

Article

Improving Transportation Technologies for Carbon Reduction in the Chinese Provinces along the Silk Road

Qiang Zhang ¹, Jun Shan ¹ and Hai Long ^{2,*} 

¹ School of Business, Xi'an University of Finance and Economics, Xi'an 710100, China; zhangqiang0292005@163.com (Q.Z.); sj2270444344@163.com (J.S.)

² International Economic School, Anhui International Studies University, Hefei 231201, China

* Correspondence: soholonghai@163.com

Abstract: As an economic corridor, the Silk Road Economic Belt (SREB) connects the East to Western nations, where carbon emissions are gradually becoming severe. This study aims to provide solutions for dealing with carbon emissions from the transportation of the SREB in the Chinese range. By employing the Malmquist index method of data envelopment analysis (DEA), this study develops models to test the different carbon-reduction performances (CRP) of transportation in the Chinese provinces along the SREB. This study shows that carbon-reduction performance has improved since 2013 because of the improvements in transportation technology. Technical efficiency, including scale efficiency and pure technological efficiency, may improve carbon reduction, while the lagged technological progress restricts the CRP. It is further suggested that the provincial CRPs are different. The southwest provinces have the best decarbonization performance, followed by the northwest, while the northeast provinces, including Inner Mongolia, underperform compared to the others. Therefore, the government should release some technology-orientated policies as soon as possible to facilitate the improvements in technical efficiency and progress in transportation vehicles and infrastructures in order to consequently reduce carbon emissions.

Keywords: carbon reduction; transportation technologies; Malmquist index; Silk Road Economic Belt



Citation: Zhang, Q.; Shan, J.; Long, H. Improving Transportation Technologies for Carbon Reduction in the Chinese Provinces along the Silk Road. *Energies* **2022**, *15*, 2718.

<https://doi.org/10.3390/en15082718>

Academic Editor: Wen-Hsien Tsai

Received: 13 March 2022

Accepted: 5 April 2022

Published: 7 April 2022

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1. Introduction

Carbon dioxide (CO₂) emitted due to fossil-fuel consumption is the main component of greenhouse gases, accounting for around 60% of global greenhouse gases [1]. Fossil-fuel consumption grows with fast-growing industrialization, leading to climate change due to increasing CO₂ emissions. In particular, transportation CO₂ emissions have increased remarkably, and this upward trend is ongoing and is expected to increase by 41% by 2030 compared with 2007 [2]. According to data from the U. S. Environmental Protection Agency (EPA), transportation has become the most significant greenhouse-gas emission source since 2017 (<https://usafacts.org/articles/transportation-now-largest-source-greenhouse-gas-emissions/> accessed on 1 January 2020).

Balancing economic growth and CO₂ emissions is a big challenge for many countries. Azam et al. [3] suggest that CO₂ emissions have a significant positive association with economic growth in China, Japan, and the USA. As such, CO₂ emission reduction and economic development are becoming hot topics worldwide. Many countries have developed a range of plans to lower carbon emissions from the transportation sector. For instance, the UK initiated “Low Carbon Transport: A Greener Future” in 2009. A range of policies have been implemented in China to achieve CO₂ emission reduction, such as the carbon tax, energy upgrades, subsidies for clean-energy vehicles, etc. Without these kinds of policy interventions, the transportation sector relies on fossil fuels [4]. Godil et al. [5] reveal that GDP growth may drive CO₂ emissions from the transportation sector. As a developing country and the second-largest economy globally, China faces more challenges

in balancing decarbonization and economic development, because China has generated approximately 235 billion tons of CO₂ in total and 12.7% of global cumulative emissions (<https://ourworldindata.org/contributed-most-global-co2> accessed on 1 January 2022).

By 2020, China had become the economy sharing the third-greatest amount of global cumulative CO₂ emissions (<https://ourworldindata.org/contributed-most-global-co2> accessed on 1 January 2022). Currently, transportation CO₂ emissions in China are on-going because of the fast-growing Chinese transportation industry. This kind of growth is relatively higher than in other countries or regions. The Silk Road Economic Belt (SREB), as the critical component of the One Belt, One Road initiative, aims to improve the regional economy along the SREB, including 12 provinces in China that possess abundant resources (see Figure 1). With the central government initiative, local governments encourage local businesses to expand internationally through a range of policy incentives [6]. Therefore, the SREB is expected to contribute to the economic momentum. The Silk Road is an economic connection between China and Europe, and a growing volume of trade generates a new round of carbon emissions from transportation, because the SREB has a large transportation network linking the East to the West, and connecting all economies to the large landmasses in Asia. Azam et al. [3] suggest a positive association between carbon emissions and economic growth. As such, the question of how to balance a sustainable economy and carbon emissions in the region along the SREB has become a vital issue.



Figure 1. Geographical locations of the Chinese provinces along the SREB. Adapted from [7].

Designed to connect China with Central Asia and Europe, the SREB facilitates international trade between China and Eurasia and provides considerable transportation along the SREB each day (transportation in this study refers to both freight and passenger transportation). As an economic corridor linking the East to the West, the SREB's transportation network will expand further in the future. Consequently, carbon emissions are very severe there, and carbon reduction is a major challenge for China. The Chinese take this issue seriously by promoting transportation decarbonization and initiating sustainable development. To achieve the carbon-reduction target, the government encourages technology innovation and the optimization of the transportation structure.

The SREB has attracted researchers' attention to this issue. Some studies have discussed the initiative from different perspectives, including motivation, concepts, approaches, environmental context, and obstacles to overcome [8,9]. Some studies have investigated economic growth, trade, and social issues for China and countries along the SREB. For example, Wang et al. [10] test the impacts of GDP, population, distance, free trade agreements, and legal systems on China's exports to the countries along the SREB and the New Maritime Silk Road; both are the One Belt, One Road Initiative's main components. Using the data envelopment analysis (DEA) method, Chen et al. [4] examine the effects of congestion on carbon-emission reduction in countries along the SREB. Ding et al. [11] show a U-shaped trend of the overall carbon-emission efficiency along the economic belt. However, these studies do not investigate any solutions for decarbonization along the economic belt.

While other studies document some options, such as policy intervention [12], information and communication technology [13], energy-efficiency improvements, waste-heat recovery [14], and alternative energy [15] for carbon reduction, the options do not work as well as expected. Feng et al. [16] assessed the effectiveness of the SREB's strategy and its industrial productivity in China and found that the strategy had no significant association with total-factor productivity for the selected provinces; namely, the system did not contribute to the SREB's sustainable development during 2014–2015. Therefore, the solutions for carbon reduction in the SREB should be different from before.

Nevertheless, little research has suggested solutions for dealing with carbon emissions from transportation on the SREB or investigated whether the current solutions facilitate carbon reduction along the SREB in the Chinese region. This study bridges this gap; it examines carbon-reduction performance (CRP) from a technology-based perspective and suggests solutions that are favorable for decarbonization. Meanwhile, in the context of the global economic downturn and China's economic slowdown, the Chinese central government has initiated the SREB to maintain economic growth and boost industrial transformation, which will inevitably lead to a new round of carbon emissions. The government encourages technological innovation and technology-dominated transportation reforms towards green and low-carbon economic development. Under these circumstances, this research is conducted to seek technology-effective carbon reduction in the SREB. It finds that decarbonization in the Chinese provinces along the SREB has improved since 2013 because of the improvement in transportation technology. Technical efficiency, including scale efficiency and pure technological efficiency, may improve carbon reduction, while the lagged technological progress restricts the CRP. This study further suggests that the provincial CRPs are different. The southwestern provinces have the best decarbonization performance, followed by the northwestern provinces, while the northeastern provinces, including Inner Mongolia, underperform compared to the others.

The rest of the paper is organized as follows: Section 2 is a literature review; Section 3 outlines the data and methodology; Section 4 presents and analyzes results; Section 5 discusses the findings; and Section 6 gives the conclusions.

2. Literature Review

Prior research has proposed some solutions for carbon reduction in many general ways. For instance, Lu et al. [12] document that the Chinese government's executive plan (National Air Pollution Prevention and Control Action Plan) efficiently reduces carbon emissions. Sourcing from G20 countries, Yao et al. [17] suggest that different countries should have different policies to deal with their particular carbon emissions. Other studies conducted in Europe and North America uncover that government policies reduce carbon emissions [18,19]. Therefore, policy intervention is crucial for carbon reduction around the world.

However, policy intervention may not maintain a nation's economic development in the long run. Researchers have focused on the sustainable development of the global economy and pursue a better way to balance the relation between carbon reduction and

economic growth. Renewable energy is one of the better choices for carbon reduction, whose consumption will gradually increase in the future [20]. Similarly, Ramli et al. [15] document that renewable energy, as a better fuel source without emissions, is an alternative to traditional fossil fuels. Additionally, renewable energy can be sourced from the ocean. Feng et al. [21] reveal that ocean-based solutions may contribute to carbon reduction in China and suggest further that the development of marine energy and low-carbon marine shipping may have more potential. Therefore, renewable energy is an alternative for reducing carbon emissions.

Furthermore, some research has explored the solutions from outside of the energy sector. Godil et al. [5] suggest that technological innovation is a more favorable option for carbon reduction because innovation may improve industrial productivity with low-carbon power. This kind of innovation consequently boosts the next round of technological advancement, with more outputs and fewer inputs. For instance, fast-growing information and communication technology (ICT) has reshaped our modern society, developing a changeover towards a green economy. As Danish et al. [13] suggested, ICT facilitates industrialization and eventually improves environmental quality and economic sustainability. Ulucak et al. [22] support this point of view and find that ICT can potentially deal with climate-change issues in the current digital age. Therefore, technological innovations and other technological advancements are more promising strategies for carbon reduction and the sustainable development of the global economy.

