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Applying the Hypothetical Extraction Method to Investigate Intersectoral Carbon Emission Linkages of China's Transportation Sector

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Abstract: The transportation sector is an indispensable link in the industrial chain of an economic system. Considering the current push to comprehensively construct new patterns of development, the transportation sector is under huge pressure to achieve the goal of "carbon peak and carbon neutral". Therefore, to develop low-carbon transportation in China, it is important to study the carbon emission linkages in its transportation sector in order to understand its potential and the factors affecting carbon mitigation. In this study, sectoral carbon emission linkages and dynamic changes during the period of 2002–2020 for the transportation sector in China were quantitatively investigated based on the input–output analysis and hypothetical extraction method (HEM). The results showed that the total carbon emission linkages for the transportation sector mainly experienced growth, increasing by 848.63 Mt from 2002 to 2020, with consistently stronger supply-side than demand-side carbon emission linkages. This indicates that the potential of the transportation sector for carbon reduction lies upstream in the chain of carbon emission linkages. Furthermore, the transportation sector was consistently a net export sector of carbon emissions, and net carbon transfer decreased with fluctuations. Regarding carbon emissions from the transportation sector, the construction sector was found to be main destination for the majority of these emissions, while the power supply sector was the largest source. The policy implications derived from this research can serve as a crucial lever for the low-carbon development of China's transportation sector.

Keywords: the transportation sector; carbon mitigation; input–output analysis; hypothetical extraction method

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1. Introduction

Climate change is one of the most important factors increasingly influencing ecological and social systems [1]. In 1992, the *United Nations Framework Convention on Climate Change* (UNFCCC) was adopted, denoting an agreement to prevent "dangerous" human interference with the climate system by stabilizing greenhouse gas concentrations in the atmosphere [2]. A special report released by the Intergovernmental Panel on Climate Change (IPCC) states that keeping global temperature increases below 1.5 °C would significantly reduce the risks posed by climate change [3]. China is striving for its carbon emissions to peak by 2030 and to achieve carbon neutrality by 2060 (the "carbon peak and carbon neutral" target). This has resulted in an energy structure shift and green low-carbon development in industrial sectors within China.

The transportation sector has become one of the fundamental sectors experiencing the most rapid development in China, and its carbon emissions represented about 10% of total final energy consumption in 2008 [4]. During the urbanization process, the transportation sector in China developed rapidly, thus imposing great challenges for carbon mitigation [5–7]. Therefore, the transportation sector in China is under huge pressure to meet the "carbon peak and carbon neutral" target.

As the lifeblood of national economic development, the transportation sector is inextricably linked to all other sectors of the economy. It had been proven that there is a strong correlation between the transportation sector and other industrial sectors [8]. In the context of the "carbon peak and carbon neutral" target, attention should be paid to the industry linkages of carbon emissions in the transportation sector.

Input–output (IO) analysis can be used to explore intersectoral linkages, including backward and forward linkages [9]; such linkage analysis has been extended to investigate a wide variety of environmental issues, such as energy consumption [10], water consumption [11], and carbon emissions [12]. Based on the IO model, the hypothetical extraction method (HEM) is used to measure the change in total output after removal of the target sector from a particular economy [13–17]. The HEM method has been used to identify the economic role of a specific sector. A proposed modification of the HEM involves classifying the industry linkages into internal effect, external backward linkage, external forward linkage, and mixed effect, which was applied in decomposing the transfer of water resources [18]. A global extraction method was developed based on the HEM method and was applied to the automotive industry in three countries [19]. The HEM was also used to estimate the total output, gross value added, and employment effects in the Croatian ICT sector [20]. The impact of the mining industry on the Korean economy was quantitated by using a modified HEM method [21].

The environmentally extended input–output (EEIO) model has been widely used to determine the industry linkages of environmental impacts, which is needed to understand and implement climate change policies on a sectoral level. For example, the Australian manufacturing sector was identified as a significant sector with the largest energy consumption reduction potential through the analysis of forward and backward linkages [10]. Structural emission reduction of the transportation sector in China was investigated based on the EEIO model and expanded structural decomposition analysis [22]. The HEM can also be used to evaluate energy consumption and environmental effect linkages. Within the context of the global "carbon peak and carbon neutral" target, scholars have paid increasing attention to the carbon emission linkages between sectors. The HEM was used to quantitatively analyze these linkage characteristics of carbon emissions among industries [23]. The carbon emission linkages of the productive sector in Italy were measured based on the HEM method, with the productive sectors being classified based on their carbon emissions transfer characteristics [24]. The association between the transportation sector and the rest of the Chinese economy was been analyzed using the HEM and the transfer of carbon emissions as a basis [25]. A hybrid multi-regional input–output model and the HEM were combined to compare carbon emission linkages and their structures in the construction sector in 41 countries [26,27]. The HEM was also used to estimate the upstream and downstream carbon linkage chains across sectors in Turkey, which led to concerns being raised regarding intra-sectoral carbon chains in the industry [27].

The modified HEM is being widely used in current studies to decompose total carbon emission linkages, which may reveal the transfer characteristics and impacts of industrial sectors. However, examples of the quantitative analysis of carbon emission linkages and their transfer characteristics and dynamic changes in relation to the transportation sector are relatively scarce in the literature. Therefore, this study aims to address this gap by measuring the sectoral carbon emission linkages and exploring dynamic changes from 2002 and 2020 in China's transportation sector based on the hypothetical extraction method (HEM), thereby providing insight on carbon mitigation for the transportation sector from a linkage perspective.

This paper is organized as follows. In Section 2, the relevant data and methodology, including the HEM, are presented. Section 3 details the carbon emission linkages and their decomposition for 27 sectors of China's economy, revealing the net carbon transfer characteristics of the transportation sector. Finally, Section 4 concludes the paper with the relevant policy implications derived from the linkage analyses.

2. Materials and Methods

2.1. Input–Output Model

The input–output method proposed by Wassily Leontief is a mathematical economic method widely used to analyze the flow of inputs and outputs between industrial sectors; its columns describe the composition of the inputs required by a particular sector to produce its output, while the rows describe the distribution of producer's output [9]. The first part in Figure 1 depicts the application of the IO method.

