Environmental efficiency of land transportation in China: A parallel slack-based measure for regional and temporal analysis

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Abstract
As the second largest economic entity in the world, China plays an important role in controlling global carbon dioxide (CO2) emissions. The land transportation sector (including railway transportation and road transportation) has been the most important source of emissions in China and the average CO2 emissions of land transportation were 529.31 million tons during the period 2009–2012. In this study, a parallel Slack-Based Measure Data Envelopment Analysis model is proposed, which is used for evaluating the overall efficiency of the land transportation sector and individual efficiencies of the railway transportation and highway transportation subsectors at the same time, considering CO2 emissions. The empirical results lead to three conclusions: (a) only Anhui province is efficient each year during 2009–2012. (b) The environmental efficiency of the Eastern area in China is the best, followed by the Central area, with the Western area being the worst. (c) The performance of railway transportation is better than that of highway transportation. These three conclusions lead to policy suggestions to promote highway transportation technological innovation and narrow the regional imbalances in land transportation. This paper makes two main contributions: the model advances improvements to methods used in the Data Envelopment Analysis technique, and also provides governments with a practical and yet easy-to-adopt perspective to implement land transportation performance measurement that aids in decision making.

1. Introduction

Since mankind entered the industrial age, the transportation industry has been developing rapidly all over the world (Wu et al., 2015a). This industry includes subsectors of highway transportation, railway transportation, water transportation, air transportation, and pipeline transportation. The rapid development of the Chinese economy over the past 30 years has resulted in the kilometers of both High-Speed Railway and Highway ranking the first in the world, reaching 16 thousand kilometers and 111.9 thousand kilometers respectively in 2014 (Ministry of Transport of the People’s Republic of China (MTPRC), 2015).

Among all industries in China, the transportation industry acts as a more and more important role of regional economic development when it meets the augmented transportation needs induced by the growth of investment (Liu and Wu, 2015). Within the whole transportation industry, land transportation (including railway transportation and highway transportation) has been the most important sector and the most important source of carbon dioxide (CO2) emissions. The passenger volume and freight volume of land transportation reached 21.44 billion people and 37.14 billion tons in 2014, accounting for 97.04% and 86.11% of the whole transportation industry (MTPRC, 2015). Furthermore, the average annual CO2 emissions of land transportation were 529.31 million tons in 2009–2012 (Chang et al., 2013; Bi et al., 2014a,b), and the average growth rate of CO2 emissions was 8.18%. From these statistics it can be seen that it is most meaningful and interesting to focus on land transportation rather than other sectors of the whole transportation industry.

Accordingly, land transportation is an active and important factor to actualize economic and environmental development. Despite and because of its importance, the transportation industry has one of the highest levels of energy consumption and pollution among industries worldwide (Ibanez and McCalley,
2011; Motasemi et al., 2014). The transportation industry proportion of total energy consumption is 25% or more in developed countries, and land transportation constitutes more than 80% of that (Nian, 2014). More seriously, air pollution in China has also become more of a problem in recent years, and one reason for this is that exhaust emissions from the transportation industry have been increasing. The transportation industry is the second-largest source of emissions of air pollutants, accounting for 25% of global CO2 emissions in 2014 according to the World Energy Outlook published by the International Energy Agency. Almost 75% of these emissions is caused by land transportation (Song et al., 2015). Regarding China’s land transportation in particular, its energy consumption is overwhelmingly dominated by fossil fuels, which can produce large quantities of undesirable gases like CO2. On the basis of the huge transportation demand, the emissions of undesirable gases such as CO2 should receive more attention (Wu et al., 2015b, 2016). In fact, the CO2 emissions and environmental pollution are currently hindering the sustainability of China’s economic growth. In 2007, China surpassed the USA and became the world’s largest contributor of CO2 emissions (Wang et al., 2013). To address this issue, China’s 12th five-year plan (2011–2015) sought to establish a “green, low-carbon, development concept” (State Council of the People’s Republic of China (SCPRC), 2011). For 2015, China planned to increase the proportion of non-fossil fuels in energy generation to 11.4%, of China (SCPRC), 2011). For 2015, China planned to increase returns to scale for evaluating the CO2 emissions performance of environmental overall technical efficiency, pure technical efficiency, and scale efficiency of different regions of China from 2000 to 2006, with the undesirable output of industrial waste gas being treated as an input in the environmental efficiency analysis. Similarly, Chen and Jia (2016) also evaluated the environmental efficiency of China’s regional industry based on a DEA approach. Song et al. (2013) utilized a Super-SBM model to measure and calculate the energy efficiency of the group of nations called BRICS (Brazil, Russia, India, China, and South Africa), and then analyzed each member country’s present status and development trend. Song and Wang (2014) calculated China’s regional environmental efficiency performance based on technological progress and government regulation by applying a DEA method, in which study the concept of DEA decomposition is proposed with a search algorithm approach. Xie et al. (2014) evaluated the environmental efficiency of electric power industries in Brazil, Russia, India, and China by using the Malmquist index method based on DEA. Balezentis and Balezentis (2011) applied energy use (which has been neglected in the present study) as an input to assess the efficiency of the Lithuanian transport sector, on the basis of which Balezentis et al. (2016) estimated the environmental performance by employing DEA. All of these studies investigated the environmental efficiency from various perspectives with different models, which contributes much to both the theory and the practice of environmental efficiency evaluation.

