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Research Article

Carbon Emission and Structure Analysis of Transport Industry Based on Input-output Method: China as an Example

Manzhi Liu [a,*], Jinfeng Wang [a], Jixin Wen [a], Gang He [b,*], Jixin Wu [a], Huayang Chen [a], Xiaotao Yang [a]

[a] School of Economics and Management, China University of Mining and Technology, Xuzhou 221116, China
[b] Department of Technology and Society, Stony Brook University, Stony Brook 11794, USA

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ABSTRACT

Due to its enormous carbon dioxide emissions, China's transport industry has become a key area for energy conservation and emission reduction. In this study, we employ the input-output method to examine the carbon dioxide emissions caused by the transport industry's energy consumption. In addition, the structure decomposition method is used to analyze the transport industry's carbon dioxide emissions in depth. The results of the research work deserve the attention of policy makers. First, the direct and indirect carbon dioxide emissions of road transport account for 53 % and 47 % of the transport industry. Second, the direct and indirect carbon dioxide emissions caused by consumption expenditure account for 55 % and 56 % of the final use structure respectively. Third, the carbon dioxide emissions produced by the five heavy industries when meeting the final use of the transport industry account for 75 % of all industries. Fourth, the adjustment of energy structure and energy intensity is expected to reduce the carbon dioxide emissions of the transport industry by 101,963 and 128,313kt in 2035 compared with the baseline scenario. The results indicate that, to control carbon dioxide emissions in the transport industry, special attention should be paid to road transport activity, consumption expenditure in the transport industry, the influence of other heavy industries, the adjustment of energy structure and energy intensity. Consequently, informatization of road transportation, development of public transportation, investment in high-tech industries, and aggressive development of clean energy become essential strategies.

1. Introduction

In recent years, climate change resulting from global warming has received considerable attention (Adedoyin et al., 2020). Carbon dioxide emission growth may cause global warming, accelerated glacier melting, frequent droughts and floods, changes in precipitation distribution, sea level rise, and other ecological environment changes, with the most severe impacts occurring in underdeveloped and climate-vulnerable fragile regions (Schleussner et al., 2015). In September 2020, at the UN General Assembly, President Xi Jinping announced that China aims to achieve carbon neutrality before 2060 in response to a series of problems, including carbon dioxide emissions and environmental pollution caused by fossil energy consumption (Han et al., 2021).

Controlling greenhouse gas emissions, which are primarily caused by carbon dioxide, is now required for countries to pursue green development. Due to its high carbon dioxide emissions, the transport industry is a priority area in the context of carbon dioxide emission reduction (Liu et al., 2015). According to the IPCC's fifth assessment report, transport is one of the industries with the highest energy consumption and the quickest increase in carbon dioxide emissions, and the combustion of fossil emissions, primarily oil, is the primary cause of this increase. Approximately 60 % of the world's oil consumption is currently utilized in the transport industry (Stocker et al., 2014). The sector's substantial contribution to carbon dioxide emissions has made it a subject of increasing research and interest. The prediction that the transport industry's GDP will grow by 25 % by 2030 will bolster efforts to reduce carbon dioxide emissions (Timilsina and Shrestha, 2009). As the world's largest carbon dioxide emitter, China's rapid growth in carbon dioxide emissions over the past four decades has garnered international attention (Guo et al., 2018).

Due to the characteristics of high fuel consumption and high emissions in the transport industry, as well as the rising trend of carbon dioxide emissions in China's transport industry, an increasing number of scholars have conducted in-depth analyses on carbon dioxide emissions in China's transport industry and emphasized the importance of resolving the carbon dioxide emissions problem in China's transport industry.

* Corresponding authors.
E-mail addresses: liumanzhi@cumt.edu.cn (M. Liu), TS21070363P21@cumt.edu.cn (J. Wang), TS20070074A31@cumt.edu.cn (J. Wen), gang.he@stonybrook.edu (G. He), TS21070365P21@cumt.edu.cn (J. Wu), TS21070353P21TY@cumt.edu.cn (H. Chen), TS21070070A31@cumt.edu.cn (X. Yang).

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Nomenclature

z_{di}	domestic demand self-sufficiency rate of sector I
z_{mi}	import demand rate of sector I
c_i^d	domestic aggregate demand
c_i^m	total import demand
X_i	the total domestic output
ex_i^d	domestic export volume
M_i	import volume
$C_{indirect}$	the indirect carbon dioxide emissions
$C_{kindirect}$	the indirect carbon dioxide emissions of k energy
E_i	carbon dioxide emission intensity of i sector
E_{ik}	carbon dioxide emission intensity of k energy in i sector
b_{ij}	the complete consumption coefficient matrix of elements in row i and column j
y_{mj}	the final use of transport activity j including consumption expenditure, capital formation and export
X	the total production of each production sector i
A	the matrix of the direct consumption coefficient
a_{ij}	the complete consumption coefficient matrix of elements in row i and column j
y	the final use
$(I-A)^{-1}$	the Leontief inverse matrix
I	the identity matrix
E	the matrix of carbon dioxide emission intensity
D	the Leontief inverse matrix
$x^{(j)}$	the output of sector j
$y^{(j)}$	the final demand of the production sector j
C_j	the carbon dioxide emissions of sector j
E_j	the carbon dioxide emission intensity of j sector
d_{ij}	the Leontief inverse matrix of elements in row i and column j
d_{jj}	the Leontief inverse matrix of elements in row j and column j
a_{ji}	the complete consumption coefficient matrix of elements in row i and column j
a_{jj}	the complete consumption coefficient matrix of elements in row i and column j
y_j	the final use of sector j