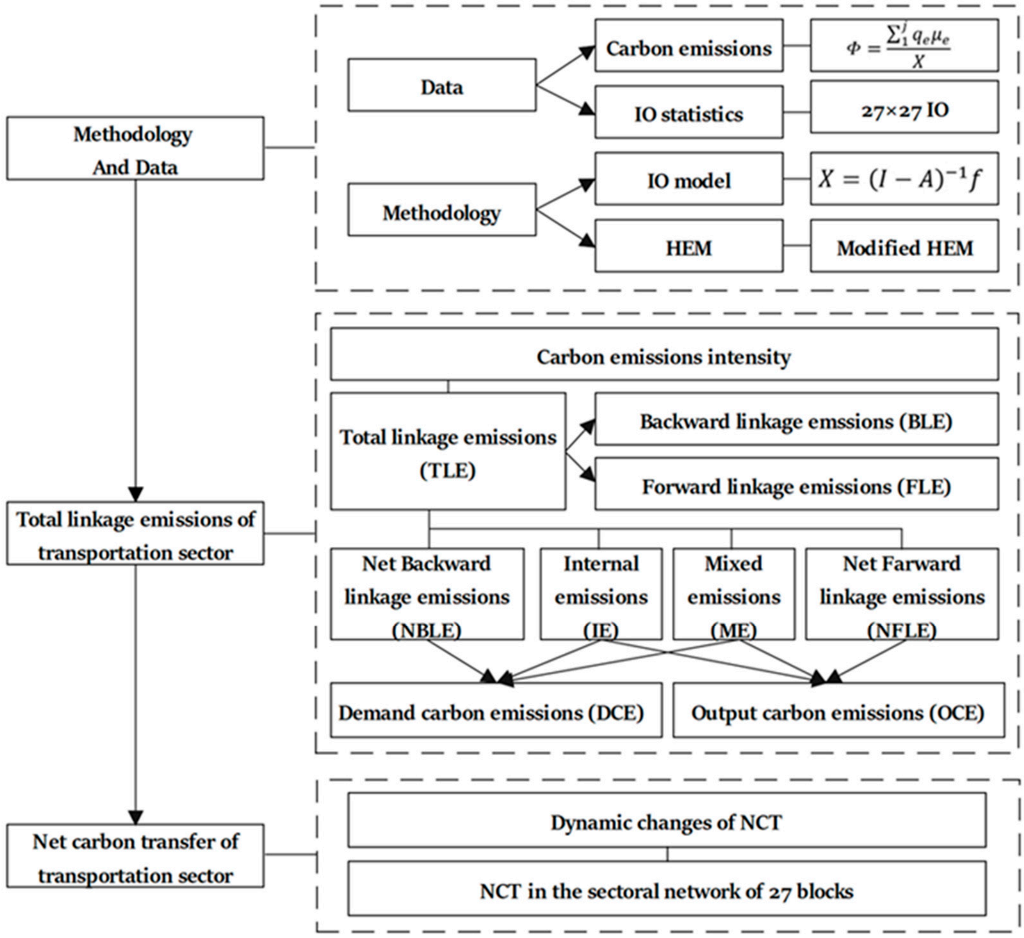


Figure 1. The IO method technical framework and structure. Note: Own elaboration.

For an input–output table with $n \times n$ sectors, the fundamental relationship can be expressed as Equation (1).

$$X = Lf = (I - A)^{-1} f \tag{1}$$

where X is the total output vector of the sector; $L = (I - A)^{-1}$ is the Leontief inverse matrix; I is the identity matrix; A is the direct consumption coefficient matrix of the sector; f is the final demand vector of the sector, which represents the total exogenous demand for the output for a specific sector.

The environmentally extended input–output (EEIO) model is an extended form of the input–output models that have been widely used to study environmental pollution and emissions reductions associated with industrial activities [9]. The basic structure of the EEIO model for carbon emissions is shown in Equations (2) and (3):

$$X = AX + f \tag{2}$$

$$C = \hat{e} L f = \hat{e} (I - A)^{-1} f \tag{3}$$

where C is the transpose of the $1 \times n$ vector of carbon emissions for each sector; e is the direct coefficient vector of carbon emissions and directly represents the carbon intensity; $\hat{e}$ represents a diagonal matrix with the vector e; $\hat{e}(I-A)^{-1}$ represents the total impact coefficient matrix of carbon emissions.

2.2. Hypothetical Extraction Method

The HEM is used to remove a particular sector from the overall economic system and analyze the consequent operating results. The middle part of Figure 1 depicts the technical framework of the HEM. We assume that the target sector, which is hypothetically removed, is the subscript s, while the subscript $-s$ represents the remaining sectors. The economy based on the HEM can be described as follows (Equation (4)):

$$\begin{bmatrix} X_s \\ X_{-s} \end{bmatrix} = \begin{bmatrix} A_{s,s} & A_{s,-s} \\ A_{-s,s} & A_{-s,-s} \end{bmatrix} \begin{bmatrix} X_s \\ X_{-s} \end{bmatrix} + \begin{bmatrix} f_s \\ f_{-s} \end{bmatrix} = \begin{bmatrix} \Delta_{s,s} & \Delta_{s,-s} \\ \Delta_{-s,s} & \Delta_{-s,-s} \end{bmatrix} \begin{bmatrix} f_s \\ f_{-s} \end{bmatrix} \tag{4}$$

where $\begin{bmatrix} X_s \\ X_{-s} \end{bmatrix}$ represents the vector of total output, $\begin{bmatrix} A_{s,s} & A_{s,-s} \\ A_{-s,s} & A_{-s,-s} \end{bmatrix}$ represents the matrix of technical coefficients, $\begin{bmatrix} f_s \\ f_{-s} \end{bmatrix}$ represents the vector of final demand, and $\begin{bmatrix} \Delta_{s,s} & \Delta_{s,-s} \\ \Delta_{-s,s} & \Delta_{-s,-s} \end{bmatrix}$ represents the Leontief inverse matrix.

Therefore, the carbon emissions matrix of the economic system based on the HEM can be represented as Equation (5):

$$\begin{bmatrix} C_s \\ C_{-s} \end{bmatrix} = \begin{bmatrix} \hat{e}_s & 0 \\ 0 & \hat{e}_{-s} \end{bmatrix} \begin{bmatrix} \Delta_{s,s} & \Delta_{s,-s} \\ \Delta_{-s,s} & \Delta_{-s,-s} \end{bmatrix} \begin{bmatrix} f_s \\ f_{-s} \end{bmatrix} \tag{5}$$

where $C = \begin{bmatrix} C_s \\ C_{-s} \end{bmatrix}$ represents the vector of total carbon emissions. $\begin{bmatrix} \hat{e}_s & 0 \\ 0 & \hat{e}_{-s} \end{bmatrix}$ represents the diagonal matrix of direct carbon intensity.