The solutions are diversified in various industrial sectors. In terms of the iron and steel industry, Morefeldt et al. [23] uncover that energy efficiency improvements in steel-production processes can meet the binding climate targets if combined with carbon capture and storage. In the cement industry, Ishak and Hashim [14] document some carbon-reduction strategies, such as energy-efficiency improvements, waste-heat recovery, the substitution of fossil fuels with renewable energy sources, and the production of low-carbon cement. Additionally, supplementary cementitious materials, such as fly ash and copper slag, are solutions for carbon reduction [24]. For the rubber industry, Dayaratne and Gunawardena [25] suggest that rubber manufacturing should use a cleaner manufacturing model and adopt energy-efficient solutions to meet sustainable production, and its financial barriers are accordingly able to be copied by a pure development strategy.

Furthermore, Lin and Zhao [26] find that R&D expenditure and energy prices may impact energy consumption in the Chinese fiber industry. For the methanol production industry, Taghdisian et al. [27] suggest an eco-design approach for the sustainable production of methanol through a CO₂ efficiency model in order to maximize methanol production and minimize carbon emissions. As for the logistics industry, To [28] advises that the Hong Kong government should build a rail system for cargo transport. In terms of the trade sector, Zhao et al. [29] document that industrial structure adjustment, energy-efficiency improvement, new energy development, and clean-energy strategies may reduce carbon emissions in South Africa. For the education sector, Versteijlen et al. [30] document that online education is a measure for reducing carbon emissions in the Netherlands.

Meanwhile, the methods of measuring carbon-reduction performance vary in many sectors. The first one is called one-way analysis, which gauges a single factor of carbon emissions and compares it with any other critical factor [31,32]. Nevertheless, this method cannot test the substitution relation between the variables because it does not test multivariate significance. The advanced method is data envelopment analysis (DEA), which is performed by building multivariate time series, and it examines the total factor of CRP and the substitution relation between the variables [33]. The last method is the Malmquist method, which has been widely used in many studies.

Although prior research has suggested some solutions for carbon reduction in many industrial sectors, little research has discussed the solutions for CRP along the SREB in the Chinese region. This study investigates whether the current solutions facilitate carbon reduction in the field; it aims to evaluate CRP from a technology-based perspective and suggests solutions that are favorable for carbon reduction.

To investigate carbon-reduction performance, there are three kinds of methods. The first one is the log-mean divisia index method (LMDI), which is widely used to test carbon reduction in the transportation sector based on various factors, such as energy structure, energy-consumption strength, and logistic structure. This approach is employed to investigate the mentioned factors from different regions, such as a regional area [34], and economic belt or space [35,36], or a whole country [37]. These studies show that technology-oriented factors may improve carbon reduction. Therefore, technological upgrades facilitate carbon reduction.

The second kind is a varying-coefficient panel-data model with fixed effects. Chai et al. [38] use this method to investigate the relationship between transportation structure and carbon reduction in various countries, such as the U.S., Japan, China, and Europe, and find that a decarbonization structure may reduce carbon emissions. There is a positive relationship between carbon reduction and railway and shipping, while a negative relationship exists for highway and air transportation.

The third kind is the dynamic Malmquist method. Wang et al. [39] employed this method to investigate total-factor production efficiency in the transportation sector and found a significant growth in technical progress, which improved carbon reduction during 2000–2005. Wang et al. [40] show a similar finding and suggest an average growth rate of 3.3% in technical progress. Zhang et al. [41] employ the DEA–Malmquist method to analyze the spatial disparity of the total-factor productivity in highway transportation and suggest that technological progress and scale efficiency reduce carbon emissions. The DEA–Malmquist method is widely used to investigate performance differences in technological progress [42] and product performance [39,40]. Therefore, this research employs this method to investigate the research question and to calculate carbon-reduction performance with input and output data.

3. Data and Methodology

3.1. Data

Raw economic data was collected from the “China Input-Output Survey in 2017” by the National Bureau of Statistics of China (NBSC). As this survey is issued every five years, the next issue is expected in 2022. Thus, the latest data available for this study were for 2016. Some data on the GDP of provinces along the SREB and their carbon emissions were collected from the “China Statistical Yearbook” for the selected years, which is available on the NBSC’s official website (<http://www.stats.gov.cn/tjsj/ndsj/> accessed on 1 October 2021).

3.2. Methodology

Total-factor analysis is a widely used and efficient way to measure product performance, although many factors contribute to carbon reduction, such as green technology [43,44], energy strength, industrial structure [45], and environmental protection capability [46]. Recently, the output-based non-parametric Malmquist method has been popular for gauging the total-factor productivity growth rate.

The Malmquist index was initially discussed by Malmquist in 1953, and then Caves et al. [47] utilized this approach to estimate productivity alterations. Meanwhile, data envelopment analysis (DEA) was introduced by Charnes et al. [48]; currently, it is extensively used in many industries, such as finance, agriculture, education, and architecture. It facilitates comparison studies between regions and nations due to its advantage by which researchers may calculate the answers of high-dimensional models even if the functions are unknown. Additionally, this method is used to investigate total-factor production efficiency in the transportation sector [39]. Therefore, the DEA–Malmquist approach is employed to investigate carbon reductions among different provinces.

Following Charnes et al. [48], the extensive employment of the DEA method to test the unexpected production of contaminants has taken place in studies for environmental evaluation. Extending its application to the IT industry, Zhang and Yang [49] use DEA to

measure Entropy Distances (differences between self-evaluation and mutual-evaluation indexes based on the full information in cross-evaluation matrix models) to identify the optimum value. Furthermore, the DEA–Malmquist method is utilized to analyze the spatial disparity of the total-factor productivity in highway transportation [41]. It is widely used to investigate performance differences in technological progress [42] and product performance [39,40]. As such, the DEA–Malmquist approach is a suitable method for investigating the performance differences in carbon reduction in the Chinese provinces.

This study, which is based on the theoretical framework of Wang et al. [39] and Wang et al. [40], employs the DEA–Malmquist approach to test transportation-carbon-reduction performance (CRP), which includes technical efficiency (TE), and technological progress (TP). TE is divided into pure technological efficiency (PTE) and scale efficiency (SE). Accordingly, CRP can be computed as

$$\text{CRP}(x^t, y^t, x^{t+1}, y^{t+1}) = \left[\frac{D_0^t(x^{t+1}, y^{t+1}) \times D_0^{t+1}(x^{t+1}, y^{t+1})}{D_0^t(x^t, y^t) \times D_0^{t+1}(x^t, y^t)} \right]^{\frac{1}{2}} \quad (1)$$

where x^t , is the input vector at time of t , including labor (L), capital (C), and energy (E);

y^t is the output vector at time of t , namely carbon emissions of transportation;

$D_0^t(x^{t+1}, y^{t+1})$ stands for a distance function at time t that measures the technology inputs compared to the technology at time $t + 1$;

$D_0^{t+1}(x^t, y^t)$ stands for a distance function at time $t + 1$ that measures the technology inputs compared to the technology at time t ;

$D_0^t(x^t, y^t)$ stands for a distance function at time t that tests the CO₂ outputs based on the technology at time t ;

$D_0^{t+1}(x^{t+1}, y^{t+1})$ stands for a distance function at time $t + 1$ that tests the CO₂ outputs based on the technology at time $t + 1$.

If $\text{CRP} > 1$, $\text{CRP} = 1$, $\text{CRP} < 1$, this indicates that the carbon-reduction performance has improved, remained unchanged, or decreased, respectively.

Equation (1) is interpreted further with the variables of technical efficiency (TE) and technological progress (TP), to analyze the contributions of these performance factors to CRP. Accordingly, TE and TP are given by

$$\text{TE}(x^t, y^t, x^{t+1}, y^{t+1}) = \frac{D_0^t(x^{t+1}, y^{t+1})}{D_0^t(x^t, y^t)} \quad (2)$$

$$\text{TP}(x^t, y^t, x^{t+1}, y^{t+1}) = \left[\frac{D_0^t(x^{t+1}, y^{t+1}) \times D_0^t(x^t, y^t)}{D_0^{t+1}(x^{t+1}, y^{t+1}) \times D_0^{t+1}(x^t, y^t)} \right]^{\frac{1}{2}} \quad (3)$$

In Equation (2), TE is measured by the potentially marginal performance from time t to time $t + 1$. If $\text{TE} > 1$, or $\text{TE} < 1$, this means that the technical efficiency has improved or decreased, respectively.

In Equation (3), TP is measured by the potentially marginal performance from time t to time $t + 1$. If $\text{TP} > 1$ or $\text{TP} < 1$, this means that the technical progress has moved forward or backward, respectively.

Because TE is determined by pure technological efficiency (PTE) and scale efficiency (SE), PTE and SE can be measured and calculated with the equations below:

$$\text{PTE} = \frac{D_0^{t+1}(x^{t+1}, y^{t+1}/\text{VRS})}{D_0^t(x^t, y^t/\text{VRS})} \quad (4)$$

$$\text{SE} = \frac{D_0^t(x^t, y^t)}{D_0^{t+1}(x^{t+1}, y^{t+1})} \quad (5)$$

where VRS indicates scale-effect changes.

If $PTE > 1$ or $PTE < 1$, the pure efficiency is effective or ineffective, respectively; a greater value indicates greater effectiveness, and vice versa.

If $SE > 1$ or $SE < 1$, the scale efficiency is effective or ineffective, respectively; a greater value indicates greater effectiveness, and vice versa.