Currently, the LMDI model and STIRPAT model are predominantly used in carbon dioxide emissions research in China's transport industry. LMDI model is a classical factor decomposition model used to drive effect analysis. The model takes the logarithmic mean as the evaluation weight, compares and analyzes a variety of influencing factors by combining the two decomposition methods of addition and multiplication, and comprehensively decomposes the influence degree of each index from many aspects (Ang and Liu, 2001). STIRPAT model is a random regression impact model, which increases the elasticity coefficient on the basis of the environmental pressure control model, and is used to explore the impact of population, economy and technology on the environment (Dietz and Rosa, 1994). Liu et al. (2021c) developed decomposition and decoupling technology based on the LMDI method, studied the primary influencing factors of carbon emissions from China's transportation industry, analyzed the state of decoupling between carbon emissions and economic growth, and formulated energy efficiency policies accordingly. Liang et al. (2017) utilized LMDI decomposition analysis technology to examine the potential factors that contribute to the growth of carbon dioxide emissions in China's transport industry. The results indicated that economic development is the primary factor promoting the growth of carbon dioxide emissions in China's transport industry, while energy efficiency is the primary factor inhibiting this growth. Wu et al. (2022) investigated the driving factors of carbon dioxide emissions from China's transport industry using Kaya identity and LMDI analysis and discovered that regional structure increased carbon dioxide emissions from China's transport industry. Wang et al. (2011) employed the proposed LMDI method to determine the nature of the factors that influence the variation of carbon dioxide emissions in the transport industry. It is determined that road transport is the largest emitter of carbon dioxide emissions, and that the effects of per capita economic activity and transportation mode change were the primary factors contributing to the increase of carbon dioxide emissions in the transport industry during the study period. Liu et al. (2021a) utilized the extended STIRPAT model to analyze the influence of driving factors on carbon emission intensity, revealing that the carbon emission intensity of China's transport industry has regional characteristics and that the influence of urbanization, energy structure, population size, and industrial structure on carbon emission intensity varies by region. Zhang and Nian (2013) used the STIRPAT model and China's provincial panel data from 1995 to 2010 to examine the national and regional carbon dioxide emissions of the transport industry. The results demonstrated that passenger transport is the leading contributor to carbon dioxide emissions in the transport industry, although its impact varies by region. Using the STRIPATA model, Gao et al. (2014) calculated the carbon emissions of transportation energy consumption in Jilin Province from 1999 to 2011 and analyzed the carbon emissions' dynamic changes and Environmental Kuznets Curve.

In addition, the structure decomposition analysis (SDA) model and input-output analysis method are employed to investigate China's carbon dioxide emissions. Input-output analysis is primarily used to examine the relationship between inter-regional carbon dioxide emissions, whereas the SDA model is utilized to determine the primary drivers of carbon dioxide emissions in China. Li et al. (2019) developed a coupled SDA and sensitivity analysis method and discussed the general and sectoral driving factors of carbon dioxide emission intensity in China from two different vantage points. Wu et al. (2020) proposed a new method of spatial-temporal structure decomposition analysis (ST-SDA) to identify the driving factors and examined the spatial-temporal changes of carbon dioxide emissions in various provinces between 1997 and 2012. The results demonstrated that the carbon intensity effect is the only factor that counteracts the growth of carbon dioxide emissions, indicating that technological advancements are continually aiding in the reduction of carbon dioxide emissions. Based on the SDA method, Zhao et al. (2022) calculated the carbon content, final consumption structure, and energy structure of 28 sectors in China from 2002 to 2018, and discovered that “fixed capital formation and construction” and “domestic consumption of other services” are the two most significant contributors to carbon emissions. Zhang and Zhang (2018) analyzed the carbon dioxide emission relationship between China, the European Union, and the United States using the 2009 World Input-Output Table and the environmental accounts from the World Input-Output Database. Zhao et al. (2014) developed an environmental multi-regional input-output model and calculated China's international trade's carbon dioxide emissions from 1995 to 2009. Using the newly developed interregional input-output model, which distinguished the processing trade from other regional trades, Yan et al. (2020) recalculated the carbon dioxide emissions of China's exports at the regional and industrial levels.

In other studies, the SDA model and the input-output model have been combined. On the one hand, they conducted a discussion on the causes of China's carbon dioxide emissions, and on the other, they determined the relationship between regional carbon dioxide emissions. Du et al. (2011) analyzed the influencing factors of China's export of carbon dioxide emissions to the United States from 2002 to 2007 and found that the total export volume was the most influential factor in the increase of specific carbon dioxide emissions from 2002 to 2007, followed by the intermediate input structure. Pan et al. (2018) analyzed China's interregional carbon emissions and discovered that final demand has the most obvious positive effect on carbon emissions, but its structure is shifting. Zhao et al. (2016) calculated the carbon dioxide emissions in Sino-Japanese trade from 1995 to 2009 and elaborated the effects of scale effect, technology effect, and structure effect on those emissions.