According to Zhao et al. [28], the carbon emissions related to the hypothetical productive relationship of the HEM $C^* = \begin{bmatrix} C_s^* \\ C_{-s}^* \end{bmatrix}$ can be represented as Equation (6):

$$\begin{bmatrix} C_s^* \\ C_{-s}^* \end{bmatrix} = \begin{bmatrix} \hat{e}_s & 0 \\ 0 & \hat{e}_{-s} \end{bmatrix} \begin{bmatrix} (I-A_{s,s})^{-1} & 0 \\ 0 & (I-A_{-s,-s})^{-1} \end{bmatrix} \begin{bmatrix} f_s \\ f_{-s} \end{bmatrix} \tag{6}$$

Then, the effect of the extracted block to the changes in carbon emissions can be obtained, which can be represented as Equation (7) and (8):

$$\begin{bmatrix} C_s \\ C_{-s} \end{bmatrix} - \begin{bmatrix} C_s^* \\ C_{-s}^* \end{bmatrix} = \begin{bmatrix} \hat{e}_s & 0 \\ 0 & \hat{e}_{-s} \end{bmatrix} \begin{bmatrix} \Delta_{s,s} - (I-A_{s,s})^{-1} & \Delta_{s,-s} \\ \Delta_{-s,s} & \Delta_{-s,-s} - (I-A_{-s,-s})^{-1} \end{bmatrix} \begin{bmatrix} f_s \\ f_{-s} \end{bmatrix} \tag{7}$$

or

$$\begin{bmatrix} C_s \\ C_{-s} \end{bmatrix} - \begin{bmatrix} C_s^* \\ C_{-s}^* \end{bmatrix} = \begin{bmatrix} \Omega_{s,s} & \Omega_{s,-s} \\ \Omega_{-s,s} & \Omega_{-s,-s} \end{bmatrix} \begin{bmatrix} f_s \\ f_{-s} \end{bmatrix} \tag{8}$$

Furthermore, we can calculate, for the target sector, the total carbon emissions linkage effect (*TLE*) through Equation (9), backward carbon emissions linkage effect (*BLE*) through Equation (10), and forward carbon emissions linkage effect (*FLE*) through Equation (11).

$$TLE = i' \begin{bmatrix} \Omega_{s,s} & \Omega_{s,-s} \\ \Omega_{-s,s} & \Omega_{-s,-s} \end{bmatrix} \begin{bmatrix} f_s \\ f_{-s} \end{bmatrix} \tag{9}$$

$$BLE = i' \begin{bmatrix} \Omega_{s,s} \\ \Omega_{-s,s} \end{bmatrix} f_s \tag{10}$$

$$FLE = i'\begin{bmatrix}\Omega_{s,-s}\\ \Omega_{-s,-s}\end{bmatrix}f_{-s} \tag{11}$$

2.3. Modified Hypothetical Extraction Method

A modified hypothetical extraction method was proposed by Durate [12]. In this paper, we refer to his ideas for a more refined decomposition of the total linkage emissions (*TLE*). We indicate that Q_S represents the removed target sector, and Q_{-S} represents the remaining sectors. The internal emissions (*IE*) effect refers to the carbon emissions that are generated by the removed target sector Q_S, which is not associated with Q_{-S}. This part of carbon emissions is generated when the target sector consumes its own independently produced output in order to meet the final demand of itself, as shown in Equation (12):

$$IE = \hat{e}_s(I - A_{s,s})^{-1}f_s \tag{12}$$

The mixed emissions (*ME*) effect refers to the carbon emissions generated when Q_{-S} purchases the output of Q_S as an intermediate input for production, which is later purchased back by the target sector Q_S to satisfy its own demand. It is shown as Equation (13):

$$ME = \Phi_s\left[\Delta_{s,s} - (I - A_{s,s})^{-1}\right]f_s \tag{13}$$

Net backward linkage emissions (*NBLE*) refers to the carbon emissions generated by Q_S when purchasing the output of Q_{-S} as intermediate inputs for production in order to meet its own final demand. It is the net carbon emissions import of Q_S. The expression is shown in Equation (14):

$$NBLE = \Phi_{-s}\Delta_{-s,s}f_s \tag{14}$$

Net forward linkage emissions (*NFLE*) refers to the carbon emissions generated when Q_S is purchased by Q_{-S} as an intermediate input for production to meet the final demand of Q_{-S}. It is the net carbon emissions export of Q_S. The expression is shown in Equation (15):

$$NFLE = \Phi_s\Delta_{s,-s}f_{-s} \tag{15}$$

According to the method proposed by Huang et al. [29], this paper defines demand carbon emissions (*DCE*) and output carbon emissions (*OCE*), which represent the carbon emissions generated by the target sector to meet its own final demand and its total carbon emissions output, respectively. *DCE* and *OCE* are calculated as shown in Equations (16) and (17):

$$DCE = IE + ME + NBLE \tag{16}$$

$$OCE = IE + ME + NFLE \tag{17}$$

For the whole economic system, Equation (18) indicates that the sum of demand carbon emissions of all sectors is equal to the sum of their output carbon emissions.

$$DCE_S + DCE_{-S} = OCE_S + OCE_{-S} \tag{18}$$

For the target sector, the net carbon transfer (*NCT*) can be expressed as the difference between output carbon emissions (*OCE*) and demand carbon emissions (*DCE*), as expressed by Equation (19), which is depicted in the last part of Figure 1.

$$NCT = OCE - DCE = NFLE - NBLE = \Phi_s\Delta_{s,-s}f_{-s} - \Phi_{-s}\Delta_{-s,s}f_s \tag{19}$$

The calculation results of Equation (19) show the carbon transfer characteristics of the target sector. A positive value of *NCT* indicates that the carbon emissions from this sector are transferred to other sectors in the economic system, while a negative value of *NCT* indicates that the target sector absorbs carbon emissions from other sectors.

To further analyze the carbon emissions transfer between the target sector and the remaining sectors, it is assumed that sector h is one of the remaining sectors of Q_{-S}. Based on the above analysis, the net backward linkage emissions (Equation (20)), net forward linkage emissions (Equation (21)), and net carbon transfer (Equation (22)) between Q_S and sector h can be calculated as follows.

$$NBLE_{h,s} = \Phi_h \Delta_{h,s} f_s;\ NBLE_{-s,s} = \sum NBLE_{h,s}, h \in (-s) \quad (20)$$

$$NFLE_{s,h} = \Phi_s \Delta_{s,h} f_h;\ NFLE_{s,-s} = \sum NFLE_{s,h}, h \in (-s) \quad (21)$$

$$NCT_{s,h} = NFLE_{s,h} - NBLE_{h,s} = \Phi_s \Delta_{s,h} f_h - \Phi_h \Delta_{h,s} f_s, h \in (-s) \quad (22)$$

Similarly, a positive value for $NCT_{s,h}$ means that Q_S generates a net outflow of carbon emissions to sector h, while a negative value for $NCT_{s,h}$ means that Q_S absorbs a net inflow of carbon emissions from sector h.

