, Liaoning, Hainan, and Gansu all have mean transportation efficiencies greater than 0.8000. Seventeen regions' mean efficiencies are less than the overall average score of 0.6949 (such as Jilin, Heilongjiang, and Sichuan). This indicates that there is a significant potential for these regions to improve their transportation performance. These results again emphasize that the regions with higher efficiencies are mainly economically developed in the east area, while the regions with lower efficiencies are mainly underdeveloped in the center and west areas. This is confirmed by the mean efficiencies of the three areas, which are 0.7926, 0.6319, and 0.6265, respectively.

Table 5. Mean transportation efficiency results based on Model (2).

Region	ρ_0	ρ_1	ρ_2	ρ_3
Tianjin	1.0000	1.0000	1.0000	1.0000
Hebei	0.9595	1.0000	0.9559	0.9501
Shanxi	0.8498	0.9349	0.5807	1.0000
Liaoning	0.9123	0.7886	0.8318	1.0000
Jilin	0.6063	0.7385	0.7065	0.5033
Heilongjiang	0.4864	0.7459	0.5396	0.3774
Shanghai	1.0000	1.0000	1.0000	1.0000
Jiangsu	0.5243	0.7715	0.6182	0.3924
Zhejiang	0.5937	0.7679	0.7271	0.4572
Anhui	0.6605	0.7964	1.0000	0.4012
Fujian	0.6220	0.7361	0.6997	0.5389
Jiangxi	0.6162	0.7677	0.8907	0.3947
Shandong	0.6213	0.8200	0.7754	0.4643
Henan	0.6238	0.8775	0.7438	0.4731
Hubei	0.6126	0.7964	0.7668	0.4599
Hunan	0.6217	0.7854	0.8882	0.4018
Guangdong	0.7220	0.7335	0.7284	0.7146
Guangxi	0.6099	0.7669	0.8421	0.4141
Hainan	0.9713	0.8908	1.0000	0.9758
Chongqing	0.5731	0.7816	0.6450	0.4668
Sichuan	0.5153	0.7849	0.5683	0.4036
Guizhou	0.6029	0.8206	0.7070	0.4729
Yunnan	0.5255	0.7716	0.5767	0.4217
Shaanxi	0.6569	0.8662	0.7534	0.5343
Gansu	0.8855	0.9007	0.7025	1.0000
Overall	0.6949	0.8257	0.7699	0.6087
East	0.7926	0.8508	0.8336	0.7493
Center	0.6319	0.8011	0.7732	0.4917
West	0.6265	0.8209	0.6588	0.5499

To the railway sub-sector, it can be observed that only Tianjin, Hebei, and Shanghai are deemed to have efficient transportation efficiencies from 2013 to 2017. Shanxi, Henan, Hainan, Shaanxi, and Gansu have mean values greater than the overall average (i.e., 0.8257). The efficiencies of the remaining 17 regions are slightly below the overall average and the gaps are less than 0.1000. Furthermore, the differences in the efficiency of the railway sub-sector among the three areas are small (i.e., 0.8508, 0.8011, and 0.8209, respectively), which is consistent with the dynamic trend shown in Figure 3. The main reason for this is that the majority of railway transportation resources are uniformly allocated and utilized by China Railway Corporation in China. Accordingly, this operational mode has largely eliminated or abated the regional disparities in the performance of the railway sub-sector.

In terms of the highway sub-sector, only Tianjin, Shanghai, Anhui, and Hainan are rated as efficient. Hebei, Liaoning, Jiangxi, Shandong, Hunan, and Guangxi have mean transportation efficiencies greater than the overall average of 0.7699, while the other regions' mean efficiencies are less than the overall average. Regarding the highway sub-sector, China's east area (with a mean transportation efficiency of 0.8336) performs better than the center area (0.7732) and the west area (0.6588). This implies that there exists potential for improvement in transportation efficiency in the central and western provinces, especially for the provinces of Shanxi, Heilongjiang, Sichuan, and Yunnan, which have lower transportation efficiencies.