Besides evaluation of environmental efficiency, DEA models are also applied to transportation efficiency evaluation. Most of the current studies on transportation efficiency assessment mainly focus on two research perspectives: technology efficiency without considering undesirable outputs, and environmental efficiency taking undesirable outputs into account. Without considering undesirable outputs, Hayuth (1993) applied DEA mathematical programming techniques to assess the efficiency of 20 seaports and Tongzon (2001) applied DEA to provide an efficiency measurement of four Australian and twelve other international container ports. Analogously, Yoshida and Fujimoto (2004) and Barros and Diecke (2008) employed DEA models to evaluate the technology efficiency of air transportation in Japan and Italy respectively. While there are other studies on transportation efficiency evaluation (such as Frans et al. (2010) and Lu et al. (2012)), they ignore the environmental factor which has attracted more and more attention.

In order to strengthen the research by considering both technology and environmental factors, Vedantham and Oppenheimer (1998) investigated the CO2 emissions of the air transportation sector and provided some suggestions for governments. Mazzarino (2000) studied the influence of transportation on the environment in Italy. Along this research direction, González and Marrero (2012) and Okada (2012) investigated the CO2 emissions of the highway transportation sectors in various countries; and Rentziou et al. (2012) studied the CO2 emissions of passenger transportation and freight transportation. Some studies have investigated the CO2 emissions of different national transportation industries, such as Pongthanaisawan and Sorapipatana (2013) who analyzed the CO2 emissions and emissions reduction policy of Thailand’s transportation industry; and Lipsy and Schipper (2013) who discussed the relationship between the energy utilization efficiency and CO2 emissions. In terms of environmental efficiency of transportation in China, Qu et al. (2010) and Wang et al. (2012) used the system optimization method to forecast the CO2 emissions of the Chinese transportation industry in various contexts; Loo and Li (2012) and Wang et al. (2012) estimated carbon emissions from road freight transport through the method provided by the Intergovernmental Panel on Climate Change (IPCC);
Wang et al. (2011) and Zhou et al. (2013) investigated the performance of the whole transportation industry employing a similar method; Cai et al. (2012) calculated the CO2 emissions and further pointed out that methods based on the energy consumption have more accuracy than other methods; and He and Chen (2013), Huo et al. (2012a, 2012b) forecasted the demand of transportation in the future.

While the literature contains much about environmental efficiency evaluation, it lacks comprehensive consideration of the most important sector of the transportation industry — land transportation — from the perspectives of improving utilization efficiency of the resources and reducing pollution at the same time. Also, it is necessary to do comparative analysis between technology efficiency of the resources and reducing pollution at the same time.