2.4. Data Sources

The carbon emissions data used in this paper represent an inventory of China's sectoral accounting carbon emissions from 2002 to 2020, compiled by the China Carbon Emissions Accounts and Datasets (CEADs) [30–33]. This data inventory accounts for the carbon emissions of 45 sectors in China with a relatively uniform caliber. The industrial sectors in China are aggregated into 27 sectors with similar production contents in terms of industry classification of CEADs. The input–output data used in this paper are obtained from the national input–output tables compiled and released by the National Bureau of Statistics of China for a total of eight years: 2002, 2005, 2007, 2010, 2012, 2015, 2017, and 2020 [34]. The industrial sectors in input–output tables are aggregated according to the sectoral classification criteria of carbon emissions data. In addition, the input–output data for each year are deflated using the consumer price index of 2002 to eliminate the influence of price changes.

3. Results and Discussion

3.1. Carbon Emissions and Intensity

Based on Equations (2) and (3), we calculated the direct carbon emissions intensity and total carbon emissions intensity for the transportation sector. Figure 2 shows direct and total effects of carbon emissions for the transportation sector from 2002 to 2020.

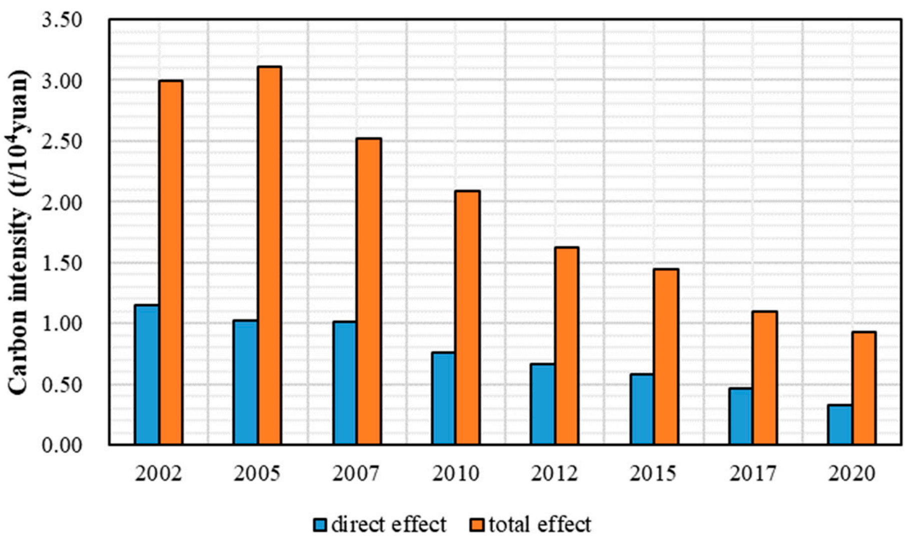
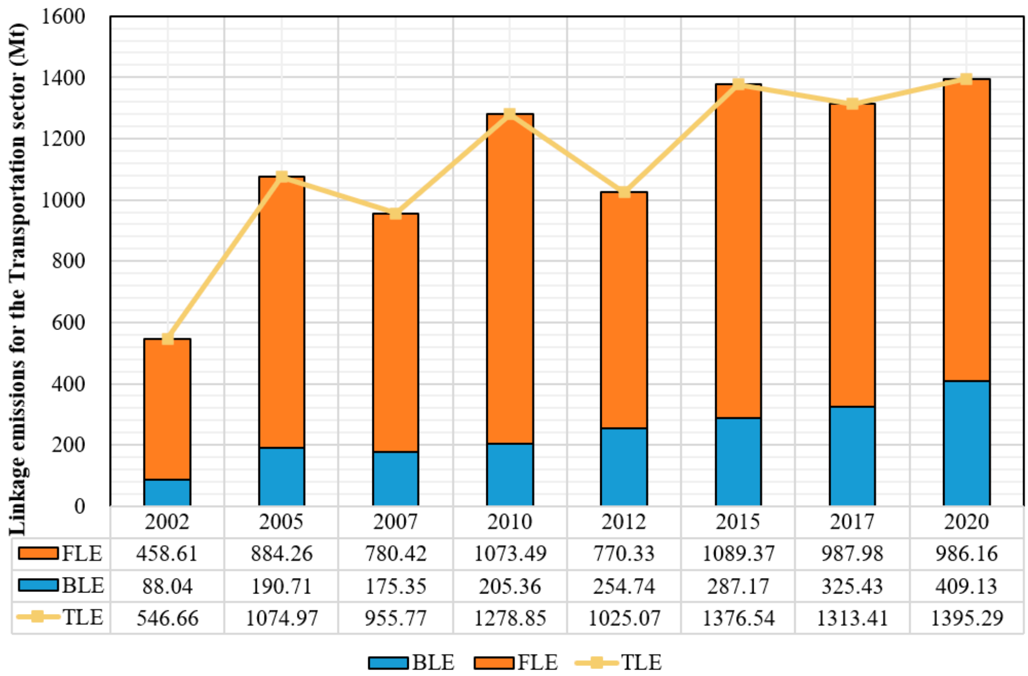


Figure 2. Direct and total effects of GHG emissions for the transportation sector from 2002 to 2020. Note: Own compilation based on Equations (2) and (3).

The direct effect of GHG emissions in the transportation sector has decreased from 1.15 t/CNY 10^4 in 2002 to 0.33 t/CNY 10^4 in 2020, while the total effect also declined from 2.99 t/CNY 10^4 in 2002 to 0.93 t/CNY 10^4 in 2020. In other words, the indirect effect of GHG emissions accounted for more than 55% of the total effect during the study period. The development of the transportation sector has a certain scale effect that is accompanied by continuous technological innovation and adjustment in the energy structure, which is the main reason for the decrease in carbon emissions intensity in this sector [35].

3.2. Total Carbon Emission Linkages in the Transportation Sector

To investigate the carbon emission linkages between the transportation sector and other industrial sectors, the HEM was adopted to account for the total carbon emissions linkage effect (*TLE*), backward carbon emissions linkage effect (*BLE*), and forward carbon emissions linkage effect (*FLE*) for the transportation sector from 2002 to 2010 based on Equations (9)–(11), as shown in Figure 3.