Regarding the waterway sub-sector, only Tianjin, Shanxi, Liaoning, Shanghai, and Gansu are observed to be efficient. Hebei, Guangdong, and Hainan have mean transportation efficiencies greater than the overall average of 0.6087, while the efficiencies of the remaining 17 regions are less than the overall average. The efficiencies in the central and western regions should be improved to reduce the gaps as compared with the eastern regions, particularly Heilongjiang, Jiangxi, Anhui, Hunan, and Sichuan. Notably, although the average transportation efficiency in the east area is higher, several regions within the east area also need to increase their transportation efficiencies, including Jiangsu (0.3924), Zhejiang (0.4572), and Shandong (0.4643), as their efficiencies are less than the overall average. Interestingly, it is discovered that the west area (0.5499) has higher mean efficiency than the center area (0.4917) during the study period. This may be attributed to the underutilization of water transport resources in the center area.

To illustrate the environmental impact on transportation performance, the transportation efficiency without the consideration of energy and CO_2 is also measured. The results are shown in Table 6. Overall, the efficiencies with the consideration of environmental impact are higher than the efficiencies without the consideration for the freight sector (0.6949 vs. 0.5419) and the three sub-sectors (0.8257 vs. 0.7386; 0.7699 vs. 0.6549; 0.6087 vs. 0.4123). In addition, when the environmental impact is taken into account, the regional disparities among China's regions are smaller, which is reflected by the standard deviation values (0.1658 vs. 0.2480). Hence, the environmental impact affects the transportation efficiency of the freight sector. We conclude that more light can be shed on the transportation performance measure if environmental impact is considered in the efficiency evaluation.

Table 6. Mean transportation efficiency results with or without the consideration of environmental impact.

Region	With				Without			
	ρ_0	ρ_1	ρ_2	ρ_3	ρ_0	ρ_1	ρ_2	ρ_3
Tianjin	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Hebei	0.9595	1.0000	0.9559	0.9501	0.9296	1.0000	0.9339	0.9067
Shanxi	0.8498	0.9349	0.5807	1.0000	0.7747	0.9024	0.3711	1.0000
Liaoning	0.9123	0.7886	0.8318	1.0000	0.8685	0.6830	0.7477	1.0000
Jilin	0.6063	0.7385	0.7065	0.5033	0.4094	0.6077	0.5597	0.2549
Heilongjiang	0.4864	0.7459	0.5396	0.3774	0.2296	0.6189	0.3094	0.0662
Shanghai	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Jiangsu	0.5243	0.7715	0.6182	0.3924	0.2864	0.6572	0.4273	0.0886
Zhejiang	0.5937	0.7679	0.7271	0.4572	0.3906	0.6518	0.5907	0.1858
Anhui	0.6605	0.7964	1.0000	0.4012	0.4908	0.6946	1.0000	0.1019
Fujian	0.6220	0.7361	0.6997	0.5389	0.4330	0.6041	0.5495	0.3083
Jiangxi	0.6162	0.7677	0.8907	0.3947	0.4243	0.6515	0.8361	0.0920
Shandong	0.6213	0.8200	0.7754	0.4643	0.4319	0.7300	0.6630	0.1964
Henan	0.6238	0.8775	0.7438	0.4731	0.4357	0.8163	0.6158	0.2097
Hubei	0.6126	0.7964	0.7668	0.4599	0.4190	0.6946	0.6501	0.1899
Hunan	0.6217	0.7854	0.8882	0.4018	0.4326	0.6781	0.8323	0.1027
Guangdong	0.7220	0.7335	0.7284	0.7146	0.5830	0.6002	0.5926	0.5719
Guangxi	0.6099	0.7669	0.8421	0.4141	0.4148	0.6504	0.7632	0.1212
Hainan	0.9713	0.8908	1.0000	0.9758	0.9559	0.8362	1.0000	0.9616
Chongqing	0.5731	0.7816	0.6450	0.4668	0.3597	0.6724	0.4675	0.2001
Sichuan	0.5153	0.7849	0.5683	0.4036	0.2729	0.6773	0.3524	0.1054
Guizhou	0.6029	0.8206	0.7070	0.4729	0.4043	0.7308	0.5605	0.2094
Yunnan	0.5255	0.7716	0.5767	0.4217	0.2882	0.6573	0.3650	0.1325
Shaanxi	0.6569	0.8662	0.7534	0.5343	0.4854	0.7994	0.6302	0.3014
Gansu	0.8855	0.9007	0.7025	1.0000	0.8283	0.8510	0.5538	1.0000
Std. Dev.	0.1658	0.0847	0.1460	0.2516	0.2480	0.1271	0.2190	0.3763
Overall	0.6949	0.8257	0.7699	0.6087	0.5419	0.7386	0.6549	0.4123
East	0.7926	0.8508	0.8336	0.7493	0.6879	0.7762	0.7505	0.6219
Center	0.6319	0.8011	0.7732	0.4917	0.4479	0.7016	0.6597	0.2376
West	0.6265	0.8209	0.6588	0.5499	0.4398	0.7314	0.4882	0.3248