According to Charnes et al. [48], the Malmquist production indexes from time t to time $t + 1$ can be calculated, and then the fourth distance functions are written, respectively, as follows:

$$\begin{cases} D_0^t(x^t, y^t) = \min \theta \\ \text{s.t. } \sum_{j=1}^n y_j^t \cdot \lambda_j \geq y^t \\ \sum_{j=1}^n x_{ij}^t \cdot \lambda_j \leq \theta x_i^t \\ \lambda_j \geq 0, j = 1, \dots, n \end{cases} \quad (6)$$

$$\begin{cases} D_0^{t+1}(x^{t+1}, y^{t+1}) = \min \theta \\ \text{s.t. } \sum_{j=1}^n y_j^{t+1} \cdot \lambda_j \geq y^{t+1} \\ \sum_{j=1}^n x_{ij}^{t+1} \cdot \lambda_j \leq \theta x_i^{t+1} \\ \lambda_j \geq 0, j = 1, \dots, n \end{cases} \quad (7)$$

$$\begin{cases} D_0^t(x^{t+1}, y^{t+1}) = \min \theta \\ \text{s.t. } \sum_{j=1}^n y_j^t \cdot \lambda_j \geq y^{t+1} \\ \sum_{j=1}^n x_{ij}^t \cdot \lambda_j \leq \theta x_i^{t+1} \\ \lambda_j \geq 0, j = 1, \dots, n \end{cases} \quad (8)$$

$$\begin{cases} D_0^{t+1}(x^t, y^t) = \min \theta \\ \text{s.t. } \sum_{j=1}^n y_j^{t+1} \cdot \lambda_j \geq y^t \\ \sum_{j=1}^n x_{ij}^{t+1} \cdot \lambda_j \leq \theta x_i^t \\ \lambda_j \geq 0, j = 1, \dots, n \end{cases} \quad (9)$$

Following the Decision-Stage Model from Kazanjian and Drazin [50] and including surplus variables and slack variables, the fourth distance functions are developed further, respectively, as follows:

$$\begin{cases} D_0^t(x^t, y^t) = \min \theta \\ \text{s.t. } \sum_j^t y_j^t \cdot \lambda_j - s^- = y^t \\ \sum_{j=1}^n x_{ij}^t \cdot \lambda_j + s^+ = \theta x_i^t \\ \lambda_j \geq 0, j = 1, \dots, n \\ s^- \geq 0, s^+ \geq 0 \end{cases} \quad (10)$$

$$\begin{cases} D_0^{t+1}(x^{t+1}, y^{t+1}) = \min \theta \\ \text{s.t. } \sum_j^t y_j^{t+1} \cdot \lambda_j - s^- \geq y^{t+1} \\ \sum_{j=1}^n x_{ij}^{t+1} \cdot \lambda_j + s^+ \leq \theta x_i^{t+1} \\ \lambda_j \geq 0, j = 1, \dots, n \\ s^- \geq 0, s^+ \geq 0 \end{cases} \quad (11)$$

$$\left\{ \begin{array}{l} D_0^{t+1}(x^{t+1}, y^{t+1}) = \min \theta \\ \text{s.t. } \sum_j^n y_j^{t+1} \cdot \lambda_j - s^- \geq y^{t+1} \\ \sum_{j=1}^n x_{ij}^{t+1} \cdot \lambda_j + s^+ \leq \theta x_i^{t+1} \\ \lambda_j \geq 0, j = 1, \dots, n \\ s^- \geq 0, s^+ \geq 0 \end{array} \right. \quad (12)$$

$$\left\{ \begin{array}{l} D_0^{t+1}(x^t, y^t) = \min \theta \\ \text{s.t. } \sum_j^n y_j^{t+1} \cdot \lambda_j - s^- \geq y^t \\ \sum_{j=1}^n x_{ij}^{t+1} \cdot \lambda_j + s^+ \leq \theta x_i^t \\ \lambda_j \geq 0, j = 1, \dots, n \\ s^- \geq 0, s^+ \geq 0 \end{array} \right. \quad (13)$$

where x indicates the input factors, including labor (L), capital (C), and energy (E); y stands for the output factor, referring to the carbon emissions of transportation; θ^t indicates the possibility that the input increases or declines in time t when the outputs are specific. When $\theta^t = 1$, it means that technology input j is less significant; when $\theta^t = 1$, $s^{-t} = 0$, and $s^{+t} = 0$, it means that non-technology input j is significant; when $\theta^t < 1$, it means that technology input j is insignificant.

According to the effectiveness and scale effect of the definition of DEA, when $\sum \lambda_j < 1$, it indicates that the scale effect increases gradually; when $\sum \lambda_j = 1$, it indicates that the scale effect is unchanged; and when $\sum \lambda_j > 1$, it indicates that the scale effect declines gradually.

This methodology is outlined by a flowchart in Figure 2. Firstly, the paper compiles the input–output table to calculate the transportation-carbon emissions in the SREB and then constructs the distance functions to calculate the carbon-reduction performance in the transportation sector. Secondly, based on the DEA–Malmquist models, the factors that affect the performance are assessed by the change figures of the technical progress and technical efficiency. After analyzing scale efficiency, the technical efficiency is measured by pure technical efficiency, if the scale effect is valid. If not, the technical efficiency can be measured by pure technical efficiency and scale efficiency. Thirdly, further analysis is to assess the extent of the major contributors to carbon-reduction performance. Having the results from these analyses, we may identify the interprovincial differences in carbon-reduction performance in the transportation sector.

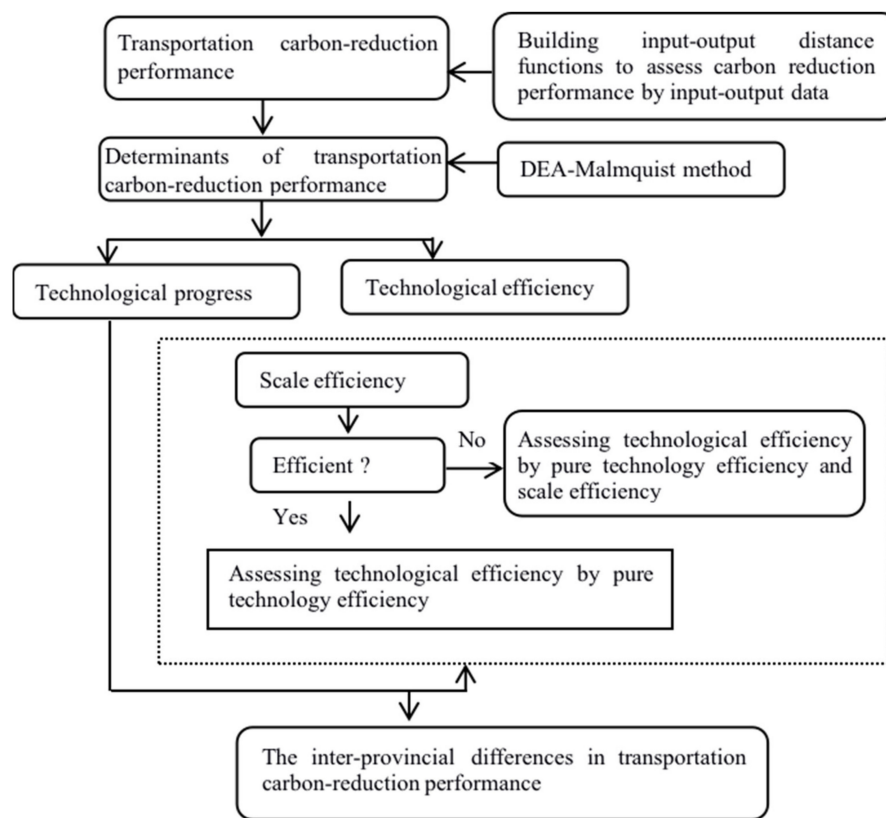


Figure 2. Methodological flowchart.

4. Results and Analysis

Table 1 shows the distributions of carbon emissions from the transportation sector in the provinces along the SREB. Carbon emissions in the SREB increased remarkably from 84,301.8 k tons in 2005 to 184,813.7 k tons in 2016. In particular, Liaoning overwhelmingly dominated in terms of carbon emissions, followed by Shannxi and Inner Mongolia, respectively, while Ningxia showed lower carbon emissions than any others, followed by Chongqing and Qinghai, respectively. This upward trend of carbon emissions in the SREB is expected to increase in the next few years because the growing Chinese GDP will generate more carbon emissions.

Table 1. Distributions of carbon emissions from the transportation sector in SREB (10 k tons).

Years Provinces	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Shannxi	1350.51	1560.30	1799.14	2083.02	2434.05	2733.21	2975.17	3478.54	2629.50	2605.19	2631.77	2676.40
Gansu	525.91	543.06	546.54	578.81	652.47	744.32	762.11	816.35	1103.14	1107.87	1015.12	1008.57
Qinghai	73.02	81.00	142.53	174.36	218.36	251.79	266.89	263.64	270.35	300.74	296.04	312.11
Ningxia	48.09	34.97	35.74	44.61	49.31	69.63	70.43	65.78	67.60	58.76	59.70	67.97
Xinjiang	792.36	872.51	933.53	922.18	962.97	1062.94	1158.02	1283.41	1496.64	1525.45	1751.59	1875.69
Liaoning	2423.51	2672.76	2937.82	2949.88	3190.13	3340.74	3593.34	3730.62	3519.02	3699.44	3888.49	4077.79
Jilin	560.64	647.60	846.66	946.78	1019.12	1117.84	1148.01	1167.95	1301.59	1424.02	1471.10	1558.07
Heilongjiang	979.16	1137.74	1114.52	1014.17	1245.72	1240.91	2036.26	2065.88	2256.07	2389.78	2474.57	2580.50
Inner Mongolia	1375.84	1527.40	1765.17	2091.89	2402.34	2706.89	2975.62	3453.55	2566.98	2537.03	2574.83	2612.03
Yunnan	86.71	327.53	319.34	335.27	394.29	518.19	500.96	510.04	583.26	652.34	556.90	601.08
Guangxi	75.80	310.80	350.05	307.12	418.90	483.87	483.95	517.43	467.41	491.05	529.19	588.05
Chongqing	88.45	203.86	211.93	285.55	148.84	182.23	199.23	203.22	250.76	279.48	289.71	323.21
SREB	8430.18	9964.91	11,044.93	11,782.57	13,186.78	14,510.70	16,261.30	17,662.34	16,621.93	17,181.66	17,704.91	18,481.37

4.1. Analysis of Carbon-Reduction Performance (CRP) and Its Contributors

Using Equations (1)–(5), the indexes of CRP, TE, TP, PTE, and SE can be calculated. Thus, the carbon-reduction performance along the SREB is measured and determined to facilitate carbon reduction.