Chen (2013), Huo et al. (2012a, 2012b) forecasted the demand of transportation sectors in China considering resource utilization and CO2 emissions. More specifically, the resource and environmental efficiency of the whole parallel system should be estimated by using a parallel production framework of railway transportation and highway transportation, both of which include passenger and freight transportation.

The first DEA model, called the CCR model, was proposed by Charnes et al. (1978). The CCR model assumes that there are n DMUs to be evaluated and each DMU has m inputs and s outputs which are denoted as \( x_{ij}(i = 1,2,...,m) \) and \( y_{ij}(r = 1,2,...,s) \) respectively. Then the input-oriented CCR model can be shown in its linear form as follows:

\[
\begin{align*}
\text{min} & \quad \theta^* \\
\text{s.t.} & \quad \sum_{j=1}^{m} x_{ij} \lambda_j + s_j^- = \theta x_{0i}, i = 1, 2, \cdots, m; \\
& \quad \sum_{j=1}^{n} y_{ij} \lambda_j - s_j^- = y_{0r}, r = 1, 2, \cdots, s; \\
& \quad \lambda_j \geq 0, j = 1, 2, \cdots, n.
\end{align*}
\]

In model (1), \( s_j^- \) are the slacks of inputs and outputs. The optimal \( \theta^* \) denotes the efficiency of the DMU under evaluation. A DMU is called DEA efficiency if both \( \theta^* = 1 \) and all optimal slacks \( s_j^- = 0 \) at the same time.

In this paper, the efficiency evaluation of land transportation sectors in 30 administrative regions of China is considered. The system produces an undesirable output (CO2 emissions) and it is a parallel structure. The detailed structure is shown in Fig. 1.

In the land transportation sector, there are both desirable outputs such as passengers transported, and undesirable outputs such as CO2 emissions. The traditional CCR model cannot handle situations with parallel structure or undesirable outputs. Moreover, the CCR model is a radial model which neglects the slacks when calculating the efficiencies of the DMUs. Therefore, the slack-based measure (SBM) is considered a more proper approach to evaluate the resource utilization and environmental efficiency of DMUs. Note that the sub-DMUs (railway transportation and highway transportation) in the parallel system have no interactions, which means that their efficiencies can be evaluated independently. Assume that each sub-DMU consumes \( m \) inputs to produce \( s_1 \) undesirable outputs and \( s_2 \) desirable outputs which are denoted as \( y_{ij}(i = 1,2,...,m) \), \( y_{0r}(r = 1,2,...,s_1) \), and \( y_{0p}(p = 1,2,...,s_2) \), respectively. Then the following SBM model (2) is proposed for calculating the efficiency of the sub-DMUs of the land transportation sector.

\[
\begin{align*}
\text{min} & \quad h_0 = 1 - \frac{1}{m + s_1} \left( \sum_{i=1}^{m} S_{i0} + \sum_{r=1}^{s_1} y_{0r} \right) \\
\text{s.t.} & \quad \sum_{j=1}^{n} x_{ij} \lambda_j + s_j^- = x_{0i}, i = 1, 2, \cdots, m; \\
& \quad \sum_{j=1}^{n} y_{ij} \lambda_j - s_j^- = y_{0r}, r = 1, 2, \cdots, s_1; \\
& \quad \sum_{j=1}^{n} y_{ij} \lambda_j - s_j^- = y_{0p}, p = 1, 2, \cdots, s_2; \\
& \quad \lambda_j \geq 0, j = 1, 2, \cdots, n.
\end{align*}
\]

In model (2), the undesirable output of CO2 emissions is handled with the assumption of strong disposability. \( s_j^-, s_j^+, s_p^+ \) are respectively the slacks of inputs, desirable outputs, and undesirable outputs. The optimal \( h_0 \) represents the efficiency of the DMU under evaluation.