4.3. Influential Factors of Transportation Efficiency

According to the above results, the inefficiencies of the freight sector can be identified in China's provinces. To improve the transportation efficiency of the freight sector, the factors that may influence transportation efficiency are explored. The transportation efficiency scores obtained from the proposed parallel DEA model are in the range 0–1. Evidently, transportation efficiency is a censored variable. The Tobit model is a suitable tool to deal with the censored data, and it has been applied in many studies [38,62–65] to evaluate the impact of contextual variables on efficiencies as a second stage analysis after the DEA evaluation. Some transportation-related applications measure efficiency using a DEA-Tobit two-stage analysis [47,66,67]. Hence, the Tobit regression method is adopted in this study to examine the impacts of factors that influence transportation efficiencies.

To the best of our knowledge, studies that analyze potentially influential factors on the efficiency of the freight sector are still scarce. The only similar exception is Li et al. [15], who examine several factors that may influence the transportation efficiency of China's regional integrated transport systems. This study tested the impacts of regional GDP (RGDP), transport supply level (TSL), and population density (PD) on transportation efficiency. We believe that transport demand is also an important factor in this study that may have a significant impact on transportation efficiency. In the freight sector, transport demand can be represented by freight volume (FV). To this end, RGDP, TSL, PD, and FV are considered to be possible explanatory variables in our regression analysis.

Generally, RGDP reflects the level of economic development of a district, which can also reflect the freight demand and investment in the transportation sector. Therefore, RGDP is deemed to affect transportation efficiency. Notably, TSL represents the level of development of the transportation sector, which is represented as the share of the fixed investment in the transportation sector to the total fixed investment in one region. The larger the TSL, the more resources invested in the transportation sector, which may affect the efficiency of the freight sector. Moreover, PD is an important indicator that reveals the population distribution of a country or region, which is measured by the population of each administrative area. The higher the PD, the greater the concentration of freight demand. Thus, it may also have an important influence on transportation efficiency. Finally, FV refers to the actual tonnage of cargo transported within a certain period. The higher the FV, the greater the transportation market, which may have an effect on transportation efficiency. The dataset for these four variables is derived from the China Statistical Yearbook 2014–2018. Here, the collinearity diagnostics method is implemented to check for a significant relationship among the variables. The results of variance inflation factors for all variables are 1.999, 1.144, 1.096, and 2.073, respectively, which indicates that there exists no serious collinearity. All variables are normalized to be adopted in the regression. The regression results are reported in Table 7. To check the robustness of the results, we also use the ordinary least squares (OLS) regression to analyze our collected data. The results of Tobit and OLS regression for the freight sector are shown in Table 7. It can be observed that there is no significant difference between the two sets of regression results. The positive and negative of coefficients and the significance levels are consistent in the Tobit and OLS regressions. The probabilities from the likelihood ratio (LR) test for the Tobit regression and the F test for the OLS regression are at the 1% significance level. This means that the regression results can be accepted from a statistical perspective. Hence, the robustness and reliability of the Tobit regression results are verified.

The impacts of the four influential factors on transportation efficiency are detected based on the samples of the freight sector, railway sub-sector, highway sub-sector, and waterway sub-sector, respectively. Here, we use the coefficient of PD as an illustrative example. The coefficient of PD is 0.7088, which indicates that if the PD increases or decreases by one unit, then the corresponding transportation efficiency would also increase or decrease by 0.7088 units. This means that PD has a positive impact on transportation efficiency. On the basis of the regression analysis, two main conclusions can be drawn.

Table 7. Regression results [a]. OLS, ordinary least squares. RGDP, regional gross domestic product; TSL, transport supply level; PD, population density; FV, freight volume; LR, likelihood ratio.