Table 2 shows that carbon-reduction performance was improved with growth from 0.9603 to 1.0151 from 2005 to 2015. In particular, after 2013, carbon reduction was successful because the CRP value was over 1, which was relatively better than during 2005–2012 when the CRP was under 1.

Table 2. Carbon reduction and contributors’ performance during 2005–2016.

Periods	Technical Efficiency (TE)	Technical Progress (TP)	Pure Technology Efficiency (PTE)	Scale Efficiency (SE)	Carbon Reduction Performance (CRP)
2006/2005	0.9890	0.9710	0.9954	0.9936	0.9603
2007/2006	0.9844	0.9922	0.9887	0.9957	0.9767
2008/2007	0.9786	0.9900	0.9816	0.9969	0.9688
2009/2008	0.9893	0.9980	1.0016	0.9877	0.9873
2010/2009	0.9937	0.9770	1.0056	0.9882	0.9708
2011/2010	0.9945	0.9924	0.9922	1.0023	0.9869
2012/2011	0.9986	0.9895	0.9880	1.0107	0.9881
2013/2012	0.9985	0.9995	0.9759	1.0232	0.9980
2014/2013	1.0159	1.0005	0.9954	1.0206	1.0164
2015/2014	1.0241	0.9941	0.9965	1.0277	1.0181
2016/2015	1.0273	0.9881	0.9984	1.0289	1.0151
Mean	0.9994	0.9902	0.9927	1.0069	0.9897

In particular, technical efficiency shows a similar growth trend to that of CRP. It performed well after 2013 because of its value of 1.0159, which was over 1, while it underperformed before 2013. However, in general, technical progress showed no improved performance for carbon reduction because most TP values were less than 1, except in 2013. Similarly, pure technological efficiency underperformed because the majority of the values were under 1; only two values (1.0016 and 1.0056) were more than 1—in 2008 and 2009, respectively.

In terms of scale efficiency, it showed significant performance growth during the period, particularly after 2013, where its SE values were over 1. Therefore, it was the most important contributor to carbon-reduction performance. Followed by technical efficiency, it has improved gradually since 2007.

Figure 3 clearly outlines the results. The SREB showed an overall gradually improving trend in carbon-reduction performance overall, particularly after 2013. This good performance is partially attributed to technical and scale-efficiency improvements. With the ongoing development of technical efficiency, the CRP is expected to gradually go down in the future.

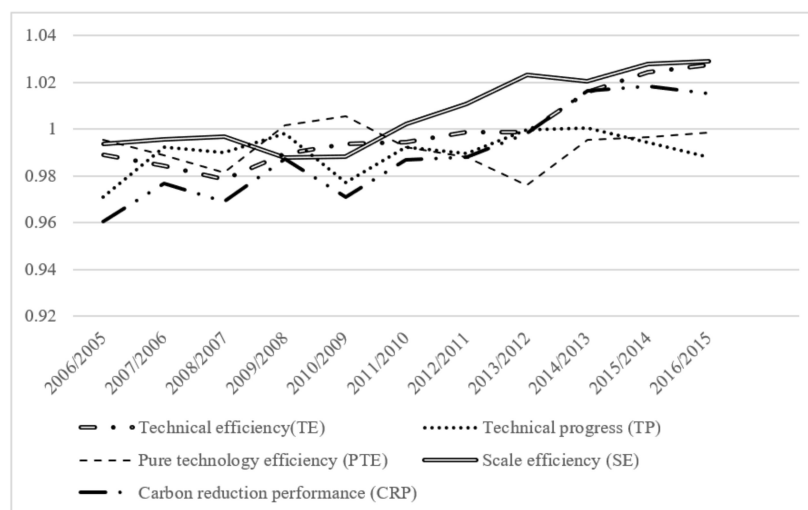


Figure 3. Carbon-reduction performance and contributors’ changes.

4.2. Analysis of CRP by Provinces

As shown in Table 3, the SREB presented an upward trend for CRP; the value gradually increased from 0.9603 to 1.0151 during 2005–2015, which means that the CRP has gradually improved along with the SREB in general.

Table 3. Transportation-carbon-reduction performance by provinces along the SREB.

Periods	Northwest			Northeast					Southwest			SREB	
	Shanxi	Gansu	Qinghai	Ningxia	Xinjiang	Liaoning	Jilin	Heilongjiang	Inner Mongolia	Yunnan	Guangxi		Chongqing
2006/2005	1.0423	1.1733	1.0287	1.0352	0.8761	0.8232	0.7207	0.8043	0.7840	1.1792	0.8898	1.1673	0.9603
2007/2006	1.0635	1.1241	0.8447	0.8596	1.0639	0.8296	1.0741	0.9759	0.9392	1.0718	0.9744	0.8567	0.9767
2008/2007	1.0450	0.9506	0.9601	0.9016	1.0163	0.9102	1.0007	0.9187	0.9778	0.9891	0.9554	1.0002	0.9688
2009/2008	0.9863	0.9524	0.9422	0.9567	1.0598	0.9683	1.1062	0.9573	0.9855	1.0008	0.9687	1.0485	0.9873
2010/2009	0.9880	0.9971	1.0002	0.8485	1.0240	1.0171	0.9964	0.8422	0.9836	1.0002	1.0369	0.9154	0.9708
2011/2010	1.0144	1.0022	1.0072	0.9219	1.0016	1.0106	0.9942	0.8498	0.9957	1.0054	1.0242	0.9663	0.9869
2012/2011	1.0147	0.9866	0.9911	0.9734	0.9989	0.9926	0.9884	0.9503	0.9863	1.0008	1.0007	0.9733	0.9881
2013/2012	1.0251	0.9439	0.9916	0.9542	0.9915	0.9874	0.9835	0.9583	0.9955	1.0038	1.0138	0.9854	0.998
2014/2013	1.0514	1.0504	1.0160	0.9889	1.0104	0.9833	0.9769	0.9964	0.9751	1.0492	1.0929	1.0054	1.0164
2015/2014	1.0712	0.9942	1.0866	0.9472	0.9769	0.9258	0.9386	1.0504	0.9551	1.0337	1.1014	1.0744	1.0181
2016/2015	1.0748	0.9956	1.0897	0.9465	0.9726	0.9207	0.9351	1.0774	0.9530	1.0317	1.1040	1.0801	1.0151
Mean	1.0342	1.0096	0.9388	0.9394	0.9987	0.9475	0.9654	0.9720	0.9565	1.0330	1.0260	1.0020	0.9897

In particular, Shanxi province had the most outstanding performance, with a value of 1.0342 on average, which was greater than those of the others. This figure increased as of 2014, indicating that this province overperformed with regard to CRP. Followed by Yunnan, it performed well during the whole period, except for 2007/2008. In addition, Gansu, Guanxi, and Chongqing performed well; their average values were over 1, although their CRP was relatively slow. By contrast, some provinces underperformed, with a value of less than 1 on average, such as Qinghai, Ningxia, Xinjiang, Liaoning, Jilin, Heilongjiang, and Inner Mongolia. Therefore, the southwestern provinces had better carbon-reduction performance than the others, followed by some northwestern provinces, but the northeastern provinces had the worst performance.

Figure 4 outlines the regional trends of the CRP. The SREB figure showed an upward trend, which means that the carbon-reduction performance has gradually improved. Most provinces showed an improved CRP in the last few years, such as Shanxi, Yunnan, Guangxi, and Chongqing, while some showed a decreased performance, including Liaoning, Jilin, and Inner Mongolia. Ningxia and Inner Mongolia always underperformed, with values of less than one.

The CRP trend in Shaanxi province is the most obvious, due to the strategical implementation of “Xi’an Xianyang Integration” and “Guantian-Tianshui Economic Zone”. meanwhile, the State Council passed the “Guanzhong-Tiansui Economic zone development plan” in 2009, which contributed to the improvement of carbon-reduction performance. It had an important role in promoting the development of low-carbon transport infrastructure in Shaanxi province and its surrounding provinces. The gradually increasing CRP from the lowest point in 2009 confirmed this point. The CRPs of Liaoning, Jilin, Inner Mongolia, and Ningxia remained relatively stable but decreased to a certain extent, which was attributed to the heavy burden and lagged economic development in Liaoning and Jilin as the traditional manufacturing provinces. Inner Mongolia and Ningxia provinces are located in a region with harsh natural conditions, and their transport infrastructure construction are lagged and difficult.