It is noted that model (2) is a non-linear programming problem. Let \( A_i = \lambda_i, \quad S_{i0} = s_i^+, \quad S_{0r} = y_{0r}, \quad S_{0p} = y_{0p}^+ \). Then, the basis of Charnes-Cooper transformation, Model (2) can be transformed into the following linear model (3).

\[
\begin{align*}
\text{min} & \quad h_0 = t - \frac{1}{m + s_1} \left( \sum_{i=1}^{m} S_{i0} + \sum_{r=1}^{s_1} y_{0r} \right) \\
\text{s.t.} & \quad t = \frac{1}{s_2} \sum_{p=1}^{s_2} y_{0p}^+; \\
& \quad \sum_{j=1}^{n} x_{ij} \lambda_j + s_j^- = x_{0i}, i = 1, 2, \cdots, m; \\
& \quad \sum_{j=1}^{n} y_{ij} \lambda_j - s_j^- = y_{0r}, r = 1, 2, \cdots, s_1; \\
& \quad \sum_{j=1}^{n} y_{ij} \lambda_j - s_j^- = y_{0p}, p = 1, 2, \cdots, s_2; \\
& \quad A, S_{i0}, S_{0r}, S_{0p} \geq 0, j = 1, 2, \cdots, n.
\end{align*}
\]

By using model (3), the efficiency of each sub-DMU of the transportation system can be obtained. However, from a global perspective, the efficiency of the whole parallel system should be evaluated also. The efficiency of the sub-DMUs needs to be aggregated. Here the following model is proposed to obtain the overall...
efficiency of the whole parallel system.

\[
\min E_0 = \omega_1 E_1 + \omega_2 E_2
\]

\[
s.t. E_1^j = \frac{1 - \frac{1}{m + s_1}}{s_1} \left( \sum_{i=1}^{s_1} x_{ij}^l - s_{i0}^l \right) + \frac{1}{s_2} \left( \sum_{p=1}^{s_2} \frac{z_{p0}^l}{y_{p0}^l} \right)
\]

\[
E_2 = \frac{1 - \frac{1}{k + z_1}}{z_1} \left( \sum_{i=1}^{z_1} x_{ij}^l - s_{i0}^l \right) + \frac{1}{z_2} \left( \sum_{p=1}^{z_2} \frac{z_{p0}^l}{y_{p0}^l} \right)
\]

\[
\min E_0 = \frac{1 + \frac{1}{s_1} \left( \sum_{i=1}^{s_1} x_{ij}^l - s_{i0}^l \right)}{s_1} + \frac{1}{s_2} \left( \sum_{p=1}^{s_2} \frac{z_{p0}^l}{y_{p0}^l} \right)
\]

Note that \( \omega_1 + \omega_2 = 1 \). By substituting the \( \omega_1 \) and \( \omega_2 \) into model (4), the following model (5) is obtained.

\[
\min E_0 = \frac{1 + \frac{1}{s_1} \left( \sum_{i=1}^{s_1} x_{ij}^l - s_{i0}^l \right)}{s_1} + \frac{1}{s_2} \left( \sum_{p=1}^{s_2} \frac{z_{p0}^l}{y_{p0}^l} \right)
\]

\[
s.t. \sum_{j=1}^{n} x_{ij}^l - s_{i0}^l = x_{i0}^l, i = 1, 2, \ldots, m;
\]

\[
\sum_{j=1}^{n} y_{ij}^1 + s_{i0}^1 = y_{i0}^1, \quad j = 1, 2, \ldots, s_1;
\]

\[
\sum_{j=1}^{n} y_{ij}^2 + s_{i0}^2 = y_{i0}^2, \quad j = 1, 2, \ldots, s_2;
\]

\[
\sum_{j=1}^{n} x_{ij}^2 \eta_j + s_{i0}^2 = x_{i0}^2, \quad j = 1, 2, \ldots, k;
\]

\[
\sum_{j=1}^{n} y_{ij}^3 \eta_j + s_{i0}^3 = y_{i0}^3, \quad j = 1, 2, \ldots, z_1;
\]

\[
\sum_{j=1}^{n} y_{ij}^4 \eta_j + s_{i0}^4 = y_{i0}^4, \quad j = 1, 2, \ldots, z_2;
\]

\[
\lambda_j \geq 0, j = 1, 2, \ldots, n.
\]

\[
\eta_j \geq 0, j = 1, 2, \ldots, n.
\]

In model (4), \( \omega_1 \) and \( \omega_2 \) are the weights attached to the efficiencies of the land transportation sector's sub-DMU1 (railway transportation) and sub-DMU2 (highway transportation) respectively. Model (4) is a non-linear programming problem, which can be transformed into a linear one with the following steps.