	Freight Sector		Railway Sub-Sector	Highway Sub-Sector	Waterway Sub-Sector
	Tobit	OLS	Tobit	Tobit	Tobit
RGDP	−0.4832 **	−0.4507 **	−0.5055 ***	−0.8736 ***	−0.3560
	(−2.5500)	(−2.6000)	(−3.7900)	(−4.0300)	(−1.3600)
TSL	−0.1822	−0.1632	−0.2337	−0.4589 **	−0.1087
	(−1.0800)	(−1.0700)	(−1.4800)	(−2.4500)	(−0.4300)
PD	0.7088 ***	0.5141 ***	0.7171 ***	0.8871 ***	0.8718 ***
	(4.7200)	(4.2300)	(5.3600)	(5.0200)	(3.7600)
FV	0.0712	0.1076	0.5614 ***	0.7634 ***	−0.3563 *
	(0.3700)	(0.6100)	(3.7600)	(3.5800)	(−1.6600)
Constant	0.5067 ***	0.4868 ***	0.4138 ***	0.5687 ***	0.5306 ***
	(5.4500)	(5.8400)	(4.8400)	(5.4400)	(4.2300)
Log likelihood	−47.6761		−44.3479	−65.9004	−99.7781
LR Chi-square	28.2300		44.8000	35.3900	19.8800
Prob. > Chi-square	0.0000		0.0000	0.0000	0.0005
Pseudo R-squared	0.2284		0.3356	0.2117	0.0906
F		5.8900			
Prob. > F		0.0002			
R-squared		0.1641			

[a] Note: The value in the bracket represents the t-statistics; ***, ** and * indicate the 1%, 5% and 10% significance levels, respectively.

First, RGDP has a significant negative impact on transportation efficiency in the freight sector and the railway and highway sub-sectors, and TSL also has a negative impact on transportation efficiency in the highway sub-sector. There are two reasons for this negative impact. One is the excessive investment in the transportation sector. China's government and transport enterprises have invested numerous resources in transport infrastructure over the past several years. This resulted in excessive investment, reconstruction, and unreasonable competition [15]. Regarding the railway and highway sub-sectors, China has constructed a perfect railway network and road network. Their mileages reach 131 and 4846.5 thousand kilometers, respectively. This means that excessive investment in infrastructure cannot improve the efficiency of the freight sector. The other one is the waste of transportation resources. In practice, some of the transportation capacity is left unused in the railway and highway sub-sectors in China. The unused transportation capacity cannot contribute to freight turnover. This results in a negative effect on transportation efficiency. Consequently, it is essential to strengthen the management of China's freight system to improve the performance of transportation resource utilization.

Second, PD has a significant positive effect on transportation efficiency in the three sub-sectors. FV has a positive effect on transportation efficiency in the railway and highway sub-sectors, but a negative effect on transportation efficiency in the waterway sub-sector. The impact of PD is strong in the railway, highway, and waterway sub-sectors as the coefficients are 0.7171, 0.8871, and 0.8718, respectively. This can be explained by the dense population distribution, which can result in the aggregation of freight demand. When freight demand is concentrated, the means of transport can achieve full-load operation. This means that a massive amount of cargo can be transported by making full use of the transportation capability, which can result in lower energy consumption and improve transportation efficiency. Regarding FV, the regression coefficients are 0.5614, 0.7634, and –0.3563 for the railway, highway, and waterway sub-sectors, respectively. This indicates that freight volume is conducive to improving the performance of the railway and highway sub-sectors and decreasing the performance of the waterway sub-sector. Regarding the railway and highway sub-sectors, because of the centralized dispatch and the range of cargo transportation directions, large-scale transportation can be organized and implemented when the freight volume in the same transportation direction reaches a certain amount. This could result in freight resources being utilized more efficiently. For the waterway sub-sector, the case is the opposite. This can be explained by the existence of freight transportation in an obvious direction in the waterway sub-sector. The transportation routes, loading ports, and discharging ports are fixed in waterway transportation. As the freight volume increases, the growth of freight volume at each port becomes more uneven. This can result in the possibility of cargo ships with a non-full loading returning to the loading ports. The "deadhead kilometers" of cargo ships would also increase. This would negatively affect the transportation performance in the waterway sub-sector.

4.4. Further Discussion and Suggestions

According to the obtained results, some implications and suggestions can be provided, based on the disparity in transportation efficiencies among the freight sub-sectors and regions. Moreover, the impacts of influential factors on transportation efficiency are discussed.