In terms of technical efficiency (TE) in relation to CRP, Table 4 outlines the provincial performance during the period. Generally speaking, technical efficiency did not improve in the SREB until 2014/2013, and it gradually improved from 1.0159 to 1.0273 during the last few years. In particular, Yunnan had the best TE performance, with a mean value of 1.0315, followed by Guangxi with a mean value of 1.0275. This result is the reason why Yunnan had better carbon-reduction performance: as shown in Table 3, its technical efficiency was better than that of the others. On the contrary, Ningxia showed the worst technical-efficiency performance because of its values being overwhelmingly under 1 during the period, except for 2006/2005. This result confirms the findings in Table 3, wherein Ningxia underperformed with regard to CRP. Therefore, technical efficiency is relatively important

for carbon reduction in the southwestern and northwestern provinces, but it is not in the northeastern provinces.

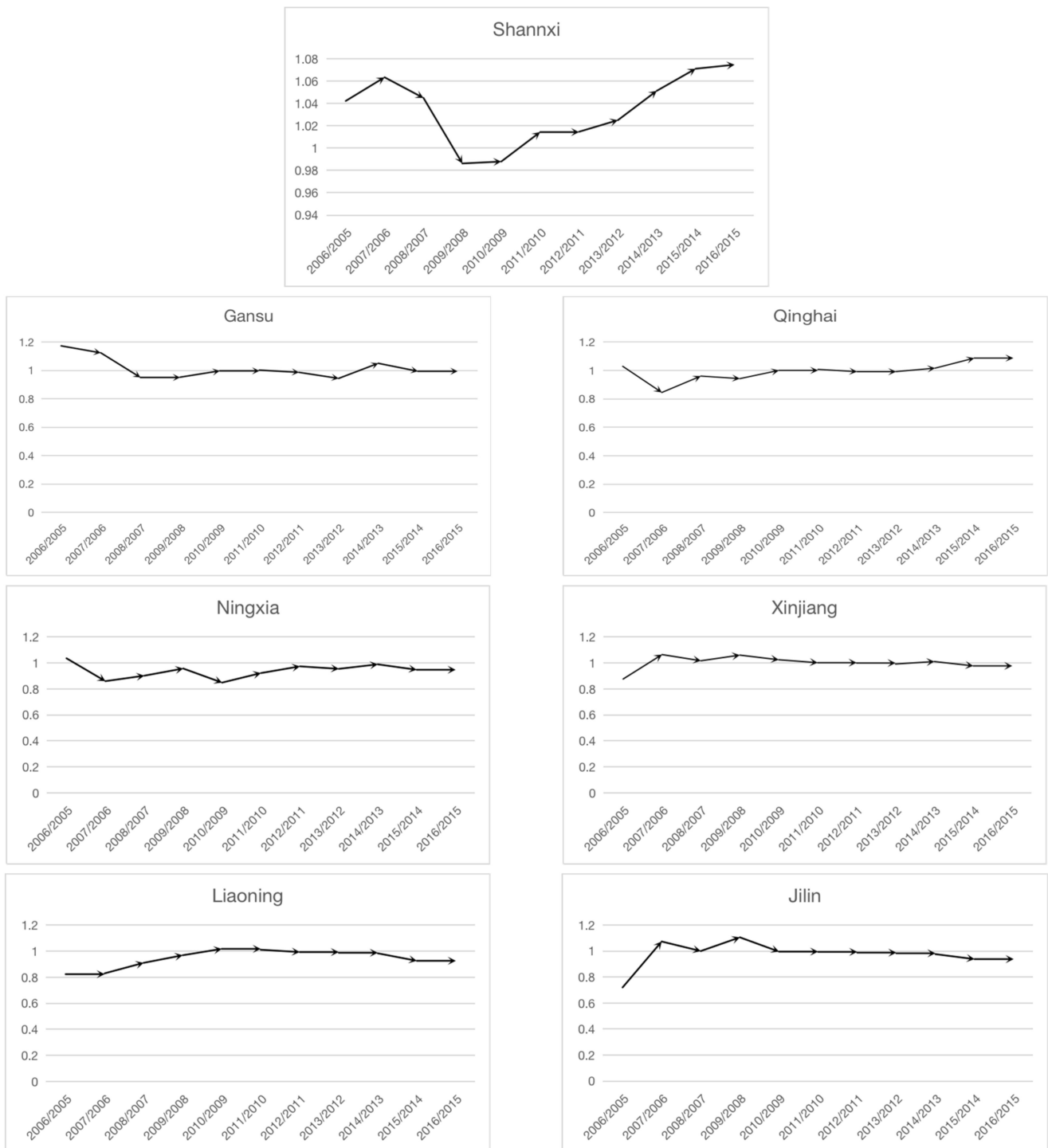


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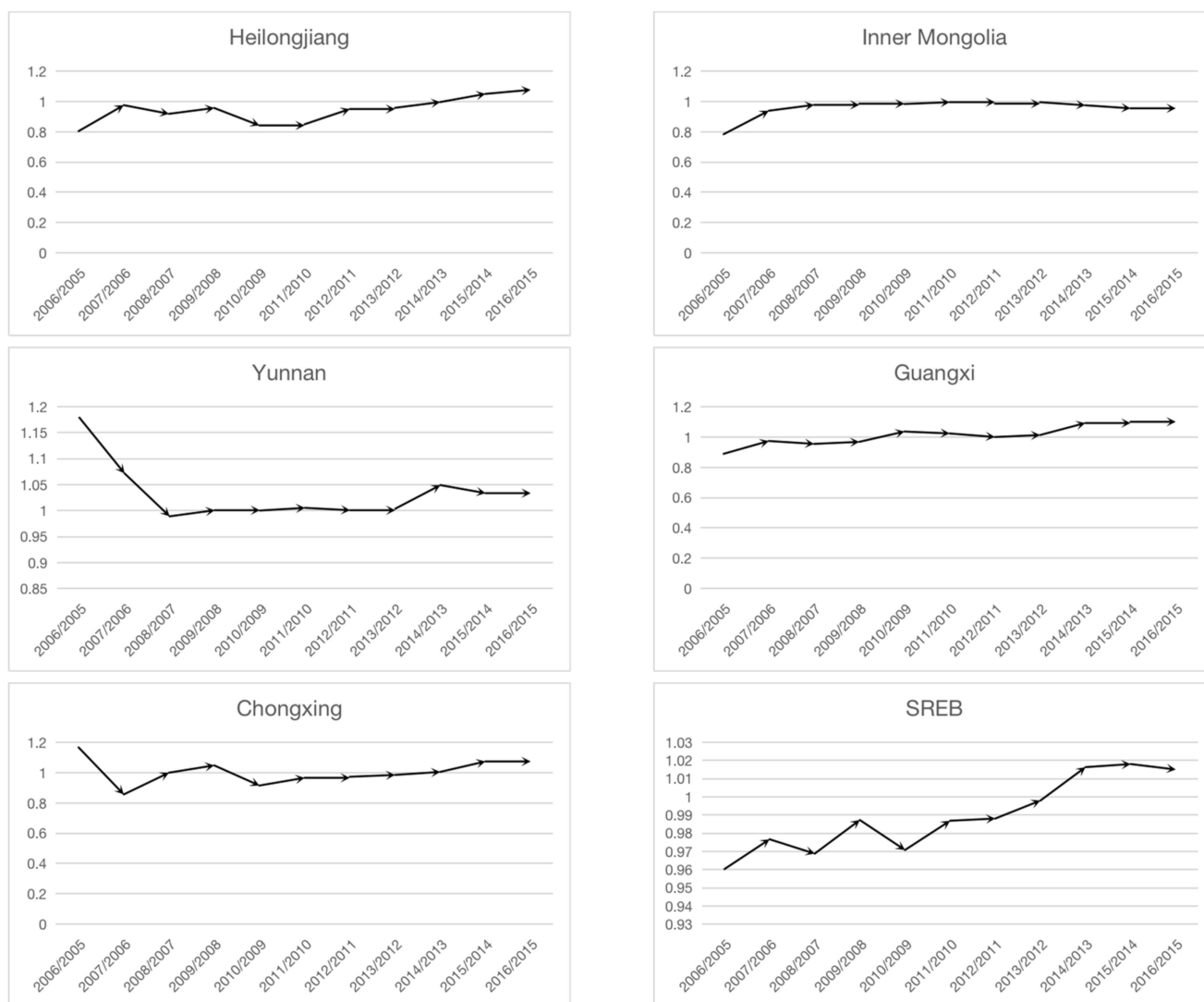


Figure 4. Change trend of CRP for the SREB and each province.

Table 4. Technical-efficiency performance by provinces along the SREB.