	2002	2005	2007	2010	2012	2015	2017	2020
FLE	458.61	884.26	780.42	1073.49	770.33	1089.37	987.98	986.16
BLE	88.04	190.71	175.35	205.36	254.74	287.17	325.43	409.13
TLE	546.66	1074.97	955.77	1278.85	1025.07	1376.54	1313.41	1395.29

Figure 3. Carbon emission linkages of the transportation sector from 2002 to 2020. Note: *BLE*, backward linkage emissions; *FLE*, forward linkage emissions; *TLE*, total linkage emissions. Note: Own compilation based on Equations (9)–(11).

The *TLE*, generated by both direct and indirect linkages, for the transportation sector generally increased, increasing overall from 546.66 Mt in 2002 to 1395.29 Mt in 2020. This is mainly due to the growth in final demand for various economic sectors, reflecting that the linkages between the transportation sector and the other economic sectors increased during the study period. Moreover, it can be attributed to the fact that China implemented a CNY 4 trillion economic stimulus plan to expand domestic demand and vigorously strengthened investment in infrastructure projects, including transportation, after the global economic crisis in 2008. From 2002 to 2005, *TLE* for the transportation sector dramatically grew by 528.31 Mt and subsequently slowed down.

The *FLE* for the transportation sector mainly experienced a trend similar to *TLE*, increasing from 458.61 Mt in 2002 to 986.16 Mt in 2020, with the highest value of 1089.37 Mt in 2015. After 2015, *FLE* steadily declined to 987.98 Mt in 2017 and 986.16 Mt in 2020. This indicates that the supply-side carbon emissions generated by the transportation sector generally increased from 2002 to 2015 in order to meet the consumption of the downstream industry chain and then decreased from 2015 to 2020. The *BLE* for the transportation sector steadily increased from 88.04 Mt in 2002 to 409.13 Mt in 2020.

It is clear that *FLE* contributed more to *TLE* than *BLE*, accounting for more than 70% of *TLE*; however, its contribution steadily decreased from 83.89% in 2002 to 70.68% in 2020. This indicates that the supply-side carbon emission linkages were much larger than the demand-side carbon emission linkages for the transportation sector from 2002 to 2020. For instance, *FLE* for the transportation sector in 2020 was 986.16 Mt, which is nearly 2.5 times the *BLE* for the transportation sector in 2020 (409.13 Mt); this indicates that the transportation sector was in a more upstream position in the chain of carbon emission linkages in the economic system.

The above findings can be explained in terms of the actual characteristics of the transportation sector, as follows. The demand for the upstream economic sectors of the transportation sector is mainly focused on transportation equipment, infrastructure construction, and the energy sectors, while the forward supply for downstream sectors is broader and includes transportation services for raw materials and product distribution for the remaining sectors. Due to the deepening division of labor and the development of the logistics industry, the transportation sector has a stronger and closer linkage with downstream sectors, thus leading to more prominent forward carbon emission linkages. Therefore, the transportation sector should pay more attention to the carbon emissions generated on the supply side when conducting carbon reduction policies.

3.3. Decomposition of Carbon Emission Linkages Using Modified HEM

To precisely depict the characteristics of carbon emission linkages for the transportation sector in China, this paper further decomposes the effect of carbon emission linkages for the transportation sector in China according to Equations (12)–(15). The demand carbon emissions (*DCE*) and output carbon emissions (*OCE*) for the transportation sector can be obtained by calculating the decomposed items according to Equations (16) and (17), as shown in Figure 4.

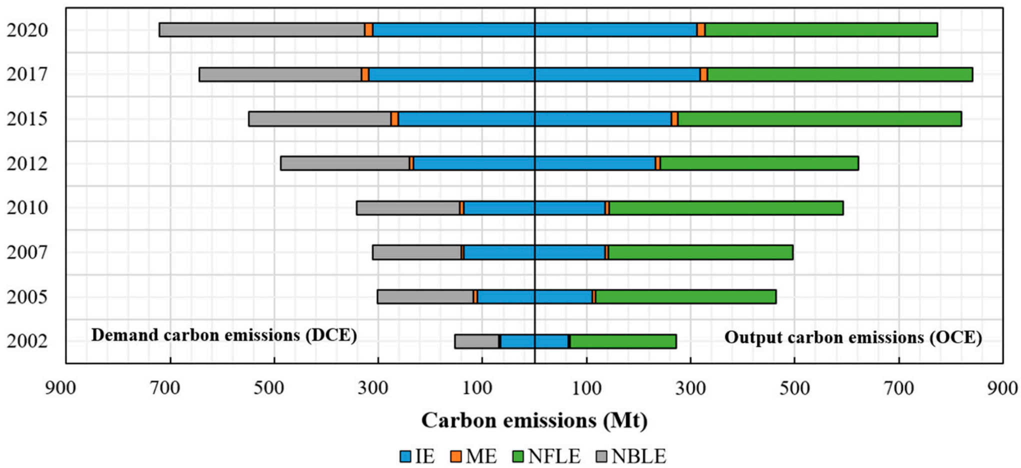


Figure 4. Demand carbon emissions and output carbon emissions for the transportation sector from 2002 to 2020. Note: Own compilation based on Equations (12)–(17).

The *DCE* for the transportation sector experienced a constant increase from 152.95 Mt in 2002 to 720.77 Mt in 2020, while the *OCE* increased from 272.41 Mt in 2002 to 773.89 Mt 2017 and subsequently declined, with the highest value of 842.18 Mt observed in 2017. It is clear that *OCE* was always larger than *DCE*. However, the difference between *OCE* and *DCE* was 119.46 Mt in 2002, which decreased to 53.12 Mt in 2020, indicating the effect of *OCE* and *DCE* became almost identical at the end of the study period. More specifically, *OCE* and *DCE* both experienced dramatical growth from 2002 to 2005, by 191.17 Mt and

148.45 Mt, respectively; *OCE* subsequently experienced a slower growth and even decreased by 68.29 Mt from 2017 to 2020.

Table 1 shows the percentages of each component of *DCE* and *OCE* in China's transportation sector from 2002 to 2020. It can be seen that the proportions of *ME* were low, and both *DCE* and *OCE* remained relatively stable, consistently remaining at around 2% and 1%, respectively.

Table 1. The proportion of the components in demand and output carbon emissions of the transportation sector from 2002 to 2020.

Year	*DCE*			*OCE*		
	IE **(%)**	***ME*** **(%)**	***NBLE*** **(%)**	***IE*** **(%)**	***ME*** **(%)**	***NFLE*** **(%)**
2002	42.44	2.11	55.46	23.83	1.18	74.99
2005	36.73	2.37	60.90	23.88	1.54	74.58
2010	39.91	2.02	58.07	22.98	1.17	75.85
2012	47.70	1.80	50.50	37.33	1.41	61.26
2015	47.75	2.34	49.91	31.96	1.57	66.47
2017	49.48	2.12	48.40	37.84	1.63	60.53
2020	43.24	2.10	54.66	40.27	1.96	57.77
2002	42.44	2.11	55.46	23.83	1.18	74.99

Note: Own compilation based on Equations (12)–(17).