At the national level, it is stated that the average transportation efficiency of the railway sub-sector is the highest during the study period, followed by the highway sub-sector and the waterway sub-sector. The balanced development of freight sub-sectors should be emphasized. The national resources that are input into each sub-sector need to be comprehensively considered. The highway sub-sector and, particularly, the waterway sub-sector should be given priority over the railway sub-sector owing to their lower performances. The authors in [11,12,15] analyze the efficiency of China's regional transportation sector, and they argue that the performance of the whole transport sector should be strengthened. Different from these studies, this study suggests transportation inefficiencies of specific sub-sectors should be improved in advance of improving regional efficiencies of the whole sector. For instance, Heilongjiang should focus on improving the waterway sub-sector's efficiency (0.3774) first, and then the highway sub-sector's efficiency (0.5396) and the railway sub-sector's efficiency (0.7459).

At the areal level, significant disparities are found in the freight sub-sectors, which, to date, have not been explored in the literature. For example, the center area performs worse than the west area in the waterway sub-sector. In specific regions, such as Jiangsu, Anhui, Jiangxi, Hubei, Chongqing, and Sichuan, the transportation efficiencies of the waterway sub-sector are found to be lower. This is the main reason for the inefficient performance of the whole freight sector within these provinces. These provinces belong to the Yangtze River Economic Belt and should have a better performance in waterway transportation. Unfortunately, they performed even worse than the western regions. More measures should be taken to fully utilize cargo ships to accelerate improvements in freight performance.

At the regional level, a significant regional disparity is also determined in the transportation inefficiencies of the whole freight sector, which are discovered across most Chinese provinces. Higher transportation efficiencies are observed in the eastern regions. This indicates that higher transportation efficiencies are more likely to occur in regions with higher economic development levels. This is in agreement with the results obtained for the transportation sector in the work of [12], which is based on the perspective of the whole transportation sector. This is because more investment would improve the technology in and management of the transportation sector in economically developed regions. Notably, some of the eastern provinces' performances, such as Jiangsu (0.5243), are lower than the overall average. Therefore, it is important to improve the performance of the sub-sectors in these inefficient provinces. Considering the regional disparity, the development of the freight sector in the eastern, central, and western provinces should be balanced.

The factors that influence transportation efficiency are also explored. It is observed that PD and FV have significant positive effects on transportation efficiency in the railway and highway sub-sectors, while RGDP and TSL negatively affect the efficiency in the highway sub-sector. The implications from the influential factors should be addressed in transportation efficiency improvement, particularly PD and FV because of their positive effects.

On the basis of the results, the recommendations for improving transportation efficiency in the freight sector are provided as follows.

(1) The government should attempt to advocate for multimodal transportation. It is found that the inefficiencies of the freight sector are mainly caused by the lower performance of the waterway

sub-sector. The energy intensity of waterway transportation is the lowest among the three sub-sectors. Hence, this attempt at advocacy may aim to guide and encourage shippers to adopt multimodal transportation (e.g., a combination of highway and waterway, a combination of railway and waterway transportation, a combination of highway, railway, and waterway transportation) try to make full use of waterway resources in long-distance transportation, and reduce energy consumption and CO_2 emissions [3,47,68]. Multimodal transportation can help to utilize the transportation capacity effectively and strengthen the transportation efficiency of the freight sector. Hence, it should be advocated for by the government based on measurements of the local performance. More financial and technological support should be provided to logistics enterprises to promote this form of transportation.

(2) To achieve multimodal transportation, establishing a national freight information platform is suggested for logistics enterprises. A national freight information platform can collect effectively cargo-related information (such as freight volume and transportation direction), and accordingly make a reasonable transportation plan. This platform may help to aggregate freight volume. Once cargoes to be sent in the same transportation direction are gathered and coordinated, logistics enterprises can implement large-scale centralized transportation to improve transportation performance and save energy consumption. This could be a crucial technical advance for increasing the transportation efficiency of China's freight sector.

(3) The government should encourage collaboration among the three areas in China. Policymakers in the center and west areas should learn from the experiences of the east area. The government should pay more attention to the waterway and highway sub-sectors. The government may organize a business exchange to achieve collaboration among transportation enterprises in different regions. This collaboration may enable enterprises to learn from the operational experiences of others, share transportation resources, and promote the development of innovations and applications for advanced technologies. It may also be conducive to the development of multimodal transportation.