**Step 1:** Following the ideas of Chen et al. (2009, 2010) and Amirtreimooiri (2013), the values of the weights \( \omega_1 \) and \( \omega_2 \) are defined as follows.

**Step 2:** Let \( \frac{1}{1} = 2 + \frac{1}{s_1} \left( \sum_{i=1}^{s_1} x_{ij}^l \right) + \frac{1}{s_2} \left( \sum_{p=1}^{s_2} \frac{z_{p0}^l}{y_{p0}^l} \right) \).
S_{ij}^1 = S_{ij}^{1b} = ts_{ij}^{1b} - ts_{ij}^{1b - }, S_{ij}^{2g} = ts_{ij}^{2g} - ts_{ij}^{2g - }, \quad \Gamma_j = \eta_j S_{ij}^2 = ts_{ij}^{2d} - ts_{ij}^{2d - },
\text{and } S_{ij}^{2g} = ts_{ij}^{2g - }.
\quad \text{Then, on the basis of the Charnes-Coooper transformation, the above non-linear programming problem (5) can be transformed into the following linear model (6).}

\begin{align*}
\min E_0 & = 2t \frac{1}{m+1} \left( \sum_{i=1}^{m} \frac{y_{ij} x_{ij}}{x_{ij}} + \sum_{j=1}^{s} \frac{y_{ij} x_{ij}}{x_{ij}} \right),
\text{s.t.} & = 2t + \frac{1}{x_{ij}} \left( \sum_{p=1}^{r} \frac{y_{ij} x_{ij}}{x_{ij}} + \sum_{p=1}^{s} \frac{y_{ij} x_{ij}}{x_{ij}} \right) \\
& \frac{n_{ij} x_{ij} A_j + S_{ij}^{1b}}{S_{ij}^{1b}} = t x_{ij}, i = 1, \ldots, m; \\
& \frac{n_{ij} y_{ij} A_j + S_{ij}^{1b}}{S_{ij}^{1b}} = t y_{ij}, r = 1, \ldots, s_1; \\
& \frac{n_{ij} y_{ij} A_j + S_{ij}^{1b}}{S_{ij}^{1b}} = t y_{ij}, p = 1, \ldots, s_2; \\
& \frac{n_{ij} x_{ij} A_j + S_{ij}^{1b}}{S_{ij}^{1b}} = t x_{ij}, k = 1, \ldots, k; \\
& \frac{n_{ij} y_{ij} A_j + S_{ij}^{1b}}{S_{ij}^{1b}} = t y_{ij}, r = 1, \ldots, z_1; \\
& \frac{n_{ij} y_{ij} A_j + S_{ij}^{1b}}{S_{ij}^{1b}} = t y_{ij}, p = 1, \ldots, z_2; \\
& \Gamma_j \geq 0, j = 1, \ldots, n; \\
& \eta_j \geq 0, j = 1, \ldots, n.
\end{align*}

(6)

By using the above proposed model (6), the overall efficiency of the whole parallel system can be obtained. With this approach, the efficiencies (E_0, E_1, \text{ and } E_2^e) respectively of the whole land transportation sector, the railway transportation subsector, and highway transportation subsector can be calculated. Compared with the classic DEA model which is used to evaluate DMU as a whole “black box” (ignoring the DMU internal structure), the current parallel SBM DEA model could help decision maker have a more thorough understanding of system internal structure, and it could make the inefficiencies of sub-systems be demonstrated fully (Liang et al., 2006).