IE and *NBLE* are the main components of *DCE*; the highest proportion of *IE* was 49.48% in 2017 and the lowest 36.73% in 2005; the highest proportion of *NBLE* was 60.90% in 2005 and the lowest 48.40% in 2017, generally showing converse trends to *IE*. *NBLE* consistently contributed the largest proportion to *DCE*, indicating that the carbon emission linkages between the transportation sector and upstream industrial sectors are relatively strong and stable.

Similarly, *IE* and *NFLE* were the main contributors to *OCE*; the percentages of *IE* generally experienced growth from 23.83% in 2002 to 40.27% in 2020, while those of *NFLE* dramatically declined from 74.99% in 2002 to 57.77% in 2020. During the study period, *NFLE* maintained the largest contribution to *OCE* for the transportation sector, at above 55%, indicating that the transportation sector exported a large amount of carbon emissions to downstream sectors, and its effect weakened during the study period. Du et al. used the same method to decompose the total carbon emission linkages during the decade of 2002–2012, with findings generally consistent with our results [25].

The changing patterns and composition characteristics of *DCE* and *OCE* are consistent with the actual development of China's transportation sector. At the end of the 20th century, China's transportation sector embarked on the road of marketization and entered a stage of unprecedented leapfrog development. During this period, China's transportation sector was dominated by extensive construction and expansion, with a strong reliance on upstream sectors such as transportation equipment manufacturing and construction, generating a large amount of *NBLE*. Additionally, during the stage where the output of the transportation sector experienced accelerated expansion, the *OCE* of this sector also continued to increase, and the rate of growth was higher. Meanwhile, the downstream sectors became more dependent on the transportation sector; thus, the *NFLE* has shown continuous expansion and consistently accounted for a large proportion of *OCE*. However, after entering the "12th Five-Year Plan" stage, China's transportation sector gradually began to transform from "scale expansion" to having qualities of "quality and efficiency" [26]. Internal restructuring and technological innovation have replaced extensive construction and expansion as the new main line of development. On the one hand, the transportation sector's linkages with upstream sectors such as the construction sector have weakened, and thus, the proportion of *NBLE* in *DCE* has decreased slightly. On the other hand, the shift of focus onto the transportation sector limits the rapid expansion of output and places greater emphasis on energy conservation, emissions reduction, and sustainable development. As a result, the growth rate of *OCE* in the transportation sector has slowed down.

3.4. Net Carbon Transfer in the Transportation Sector

3.4.1. Net Carbon Transfer and its Dynamic Changes

To further analyze the net transfer of carbon emissions in the transportation sector in China from 2002 to 2020, the net carbon transfer (*NCT*) of this sector is calculated based on Equation (19). According to the above analysis, the net transfer of carbon emissions is directional, where a positive value means that the sector is a net exporter of carbon emissions. The calculation results shown in Figure 5 indicate that the transportation sector has continuously exported a certain level of net carbon emissions to the economic system from 2002 to 2020.

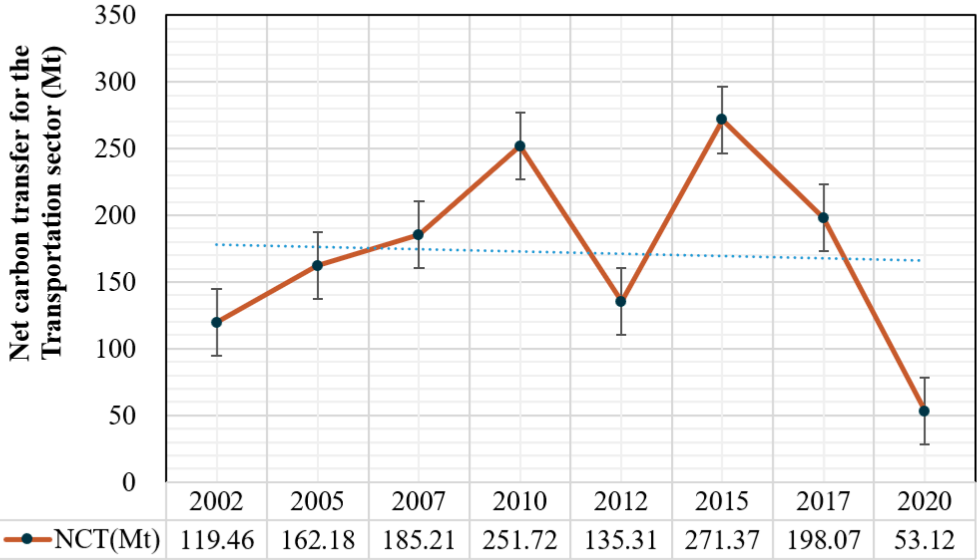


Figure 5. Net carbon transfer for the transportation sector from 2002 to 2020. Note: Own compilation based on Equation (19).

Figure 5 also shows the trend of the net transfer of carbon emissions for the transportation sector from 2002 to 2020. It can be seen that the net carbon transfer for the transportation sector has generally experienced a decline from 119.46 Mt in 2002 to 53.12 Mt in 2020, with the maximum value of 271.37 Mt in 2015. From 2002 to 2010, *NCT* experienced a constant growth of 132.25 Mt; there was a dramatical decline (−116.41 Mt) in *NCT* from 2010 to 2012, quickly followed by a dramatic rebound from 2012 to 2015 (+136.06 Mt); from 2015 to 2020, *NCT* experienced constant decline, from 271.37 Mt to 53.12 Mt. The trend of net carbon transfer for the transportation sector of expanding before 2010 reflects the high carbon emissions and high pollution of this sector. The transportation sector has become and will remain a key emitter of carbon in the long term. The transfer for this sector has, however, become less serious during the study period.

3.4.2. Net Carbon Transfer in the Network of 27 Blocks

In order to control the scale of carbon emissions for each sector, it is necessary to specifically know the transfer of carbon emissions between the transportation sector and other industrial sectors. Therefore, the direction and extent of the transfer of carbon emissions from the transportation sector to 26 other sectors are quantitatively calculated based on Equations (20)–(22). Table 2 shows that the main destinations for carbon emissions from the transportation sector were the CON, OTH, and TELM sectors, while the main sources of carbon emissions for the transportation sector were the POW, METS, FOSF, and FOSM sectors. In addition, as can be seen from Table 2, the direction of carbon transfer between the transportation sector and most industrial sectors did not change during the period from 2002 to 2020. The direction of carbon emissions transfer changed in only a few sectors, including METM, NONM, and OTM. For example, the OTM sector initially absorbed carbon emissions from the transportation sector in 2002 and then exported carbon emissions to the transportation sector between 2005 and 2020.