(4) It is necessary for the local government to develop more specific policies that are based on the local sub-sector's transportation performance. For example, considering the low performance of the waterway sub-sector, policymakers should promote the development of waterway transportation to achieve low energy consumption [47]. The regions that are spread along the Yangtze River (e.g., Jiangxi and Anhui) should enhance the efficiency in the waterway sub-sector by providing financial support, such as tax relief or subsidies. While Shannxi and Gansu should focus on strengthening the efficiency of the highway sub-sector, and Heilongjiang should make efforts to improve the efficiency in all three sub-sectors and attempt to balance their development. If a suitable policy cannot be found for each sub-sector, resources may be consumed by all sub-sectors simultaneously, which may induce resource waste and produce unsatisfactory results in practice. However, we must take into account that transportation activities are not limited to one region or a short period of time. Hence, local policies should also consider the influence of transportation activities on the surrounding regions. The sub-sector specific policies should be conducive to facilitating freight transportation in the local region as well as the surrounding regions, and consequently help cargoes to flow smoothly through the transportation network among regions.

Overall, the aforementioned empirical findings demonstrate the effectiveness of the proposed method. The introduced approach has a significant strength that can discriminate sources of inefficiencies from the sub-sectors, and it can be applied to measuring transportation efficiencies of freight (or passenger) transportation systems, which, to date, have not been discussed in the literature. Notably, there are limitations in this study that should be addressed in future research. First, this study does not consider certain pollutants that are in relation to the freight sector, such as NOx, CO, and hydrocarbons. If these pollutant factors could be taken into account, the study may be able to provide a broader environmental view in transportation performance evaluation. Additionally, this study is based on the dataset from the period 2013–2017. More insights into improving transportation performance may be obtained in a study that uses data from a longer observation period. Finally, more advanced methods should be employed to detect the impacts of influential factors on transportation efficiency in complex applications, for example, the bootstrap approach in DEA two-stage analysis. To this end, we expect more valuable future studies based on this research topic.

5. Conclusions

This study proposes a parallel slacks-based measure approach to measure the transportation efficiency of the freight sector. The internal processes within China's freight sector are then investigated in detail. On the basis of the railway, highway, and waterway sub-sectors, the proposed method is able to effectively measure the transportation efficiency of the freight sector, and discern the inefficiencies in its internal sub-sectors. As an important consideration, the environmental impact of energy and energy-related carbon emissions is also considered in the evaluation. This study also applied the parallel DEA model to measure the transportation efficiencies of regional freight sectors in China from 2013 to 2017. The influences of factors on transportation efficiency are also detected.

Findings can be drawn as follows. First, significant regional disparities and sector disparities in transportation efficiency are found. The transportation efficiency scores of the east area are found to be significantly higher than those of the center and west areas. Regarding the highway sub-sector, the center area has a higher mean efficiency than the west area. To the railway sub-sector and the waterway sub-sector, the west area performs better than the center area. These regional disparities should be considered in regional resource allocation for freight operations. Second, the inefficiencies in the freight sector in China are mainly sourced from the lower performance of the waterway sub-sector. This implies that the waterway sub-sector may play an important role in improving transportation performance and reducing carbon emissions, and its development should be encouraged by the government. Third, with regard to influence factors, population density is found to have significant positive impacts on China's freight sector and the three sub-sectors, and freight volume has a significant positive effect on the railway and highway sub-sectors. Hence, the positive effect of population density and freight volume should be addressed in practice. Some relevant suggestions are proposed, such as promoting multimodal transportation and constructing a freight information platform to aggregate the freight volume.

On the basis of the obtained findings, the policy implications can be summarized as follows: (1) the government should attempt to advocate for multimodal transportation, especial for making full use of waterway transportation to reduce energy consumption and protect the environment. (2) A national freight information platform should be built to better coordinate the multimodal transportation process. (3) Collaboration among transportation enterprises in different areas should be encouraged to promote collaborative development among the regional freight sectors. (4) The local government should enact policies to improve local sub-sector transportation performance. These policies should consider the influence of transportation activities on the surrounding regions to facilitate the effective operations of the local transportation system.

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