3. Empirical study

3.1. Indices and data

In this study, the resource utilization and environmental efficiency of the land transportation sectors of 30 provincial-level regions in China is measured, including the railway transportation subsectors and highway transportation subsectors, from 2009 to 2012. Six factors are used as inputs and outputs for railway and highway, factors which have been used in published works such as Baležentsis et al. (2016), Wu et al. (2015a), and Song and Wang (2014). For the railway transportation subsector, the two inputs are railway length and locomotives, which are the most basic resources to operate (Gao et al., 2011). As for the output variables, in general, there are two alternative sets of output indices for evaluating the performance of railways (Jain et al., 2008). The first one consists of revenue output indices. The second type of output indices consists of railway passenger turnover and railway freight turnover, which can be defined as passenger trips or freight volume multiplied by the distance they have traveled. In order to evaluate the resources and environmental efficiency, railway passenger turnover and railway freight turnover are selected as desirable outputs, and CO₂ emissions is selected as the only undesirable output. The same as railway transportation subsector, for the highway transportation subsector, highway length and automobiles are selected as the two inputs. The two desirable outputs are highway passenger turnover and highway freight turnover. Again, the only undesirable output is CO₂ emissions (Wu et al., 2015a). The input-output indices used in this paper are summarized in Table 1.

The data related to railway/highway length, locomotives/automobiles, railway passenger/freight turnover, and highway passenger/freight turnover are available in the China Statistical Yearbook, China Energy Statistical Yearbook, and other information from the Ministry of Transport of the People’s Republic of China, including the Economy Prediction System. However, there do not have official statistics yet on provincial CO₂ emissions in China. Therefore, this paper estimates the CO₂ emissions using a fuel-based carbon footprint model, which has been successfully applied by Chang et al. (2013), Bi et al. (2014a,b), and Wu et al. (2015a,b). The descriptive statistics for the inputs and outputs of these 30 administrative regions are presented in Table 2.

3.2. Results and analysis

The proposed model is used to evaluate the resource utilization and environmental efficiencies of 30 Chinese regional land transportation sectors. The efficiency scores of land transportation (E_0), railway transportation (E_1) and highway transportation (E_2^e) in the period 2009—2012 are listed in Table 3. And for comparison, the land transportation system is also assessed as a whole “black box” (Tone and Tsutsui, 2009) employing a SBM-DEA model, the efficiency scores of land transportation (E, as a black box) are also listed in Table 3.

Firstly, as to land transportation efficiency (E are listed in columns 2—5 and E_0 are listed in columns 6—9 in Table 3), the average efficiency scores of E_0 are lower than those of E, and the inefficient DMUs in columns 6—9 are more than those in columns 2—5 in Table 3, all of which indicate that the model used in this paper could disclose more inefficiency of land transportation internal structure. After a simple comparison, with regard to E_0 (columns 6—9), only Anhui is resource utilized and environment efficient each year from 2009 to 2012. Beijing is efficient in 2009, 2010, and 2012. Guangdong is efficient in 2011 and 2012, and Shanghai and Hainan are efficient only in 2010 and 2011 respectively. There is no significant correlation between efficiency and development degree of each province. Take Anhui as an example, while Anhui is not a developed region, it is efficient every year during 2009—2012. First, the raw data indicates that inputs increased less (Railway mails, Locomotives, Highway miles and Automobile increased −0.84%, 18.61%, 16.17% and 31.86% respectively only) and the outputs increased (undesirable output decreased) more (Railway passenger turnover, Railway freight turnover, CO₂ for Railway, Highway passenger turnover, Highway freight turnover, and CO₂ for Highway increased 54.41%, 8.36%, —72.32%, 103.65%, 254.36% and —49.59% respectively) than the average value of all provinces during 2009—2012, mainly because of its rapid development (the GDP growth rates of Anhui are 12.9% in 2009, 14.6% in 2010, 13.5% in 2011, and 12.1% in 2012). And meanwhile the highway desirable outputs and undesirable output are particularly outstanding. Second, as a less-developed province, the lesser CO₂ emissions is an important reason that lead to high efficiency (the efficiency scores of land transportation in 2009, 2011 and 2012 reduced from 1 to 0.83, 0.94, 0.94 respectively when evaluated without undesirable
output as shown in Table 5). Reversely, the worst performing regions are Xinjiang in 2009 and Yunnan in 2010, 2011, and 2012. For these regions with poor efficiency, the raw data indicates that the railway length in Xinjiang is 29.66% more than the average length in China in 2009, and also indicates that the average (2010–2012) railway passenger turnover and the average (2010–2012) railway freight turnover in Yunnan are 70.38% and 57.64% less than the national figures respectively. Based on Table 3, it could be inferred that the resource utilization and the prevention and control of CO2 emissions of land transportation are not very good because of the low average efficiency scores ($E_0 = 0.559$), which are shown graphically in Fig. 2.