Periods	Northwest					Northeast				Southwest			
	Shanxi	Gansu	Qinghai	Ningxia	Xinjiang	Liaoning	Jilin	Heilongjiang	Inner Mongolia	Yunnan	Guangxi	Chong-qing	SREB
2006/2005	1.0113	1.1240	1.0103	1.0211	0.9361	0.8953	0.9006	0.9019	0.8857	1.2314	0.9396	1.0109	0.9890
2007/2006	1.0117	1.0420	0.8495	0.9389	1.0336	0.8915	1.0782	1.0187	1.0152	1.0652	1.0328	0.8358	0.9844
2008/2007	0.9922	0.9506	0.9622	0.9467	1.0008	0.9516	0.9888	0.9568	1.0164	0.9878	1.0021	0.9877	0.9786
2009/2008	0.9929	0.9706	0.9626	0.9515	1.012	0.9804	1.0064	0.9589	1.0218	0.9912	1.0001	1.0230	0.9893
2010/2009	1.0016	0.9909	0.9762	0.9414	1.0009	1.0246	0.9883	0.9756	0.9953	0.9915	1.0197	1.0189	0.9937
2011/2010	1.0157	0.9955	0.9966	0.9521	1.0006	1.0151	0.9954	0.9462	0.997	1.0052	1.0141	1.0009	0.9945
2012/2011	1.0148	0.9941	1.0021	0.9984	1.0004	0.9968	0.9917	0.9833	0.9987	1.001	1.0008	1.0007	0.9986
2013/2012	1.0255	0.9932	1.0036	0.9812	1.0005	0.9882	0.9903	0.9862	0.9968	1.0036	1.0074	1.0057	0.9985
2014/2013	1.0514	1.0048	1.0033	0.9964	1.0202	0.9911	0.9849	1.0103	0.9979	1.0339	1.0899	1.0069	1.0159
2015/2014	1.0719	1.0055	1.0865	0.9951	0.9908	0.9392	0.9557	1.0508	0.9877	1.0189	1.0964	1.0901	1.0241
2016/2015	1.0829	1.0069	1.0896	0.995	0.9901	0.9343	0.9523	1.0781	0.9857	1.0169	1.0993	1.0961	1.0273
Mean	1.0247	1.0071	0.9948	0.9743	0.9987	0.9644	0.9848	0.9879	0.9907	1.0315	1.0275	0.9988	0.9994

As Figure 5 shows, some provinces, including Shanxi, Heilongjiang, Guangxi, and Ningxia, indicated that they intended to upgrade their technological efficiency. Nevertheless, some did not, such as Liaoning, Jilin, and Inner Mongolia; they showed a declining technical efficiency trend. It is understandable that Shanxi, Yunnan, and Guangxi had better CRP, as shown in Table 3, which was partially due to their improved technical efficiency. On the contrary, the worst CRP, which was observed for Ningxia, Liaoning, and Jilin, was attributed to their declining efficiency.

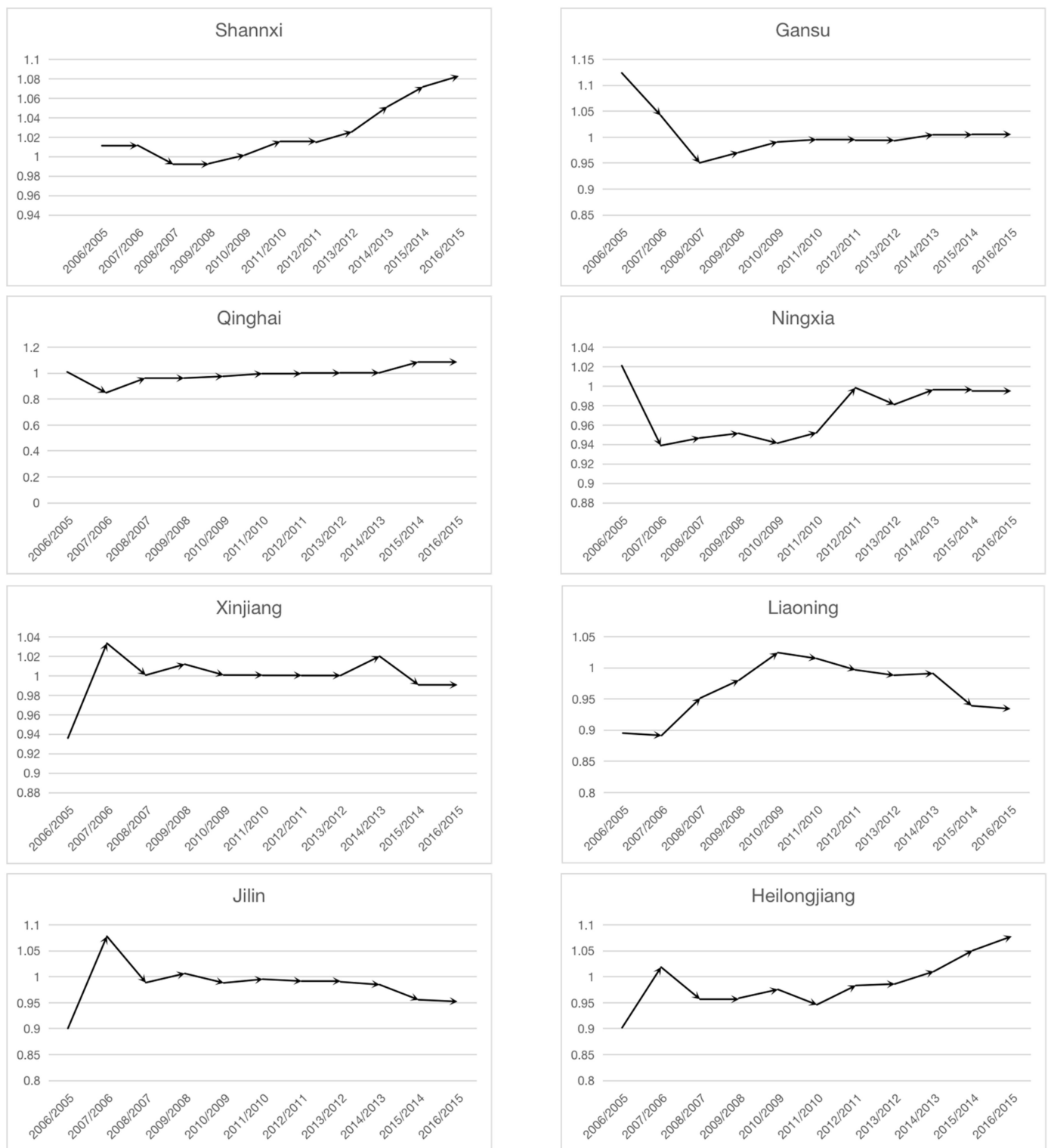


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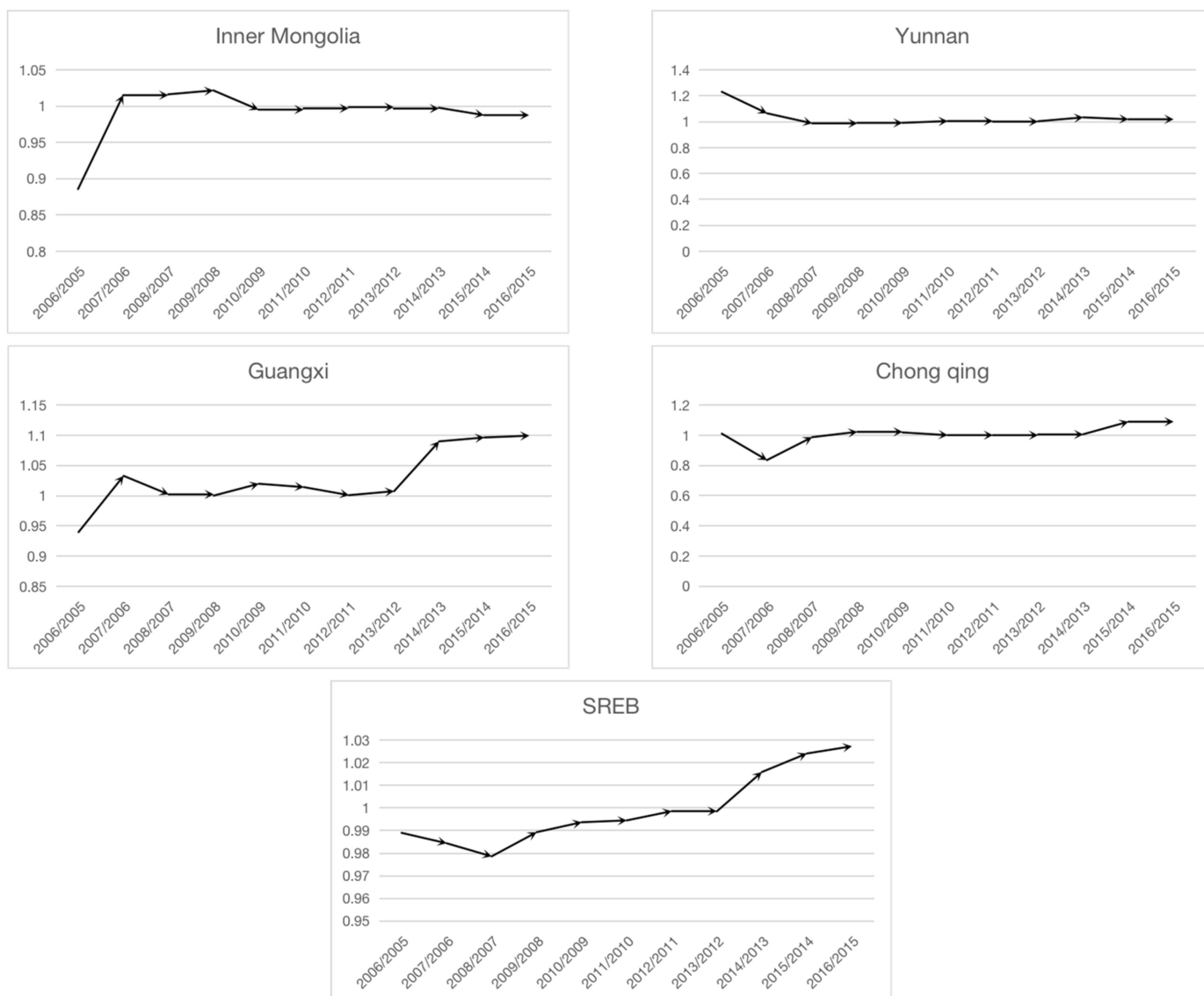


Figure 5. Technical-efficiency performance by provinces.