Table 2. Net carbon transfer (NCT) from the transportation sector to 26 blocks.

Sectors	2002	2005	2007	2010	2012	2015	2017	2020
AGR	8.61	7.99	6.66	6.63	6.73	4.70	8.06	7.06
FOSM	−5.48	−9.80	−11.18	−14.61	−18.46	−10.73	−12.70	−10.80
METM	−0.17	0.15	−0.34	−0.42	−0.75	−0.74	−0.53	−0.75
NONM	0.21	−0.21	0.00	0.01	−0.63	−0.40	−0.32	−0.32
FOO	8.49	14.14	15.08	21.08	21.10	20.84	31.29	19.74
TEX	3.95	6.42	7.25	6.28	10.04	3.35	15.24	10.75
WEA	6.97	12.13	10.78	12.00	4.49	14.39	7.39	5.12
WOO	1.91	2.95	4.29	4.43	4.12	5.98	5.65	3.97
PAP	1.20	0.92	1.47	1.22	3.60	7.18	4.35	3.09
FOSF	−5.21	−9.75	−11.98	−12.55	−14.63	−15.86	−16.03	−23.78
CHE	3.25	2.64	4.70	6.59	2.61	4.03	4.98	4.44
NONP	−3.65	−13.41	−5.71	−6.61	−9.60	−9.53	−7.55	−10.06
METS	−11.54	−29.07	−19.71	−27.93	−35.65	−43.92	−40.81	−55.67
METP	3.11	6.75	5.10	3.85	4.99	7.06	4.33	3.25
COM	12.08	26.76	22.55	30.33	30.62	35.94	26.18	25.09
TRAM	5.81	13.14	15.54	27.92	27.42	34.81	29.52	22.90
ELEM	5.99	13.60	15.02	22.14	15.73	21.96	15.33	13.33
TELM	13.17	38.14	30.56	33.35	26.45	32.47	35.87	33.19
MANM	4.13	9.88	4.74	5.17	2.10	3.15	2.16	1.72
OTM	−0.05	2.01	2.29	3.46	0.27	0.94	0.43	0.11
POW	−45.20	−92.03	−90.85	−106.51	−135.11	−155.47	−201.56	−264.71
GAS	0.16	0.30	0.12	0.73	0.59	1.73	0.26	0.42
WAT	0.13	0.18	0.17	0.44	0.30	0.65	0.34	0.53
CON	58.92	79.12	104.28	148.03	96.74	176.13	136.96	119.56
RET	11.12	15.23	21.70	17.50	15.89	22.07	26.31	23.49
OTH	41.57	64.01	52.66	69.20	76.37	110.64	122.93	121.44

Note: Own compilation based on Equations (20)–(22); TRA, transportation, storage, post, and telecommunication services; AGR, farming, forestry, animal husbandry, fishery, and water conservancy; FOSM, fossil mining dressing and extraction; METM, metals mining and dressing; NONM, non-metal minerals mining and dressing; FOO, food, beverage, and tobacco production and processing; TEX, textile industry; WEA, clothing, leather, down, and related products; WOO, wood processing and furniture manufacturing; PAP, papermaking, printing, and educational and sporting articles; FOSF, petroleum processing and coking; CHE, chemical industry; NONP, non-metal mineral products; METS, smelting and pressing of metals; METP, metal products; COM, ordinary and special machinery; TRAM, transportation machinery; ELEM, electric equipment and machinery; TELM, electronic and telecommunications equipment; MANM, instruments, meters, cultural, and office machinery; OTM, other manufacturing industry (scrap and waste); POW, production and supply of electric power, steam, and hot water; GAS, production and supply.

The average value of the net carbon transfer from the transportation sector to other industrial sectors in each statistical year is plotted in Figure 6. We can see that a total of 19 sectors absorbed the net output of carbon emissions from the transportation sector, while another 7 sectors had a net input of carbon emissions to the transportation sector.

Figure 6 shows that the transportation sector transferred an average of 114.97 Mt of carbon emissions to the CON sector each year, which was the most significant carbon emissions exporting sector of the transportation sector, accounting for 30.59% of the total net carbon emissions export, a much higher proportion than of the other sectors. TRAM, FOO, MANM, and RET also absorbed huge net carbon emissions transfer from the transportation sector each year, at 82.35 Mt (21.91%), 30.40 Mt (8.09%), 26.19 Mt (6.97%), and 22.13 Mt (5.89%), respectively. The top five carbon emissions exporting sector together accounted for 73.44% of the total net carbon emissions export. The net transfer of carbon emissions exported from the transportation sector to other destination sectors was thus relatively small. The reasons for these sectors being a destination for carbon emissions from the transportation sector include investment in infrastructure construction, the scale manufacturing of transportation equipment, the increase in consumption levels, and the growing prosperity of e-commerce, which is consistent with the linkage characteristics between these sectors.