Secondly, when decomposing the overall land transportation efficiency into the two subsector efficiencies, great differences between the subsectors can be found. Considering railway transportation efficiency (columns 10–13 in Table 3), 8 regions (Beijing, Tianjin, Hebei, Inner Mongolia, Anhui, Jiangxi, and Ningxia) are continuously resource utilized and environmental efficient during the period 2009–2012. Four regions are efficient in three years (Shanghai, Guangdong, and Zhejiang in 2010–2012; Henan in 2009–2011). Hainan is efficient in 2011 and 2012, and Fujian, Shandong, Hunan, Guangxi, and Chongqing are efficient in only one year. The regions with the worst performance are Shaanxi in 2009, Hainan in 2010, Qinghai in 2011, and Yunnan in 2012. From Fig. 2 it could be easily seen that the resource utilization and the prevention and control of CO2 emissions of rail transportation are the best with high average efficiency score ($E_0 = 0.799$) compared to the highway transportation subsector and the overall land transportation sector.

Finally, looking at highway transportation efficiency (columns 14–17 in Table 3), the performances of different regions are similar to the overall situation, but worse in terms of efficiency. Anhui is the only region that is efficient in terms of both resource utilization and environment throughout 2009–2012. It is followed by Hainan which is efficient in three years (2009, 2010, and 2011). Shanghai, Jiangsu, and Guangdong are efficient in two years, and Shaanxi is efficient in 2011. From the perspective of average score ($E_0 = 0.466$), the highway subsector efficiency is the worst (in Fig. 2).

In a word, using this proposed approach for land transportation efficiency, decomposition can distinguish the performances of railway transportation and highway transportation for better analysis.

To gain more understanding, it is necessary to analyze the efficiency of land transportation sectors on a larger scale, therefore the 30 regions are grouped into three categories (Eastern area, Central area, and Western area) on the basis of geography. These groups and their constituent regions are listed in Table 4.

Table 4 shows that 11, 10, and 9 regions are considered in the eastern, central, and western areas of China respectively. In order to reflect the difference of the three areas, Table 5 and Figs. 3–5 illustrate each area’s average efficiency from the view of space-time.
higher than those of other areas, and that of Western China is not good, no matter which aspect is considered (overall land transportation efficiency, railway transportation efficiency, or highway transportation efficiency). This conclusion has been verified by Wu et al. (2015a) and Liu and Wu (2015). The reason is that the Eastern area has relatively better development of economy and transportation. Furthermore, the land transportation efficiency score is just 0.855 because of the high demand for railway transportation in the Eastern area, especially the demand for railway transportation (Mao, 2010). The low demand leads to poor utilization of railway transportation in the east of China.

It is interesting to see in column 6 of Table 5 that the environmental efficiency of the Eastern area is decomposed into railway transportation efficiency and highway transportation efficiency, as shown in rows 5–10 of Table 5. While the average railway transportation efficiency score in the Central area is the best, the Eastern area has the highest average highway transportation efficiency score. It is clear that the high land transportation efficiency in the Eastern area owes much to the good highway transportation.

From Table 5, it can be found that the average land transportation efficiency of Eastern China (\(E_0 = 0.663\)) in 2009–2012 is higher than those of other areas, and that of Western China (\(E_0 = 0.393\)) is the worst. That is, the east of China does the best in the land transportation sector considering the resource and environmental factors. This conclusion has been verified by Wu et al. (2015a) and Liu and Wu (2015). The reason is that the Eastern area has relatively better development of economy and transportation. Furthermore, the land transportation efficiencies of different areas are decomposed into railway transportation efficiency and highway transportation efficiency, as shown in rows 5–10 of Table 5. While the average railway transportation efficiency score in the Central area is the best, the Eastern area has the highest average highway transportation efficiency score. It is clear that the high land transportation efficiency in the Eastern area owes much to the good highway transportation.