The SREB in the northwestern provinces (Shannxi, Gansu, and Ningxia) showed a remarkable inflection point in 2007–2008 because of the rare snow disaster and the “5.12 earthquake” in China during the period, which caused great damage to China’s economic development and transportation infrastructure. In order to restore the economy, the Chinese Government implemented the CNY 4 trillion fiscal stimulus plan in 2009, and mainly invested in infrastructure construction. It played an important role in improving the technical efficiency of low-carbon emissions and promoting transportation infrastructure in general.

Regarding technical progress, as shown in Table 5, the SREB underperformed during the period because the values were less than 1. In particular, three provinces (Shannxi, Gansu, and Qinghai) from the northwest and two provinces (Yunnan and Chongqing) from the southwest had relatively good performance compared to the others. Especially in Yunnan, the technology progressed each year, except for the two periods of 2006/2005 and 2012/2011. However, the three provinces (Liaoning, Heilongjiang, and Inner Mongolia) from the northeast showed the worst performance in terms of technical progress, as their values were overwhelmingly less than 1 in each period.

Table 5. Technical-progress performance by provinces along the SREB.

Periods	Northwest					Northeast				Southwest			SREB
	Shannxi	Gansu	Qinghai	Ningxia	Xinjiang	Liaoning	Jilin	Heilongjiang	Inner Mongolia	Yunnan	Guangxi	Chongqing	
2006/2005	1.0306	1.0439	1.0182	1.0137	0.9359	0.9195	0.8002	0.8918	0.8852	0.9576	0.9470	1.1547	0.9710
2007/2006	1.0512	1.0788	0.9944	0.9155	1.0293	0.9306	0.9962	0.9580	0.9252	1.0063	0.9435	1.0250	0.9922
2008/2007	1.0532	1.0000	0.9979	0.9524	1.0155	0.9565	1.0120	0.9601	0.9620	1.0014	0.9534	1.0127	0.9900
2009/2008	0.9933	0.9813	0.9788	1.0054	1.0472	0.9876	1.0992	0.9984	0.9645	1.0097	0.9686	1.0249	0.9980
2010/2009	0.9864	1.0063	1.0247	0.9014	1.0231	0.9927	1.0082	0.8633	0.9882	1.0089	1.0169	0.8984	0.9770
2011/2010	0.9987	1.0067	1.0107	0.9684	1.0010	0.9956	0.9988	0.8981	0.9987	1.0003	1.0099	0.9655	0.9924
2012/2011	0.9999	0.9924	0.9890	0.9750	0.9985	0.9958	0.9967	0.9665	0.9876	0.9999	0.9999	0.9726	0.9895
2013/2012	0.9996	0.9504	0.9881	0.9725	0.9910	0.9992	0.9932	0.9716	0.9987	1.0002	1.0064	0.9798	0.9995
2014/2013	1.0000	1.0453	1.0126	0.9925	0.9904	0.9922	0.9919	0.9863	0.9772	1.0148	1.0028	0.9985	1.0005
2015/2014	0.9994	0.9887	1.0001	0.9518	0.9860	0.9857	0.9821	0.9996	0.9669	1.0145	1.0045	0.9855	0.9941
2016/2015	0.9925	0.9887	1.0001	0.9512	0.9824	0.9855	0.9820	0.9994	0.9668	1.0145	1.0043	0.9854	0.9881
Mean	1.0095	1.0075	1.0013	0.9636	1.0000	0.9764	0.9873	0.9539	0.9655	1.0025	0.9870	1.0003	0.9902

Table 6 shows the contributors to CRP. Similarly to the results in Table 3, two northwestern provinces (Shannxi and Gansu) and three southwestern provinces (Yunnan, Chongqing, and Guangxi) had improved carbon-reduction performance, and Table 6 shows the significance of the contributors. The values of these contributors were greater than 1, except in Guangxi, which had a TP value of 0.9985, while the rest of the values of TE, TP, and PTE in the other provinces were less than 1. Interestingly, all of the regions along the SREB showed improving scale-efficiency performance, with values that were overwhelmingly over 1. However, SE had no significant contributions to CRP.

Table 6. Comparison of carbon reduction and its contributors among the provinces along the SREB.

Provinces	Technical Efficiency (TE)	Technical Progress (TP)	Pure Technological Efficiency (PTE)	Scale Efficiency (SE)	Carbon-Reduction Performance CRP
Shannxi	1.0247	1.0095	1.0022	1.0225	1.0344
Gansu	1.0071	1.0025	1.0031	1.0040	1.0096
Qinghai	0.9948	1.0013	0.9934	1.0014	0.9961
Ningxia	0.9743	0.9636	0.9723	1.0021	0.9388
Xinjiang	0.9987	1.0000	0.9883	1.0105	0.9987
Liaoning	0.9704	0.9764	0.9632	1.0075	0.9475
Jilin	0.9848	0.9803	0.9828	1.0020	0.9654
Heilongjiang	0.9879	0.9839	0.9868	1.0011	0.9720
Inner Mongolia	0.9907	0.9655	0.9853	1.0055	0.9565
Yunnan	1.0315	1.0015	1.0287	1.0027	1.0330
Guangxi	1.0275	0.9985	1.0021	1.0253	1.0260
Chongqing	1.0019	1.0001	1.0014	1.0005	1.0020
Average	0.9994	0.9902	0.9927	1.0069	0.9897

Note: All values were calculated with the geometric mean.

Accordingly, the good carbon-reduction performance of the southwestern provinces can be attributed to their technology-related improvements, while the underperformance of the northeastern provinces was due to their lagged transportation technology. Therefore, transportation-technology upgrades may facilitate carbon reduction.

Figure 6 outlines the overall carbon-reduction performance and its contributors in each province and the SREB. Although carbon reduction gradually improved (see Figure 3) in the SREB, the SREB underperformed in general because its performance value was over 1. As mentioned above, three provinces (Shannxi, Yunan, and Guangxi) reduced their carbon emissions remarkably, which was partly attributed to their TE improvements. However, some dramatically underperformed, such as Ningxia, Liaoning, and Inner Mongolia. Meanwhile, each province performed well in terms of SE, but its contributions to carbon reduction were limited. For instance, both Liaoning and Ningxia had good SE performance, but their CRP did not improve accordingly. Therefore, technology-related improvement is an effective way to facilitate carbon reduction in the transportation sector.

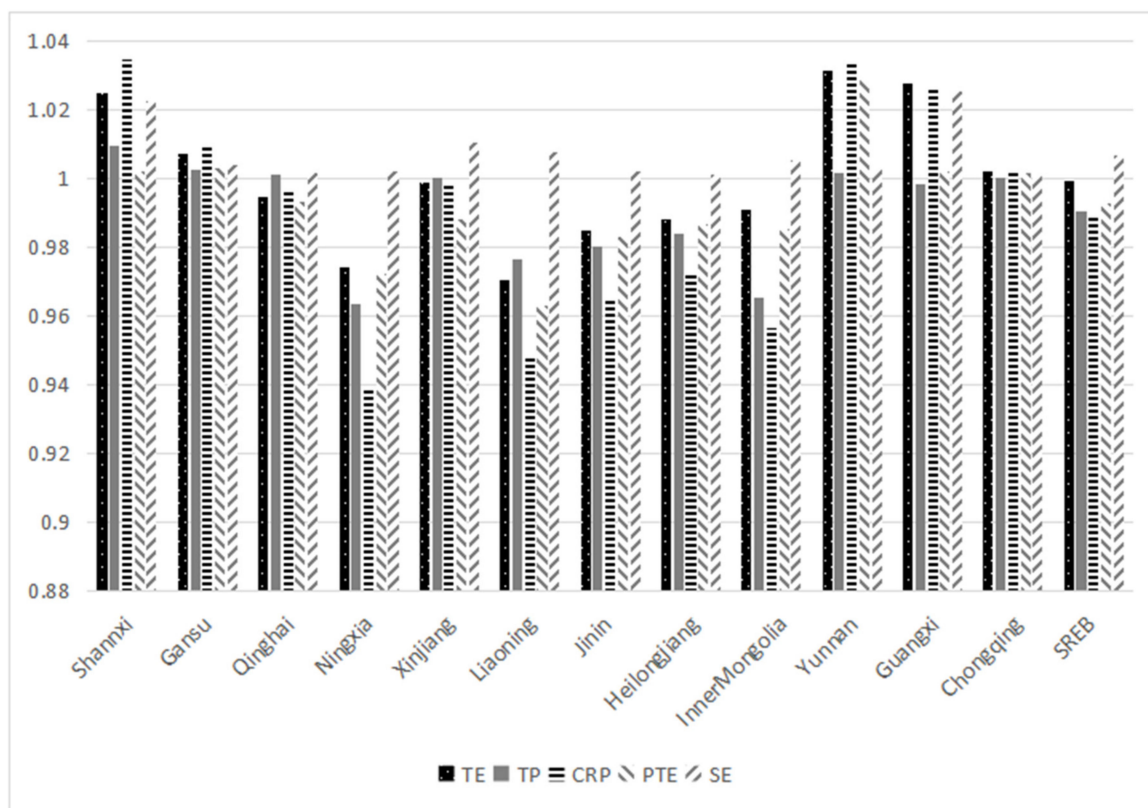


Figure 6. Provincial comparisons of CRP, TE, TP, PTE, and SE.

5. Discussion

By using the DEA–Malmquist method and developing CRP models, this research investigates CRP in the SREB and the differences among the twelve provinces along the SREB. First of all, this study shows that carbon reduction in the SREB has gradually improved gradually since 2013, which was attributed to the “CNY 4 trillion fiscal stimuli” by the Chinese central government. This amount of capital was invested into the national infrastructures, and most of them were spent on improving technical efficiency and progress of the transportation. Technology-oriented factors may improve carbon reduction; therefore, technological upgrades facilitate carbon reduction. These findings align with those of the prior studies [34,36,37].