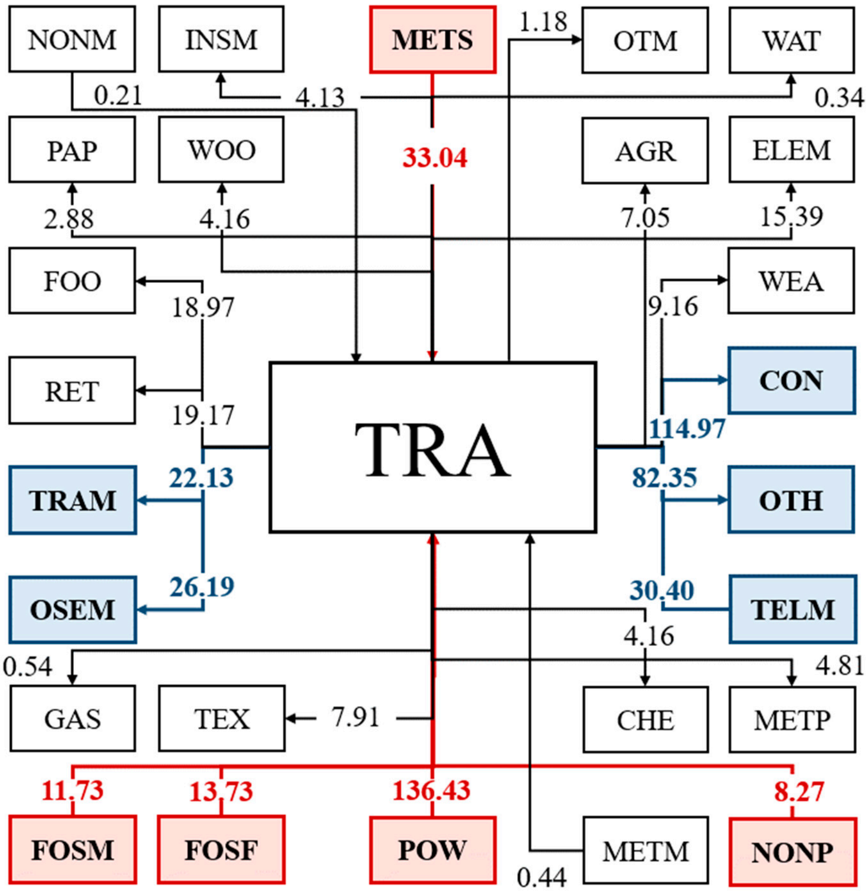


Figure 6. Average net carbon transfer (NCT) in the network of 27 blocks from 2002 to 2020. Note: Own compilation based on Equations (20)–(22).

The transportation sector absorbed an average of 136.43 Mt of net carbon emissions transferred from the POW sector each year, accounting for 66.93% of the total net input carbon emissions. POW was the sector with the largest net transfer of carbon emissions to the transportation sector, and there was a large gap compared to the other sectors. Second only to the POW sector as a source of carbon emissions for the transportation sector was the METS sector, which transferred an average of 33.04 Mt of carbon emissions to the transportation sector each year, accounting for 16.21% of the total net input carbon emissions transferred toward the transportation sector. The net transfer of carbon emissions from other sectors, as sources, to the transportation sector was relatively small. Industries such as automobile manufacturing and energy supply are upstream of the transportation sector and closely control the normal operation of this sector on the supply side. The energy supply and metal sectors, which provide raw materials for the automobile manufacturing sector, produce carbon emissions that flow down the chain to the transportation sector. The transportation sector thus becomes a carbon absorber for these sectors.

4. Conclusions and Policy Implications

4.1. Conclusions

In this study, IO tables were combined with the sectoral carbon emissions from 2002 to 2020, and the hypothetical extraction method was then applied to quantitatively calculate the characteristics of carbon emission linkages for the transportation sector. Thus, the position of the transportation sector in the industry-wide carbon emissions mitigation system is demonstrated along with its transfer characteristics and dynamic change trend. The conclusions are as follows.

First, the indirect carbon intensities were found to account for more than 55% of total emissions intensity, representing the significance of carbon emission linkages with other industrial sectors in the economic system. Meanwhile, the direct carbon emissions intensity for the transportation sector remained at a high level, ranking fifth of 27 industrial sectors in 2020.

Second, *TLE* for the transportation sector mainly experienced an increase. *TLE* between the transportation sector and other industrial sectors was 1395.29 Mt in 2020, which is more than 2.5 times the value in 2002. *FLE* generally increased, indicating that the linkage effect of supply-side carbon emissions gradually increased. The contribution of BLE was relatively limited; thus, *FLE* dominated the changes in *TLE*. For the transportation sector, *FLE* was generally much larger than *BLE*, indicating that the supply-side carbon emission linkages of China's transportation sector were more prominent and that the transportation sector lies upstream in the chain of carbon emission linkages in the economic system.

Third, the results of *TLE* decomposition show that for the transportation sector, both *OCE* and *DCE* experienced an increase. *DCE* showed a constant increase, while *OCE* generally increased with fluctuation. The difference between *OCE* and *DCE* was reduced in 2020 to 53.12 Mt. *NFLE* represented a smaller proportion of the OCE at 57.77%, indicating that the carbon emission linkages between the transportation sector and downstream sectors became weaker.

Fourth, the results for the calculation of net carbon transfer show that the transportation sector was consistently a net exporter of carbon emissions during the period, and the net transfer of carbon emissions generally decreased. The carbon emissions from the transportation sector were transferred to 19 sectors, including CON, TRAM, FOO, MANM, and RET, while the transportation sector mainly absorbed the carbon emissions input of 7 sectors, including POW, METS, and FOSF. Among them, the CON sector was the destination for most of the carbon emissions from the transportation sector, while the POW sector was the largest source of carbon emissions.

4.2. Policy Implications

The goal of policymakers is to achieve "ting and carbon neutrality" as soon as possible to ensure the stable development of the transportation sector. Based on the empirical results, the following carbon emissions reduction policies are proposed for the Transportation sector from the perspective of carbon emission linkages.

First, a more specific accounting system for carbon emission linkages should be built for the transportation sector to clarify its responsibility regarding carbon emissions. According to the results, the indirect intensity of the transportation sector accounted for more than 50% of the total intensity, indicating that most carbon emissions are embodied in the related supply chains rather than directly generated by the sector itself. For the transportation sector, policy makers should devote more attention to regulating large inter-industrial transfers by when considering how to realize carbon mitigation [25]. In addition, the construction of an accounting system for carbon emission linkages and the timely standardization of measurements of carbon emission linkages in this sector will help to clarify the responsibility of the transportation sector regarding carbon emissions reduction in an honest and equitable manner and help in forming an efficient carbon emissions reduction mechanism of "who pollutes, who governs".

Second, the government should develop a low-carbon industrial chain, collaborating with the transportation sector and other industrial sectors toward strengthening the transmission effect of carbon emissions reduction. Policymakers should attach great significance to the key sectors that are closely related to carbon emissions in the transportation sector. In particular, the results emphasize that there are strong carbon emission linkages between the transportation sector and downstream sectors. At the front end of the chain, government should pay attention to the key upstream sectors on the demand side of the transportation sector, such as the energy supply industry, prioritizing the adoption of low-carbon technologies and production methods in providing low-carbon raw materials to the chain. At the back end of the chain, government should focus on the downstream sectors on the supply side of the transportation sector, such as the construction sector and the wholesale and retail sector, encouraging them to cultivate low-carbon consumption awareness and form a preference for low-carbon transportation methods, thereby stimulating the transportation sector to reduce carbon emissions.

4.3. Limitations

The aim of this study was to measure inter-sectoral carbon emission linkages and dynamic changes. The study has some limitations due to the model and data used. The data of the Chinese IO tables used in this study did not cover continuous years, which might have led to some temporal changes in carbon emission linkages being missed. To address this, the data for IO tables could be estimated for the missing years using the RAS method. However, calculating all data of the missing IO tables is a challenge and may also result in an inaccurate result. Thus, the IO tables used in this study were those released by the National Bureau of Statistics of China, covering a total of nine years.

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