Figs. 3–5 show that the Eastern area has the highest efficiency not only in terms of land transportation efficiency, but also in each subsector (railway transportation efficiency and highway transportation efficiency) with one exception — 2009 — because of the Global Financial Crisis in 2009 which reduced the demand for land transportation in the Eastern area, especially the demand for railway transportation (Mao, 2010). The low demand leads to poor utilization of railway transportation in the east of China.
emissions) are also evaluated; these technical efficiencies are listed in column 6 (scores in parenthesis) of Table 5. In the Eastern area, the environmental efficiency scores are always lower than the technical efficiency (without undesirable output) scores, no matter for the whole land transportation sector (0.663 (0.683)), the railway transportation subsector (0.826 (0.866)) or the highway transportation subsectors (0.596 (0.604)). It means that the calculated efficiencies of land transportation, railway transportation, and highway transportation are lower when the undesirable output (CO2 emissions) is considered. In the Central area, a contrasting result was found: the environmental efficiency score of railway transportation is lower but the environmental efficiency score of highway transportation is higher than efficiency scores without considering undesirable output (CO2 emissions). Moreover, the situation in the Western area is the same as that in the Central area. Finally, opposite to Eastern area, the environmental efficiencies are better than those without considering CO2 emissions in central and western areas, which conforms to the truth that China’s development strategy has paid more attention to expanding the transportation industry than to handling the accompanying problems of environmental pollution.

4. Conclusions

The goal of this paper is to analyze the resource utilization and environmental efficiency of China’s regional land transportation sectors. Firstly, a framework is developed for measuring resource and environmental efficiency of land transportation sector considering resource utilization and CO2 emissions based on a parallel SBM-DEA model. Secondly, the models are employed to assess the environmental efficiency and the technology efficiency (i.e. without considering undesirable output) of land transportation and its two dominant subsectors. The empirical study of China’s 30 administrative regions concludes that: (a) The region with the best efficiency for land transportation is Anhui, which had optimal efficiency in both railway and highway transportation in each year considered; and the regions with optimal efficiencies for railway transportation are Beijing, Tianjin, Hebei, Shanxi, Inner Magnolia, and Jiangxi in 2009—2012. (b) The average overall efficiency of Chinese land transportation sectors reveals that many regions have poor environmental and technology efficiency, and that the Eastern area is better than the others. (c) Analyzing subsector efficiencies instead of overall efficiency (i.e. decomposition of the land transportation sector into two subsectors), the results reveal that railway transportation has relatively better environmental efficiency and technology efficiency than highway transportation.

Based on this study, some policy recommendations are provided for the Chinese national government: (a) Narrow the regional imbalances in the land transportation sector. Considering the environmental performance of railway transportation, the government should pay more attention to reducing CO2 emissions in Eastern, Central and Western areas. Considering the environmental performance of highway transportation, the government should pay more attention to reducing CO2 emissions in Eastern areas. (b) Promote highway transportation technological innovation and upgrade vehicle emissions standards because of the bad
environmental and technology efficiency in all areas. Thus, more measures should be taken by highway transportation departments and the public to reduce CO₂ emissions and improve resource utilization.

The main contributions of this paper lie in two aspects. Firstly, the proposed model can be used for evaluating the overall efficiency of land transportation sectors and decomposition efficiency of railway transportation and highway transportation at the same time. This is a major difference of this model from the other current models. Secondly, some different policy and operational measures are pointed out to improve the resource utilization and to reduce CO₂ emissions in pointed areas.

The current study investigated the environmental efficiency of China’s regional sectors using data from 2009 to 2012. Accordingly, further research directions can be drawn from our study. One is that the environmental efficiency of combined transportation should get more attention, such as sea-railway combined transportation. Another one is to use these methods on cold chains (i.e. temperature-controlled supply chains) to see if the environmental efficiency results are the same as those of the general transportation chains considered here.

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