This finding suggests that technological improvement is a sustainable countermeasure to carbon emissions. Although other studies document some options, such as policy interventions [12], information and communication technology [13], etc. for carbon reduction, the options do not work as well as expected. Rio et al. [51] shows that the subsidy policies for new energy investments have some advantages and disadvantages. Himpler and Madlener [52] find that the repowering of wind turbines is underdeveloped in Denmark due to high uncertainty in terms of revenues, and the lower profitability because the selling price of the used turbines has a minor effect on the optimum timing of repowering. Additionally, the efficiency of wind turbines gradually decreases as time goes by (<https://www.powermag.com/wind-turbine-repowering-horizon/> accessed on 20 January 2022). All these measures have some drawbacks and are not sustainable.

Furthermore, carbon emissions are subject to energy prices that are impacted by macrofactors. For instance, Norouzi [53] shows that oil and gas consumption has decreased by 25% since the COVID-19 outbreak, which means carbon emissions will increase when the economy recovers from the pandemic; Norouzi et al. [54] support this point of view. Therefore, improving technology is a sustainable way to reduce carbon emissions.

Secondly, this study shows that provincial CRP values are different. The southwestern provinces had the best performance, followed by those of the northwest, particularly in

Shannxi province, which is partially attributed to the fact that the government implemented a couple of strategic policies facilitating carbon reduction in the province. In addition, Li et al. [55] suggest that investments may not only drive GDP growth, but also facilitate carbon reduction in the SREB. Shannxi was the biggest-GDP province, generating 2980 billion RMB, ranked fourteenth across China in 2021. On this basis, Shannxi attracted more investments and had more money to invest in infrastructure than the others, including transportation systems. This fact may account for why Shannxi performed well in carbon reduction.

On the contrary, the northeastern region, including Inner Mongolia, had relatively lower performance than that of the others, which partially resulted from the lagged manufacturing industry in Jinlin and Liaoning as the traditional industrial provinces. This finding is consistent with others. Wang et al. [40] uncovered that carbon reduction was better in western than in northeastern China. The central part was better than the east because the economy in the northeast and east is better-developed than its counterparts in western and central China, respectively. This accounts for the fact that economic growth stimulates carbon emissions. Furthermore, this research shows that the disparities in CRP between provinces are obvious, in contrast to the results from Wang et al. [40], which revealed that the differences between regions gradually became less pronounced.

Thirdly, the finding that carbon emissions gradually decreased since 2013 may attribute to the technological initiative of transportation. On 30 December 2021, the Chinese Transportation Bureau announced that the transportation sector is the key to carbon reduction. According to “The Fourteenth Five-Year Development Plans of Complex Transportation Services”, the Chinese government aims to use innovation-orientated development and AI-technology applications to set up green transportation systems. Under these circumstances, this research was conducted to seek technologically efficient carbon reduction in the SREB. To achieve the green and low-carbon economic development target, the Chinese government encourages technological innovation and technology-dominated transportation reforms. Li et al. [56] analyze green transportation development and carbon emissions and suggest some solutions, such as further optimizing transportation structures, improving the efficiency of transportation equipment, promoting the applications of lower-carbon equipment, and increasing transportation-organization efficiency. Huang et al. [57] suggest that enhancing low-carbon technology promotions and encouraging technological innovation may help achieve the carbon-reduction target. Our results are in line with these viewpoints, and verify that technological upgrades may contribute to carbon reduction.

However, our findings are different from some of the other research. Some existing studies on carbon reduction are interested in environment curve tests, policy tools [58,59], stochastic frontier models, and LMDI-PDA decomposition methods [60,61], and they involve comparisons among some provinces in China, metropolitan areas, and economic belts [62,63]. Hu et al. [64], by sampling panel data from the Chinese provinces along the Yangtze River Economic Belt during 1998–2018, investigated carbon emissions from railway, highway, airline, and water transportation, and showed that the emissions were higher in eastern and western China than in central China. Sichuan province and Shanghai city in the Yangtze’s upstream and downstream regions, respectively, had the highest carbon emissions. The key carbon-emission region was moving from southwestern to northeastern China; meanwhile, the emissions decreased from the southwest to the northeast. Pan [65] finds a gradually decreasing trend in carbon emissions and lower emissions in western China and higher emissions in eastern China. These findings are different from our findings.

Furthermore, Wei et al. [66] reveal that optimizing transportation structures can facilitate carbon reduction, and suggest that more and more commuters should be encouraged to use lower-carbon transportation. This point of view is inconsistent with our findings because it is difficult to meet the carbon-reduction target by upgrading transportation structures without improving the efficiency and progress of transportation technology.

6. Conclusions

Summary: Based on input–output data from the 12 provinces in the Chinese region of the SREB, this study employs a theoretical framework from prior research [39–41] to develop some DEA–Malmquist models to investigate carbon-reduction performance in the transportation sector. This research suggests that the two key factors (scale efficiency and technical progress) restrain carbon-reduction performance. The major findings are described below.

Findings: This study shows that the SREB underperformed in terms of carbon reduction during 2005–2012 because the CRP values ranged from 0.9980 to 0.9603 during this period, while the performance improved, with CRP values over 1, from 2013 (see Table 2 and Figure 3), particularly in the provinces of Shannxi, Heilongjiang, Guangxi, Yunnan, and Chongqing (see Table 3 and Figure 4), though the growth of decarbonization was weak. The technical efficiency was a significant contributor to carbon reduction, but the lagged technological progress restricted carbon-reduction performance (see Table 2), due to the restriction of pure technological efficiency (PTE), but scale efficiency contributed to carbon reduction (see Tables 2 and 6).

Moreover, the “One Belt, One Road” initiative became the Chinese national strategy in 2013, and technical efficiency improved significantly in many provinces (see Table 4), which contributed to transportation-carbon reduction, particularly in Shannxi, Qinghai, Guangxi, Yunnan, and Chongqing (see Figure 5), because the most of their technical efficiency indexes were greater than 1. However, technical progress contributed to carbon reduction in Qinghai, Gansu, and Yunnan, because their mean values were greater than 1, and technical progress (>1) was good for many years (see Table 5), while it restrained the CRP in most provinces.

Furthermore, empirical evidence shows that the provincial CRP values are different (see Figure 6). Table 6 indicates that the southwestern provinces (Yunnan, Guangxi, and Chongqing) have the best performance because of their improved technical efficiency, followed by the northwestern provinces (Shannxi and Gansu). The contributors to CRP have various values in these provinces. Shannxi has a relatively higher technical progress value (1.0095) and technical efficiency value (1.0247), which contributes to the improvement of technical progress; consequently, it has better carbon-reduction performance than the others. On the contrary, the northeastern region, including Inner Mongolia, has the worst carbon-reduction performance; its underperformance in terms of pure technical efficiency restrains its technical progress, consequently leading to overall underperformance. The findings imply that both technical efficiency and technical progress may contribute to CRP in the transportation sector.

Implications: The practical implication for policymakers, first of all, is to upgrade transportation-technology systems in a way that includes technical progress and technical efficiency, and to develop the scale effect, which is essential for economic sustainability along the SREB. These findings suggest some ideas on how to develop lower-carbon transportation in the provinces along the SREB, such as upgrading to low-carbon technology and enhancing technical efficiency, in order to achieve sustainable and high-quality development with the initiative “Green Development, Beautiful China”. All in all, it is suggested for the government to initiate some technology-favoring policies as soon as possible, such as carbon-emission taxes and lower carbon subsidies, to improve the technical efficiency and progress in transportation vehicles and infrastructures, in order to facilitate transportation-carbon reduction.

Secondly, the government should guide investments into technology-oriented industries and environmentally friendly companies, and encourage them to engage in technological innovation for sustainable development in the long run. As technological innovation is cost-consuming, the government is expected to offer some favorable financial and tax policies to support the innovation and transformation.

Thirdly, it is suggested that the government implement appropriate environmental regulations and policy tools to strengthen the governance of the regional carbon emissions

in the SREB. For instance, encouraging clean energy and other alternative energies to achieve carbon-reduction targets, and even accelerating technological promotions in fossil-fuel resources. Meanwhile, it is suggested that the government improve the transportation system by introducing non-polluting and hybrid vehicles to minimize carbon emissions.

Last but not least, the Malmquist index method of DEA for evaluating carbon-reduction performance is very valuable and practical in the transportation sector. This method can be utilized not only in the transportation sector in Chinese provinces but also in other sectors in different countries having similar issues.

Research limitations and recommendations: The limitation of this study is that the available data is lagged because the data is issued every five years. The next issue is expected to be released in 2022 and would be a relevant subject for future research. Additionally, future research is expected to utilize the Malmquist index method to investigate the carbon-reduction performance in other countries along the Silk Road.

Author Contributions: Conceptualization, Q.Z. and J.S.; methodology, Q.Z.; software, Q.Z.; validation, Q.Z. and H.L.; formal analysis, Q.Z. and H.L.; investigation, Q.Z.; resources, Q.Z.; data curation, J.S.; writing—original draft preparation, H.L.; writing—review and editing, H.L.; visualization, H.L.; supervision, H.L.; project administration, Q.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Shaanxi Social Science Fund Planning Project “A study on the relationship between R&D expenditure of contamination-dominated companies and environment performance”, grant number 2020R001. And Soft Science Research Project “A study on the affection of ecological environment policy on the economic growth of Shaanxi province” from the Bureau of Science and Technology of Shaanxi, grant number 2021KRM115. This research also received support from the Excellent Research Team Fund of Anhui International Studies University, grant number Awkytd1908.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data may be available with the corresponding author upon request.

Conflicts of Interest: The authors declare no conflict of interest.

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