However, a review of the aforementioned literature reveals that the input-output model is rarely used to analyze the carbon dioxide emissions of the transport industry. Thus, the current research on carbon dioxide emissions in the transport industry is primarily restricted to the industry's perspective, and it is difficult to conduct correlation analyses with other industries. In addition, the current analysis of carbon dioxide emissions in the transportation industry focuses primarily on the driving factors while ignoring its own structural analysis. Due to the aforementioned reasons, this paper further dissects final use based on the traditional input-output model, which allows us to analyze the contribution of various final use components to carbon dioxide emissions.

This paper is novel in the following ways: (1) in analyzing the carbon dioxide emissions of the transportation industry, we use the input-output model, which is rarely used in the transportation field at present; (2) the input-output table is transformed; and (3) the input-output subsystem model is novel. The significance of the innovations is as follows: theoretically, using the input-output model to examine the carbon dioxide emissions of the transport industry can fill in gaps in the existing literature in this field and provide a new idea and perspective for the subsequent research in this area. In addition, using the concept of structural decomposition, we combine the analysis of demand structures, transport industrial structures, and related industrial structures to develop a model of the transport industry's total carbon emissions, structure, and transmission relationship at the global and structural levels. Moreover, by converting the competitive input-output table into the non-competitive input-output table, the import portion of each industry can be distinguished from the domestic production portion, so that only the carbon dioxide emissions resulting from the domestic production portion of the transport industry will be calculated. The structural analysis of carbon dioxide emissions in the transport industry, such as the structure of transport activities, the structure of carbon dioxide emissions caused by energy consumption, and the structure of final use, can provide a more comprehensive understanding of carbon dioxide emissions in the transport industry. It is beneficial for the nation and industry to analyze the laws governing transport industry activities, energy consumption, carbon dioxide emissions, and transmission-related industries to gain insight into key carbon dioxide-emitting industries and activities and to inform the design of emission reduction policies.

The remainder of this paper is as follows. The second section presents methods and data, including the definitions of direct and indirect carbon dioxide emissions in the transport industry, the definition of the transport industry, the splitting method of the non-competitive input-output table, and the estimation method of indirect carbon dioxide emissions and input-output decomposition analysis (own internal one component, own internal two component, own internal three component, feed-back one component, feed-back two component, feed-back three component, spillover one component, spillover two component, spillover three component, and final use one component, final use two component and final use three component). The third section discusses the results, which include the direct and indirect carbon dioxide emissions of the transport industry in 2018 based on the non-competitive input-output table, the proportion of carbon dioxide emissions generated by energy consumption, structural decomposition, Sanki diagram, sensitivity analysis, and scenario prediction. The fourth section contains the conclusions and implications.

2. Methodology and Data

2.1. Definition

Referring to the definitions given in this article (Alcántara et al., 2017), direct carbon dioxide emissions refers to the carbon dioxide emissions directly related to the final demand of the transport industry, while indirect carbon dioxide emissions refers to the carbon dioxide emissions generated during the intermediate input process of the transport industry and the input and production process of other industries to meet the final demand of the transport industry. The required information can be found in the China Energy Statistics Yearbook (National Bureau of Statistics of China, 2020). In addition, the transport industry refers to the business activities of delivering goods or passengers to their destination and transferring their spatial location via means of transport. In general, it includes services for land transportation, water transportation, air transportation, and pipeline transportation. The transportation industry is typically grouped with the warehousing and postal industries in industrial classifications of national economic activities. Considering this classification criterion, this paper classifies the warehousing and postal industries as the transport industry. As stated previously, the transport industry analyzed in this paper is primarily divided into eight types of transport activities: railway transport, road transport, water transport, air transport, pipeline transport, multimodal transport and transport agents, loading, unloading, handling, and warehousing, and postal service.

Railway transport, road transport, water transport, air transport and pipeline transport refer to the transportation modes that use railway trains, automobiles, ships, planes, and pipelines to transport passengers, goods or materials. Multimodal transport refers to the composite transport of goods jointly completed by the connection and transshipment of two or more means of transport; transport agents refers to the activity of completing transportation tasks for customers according to the instructions of customers. Loading, unloading and handling refers to loading, unloading and handling activities and goods distribution activities, and also includes acquisition activities for the purpose of warehousing; warehousing refers to the storage and safekeeping of commodities and articles through the warehouse. Postal service refers to the postal services such as the distribution of letters, parcels, newspapers and periodicals provided by postal enterprises or enterprises entrusted by postal enterprises, as well as other postal services stipulated by the state.

It is also necessary to explain how some transport activities cause carbon dioxide emissions. For loading, unloading and handling, taking the operation in the logistics park as an example, many handling tools will be used. For example, the warehouse handling equipment includes forklift (diesel) and bridge crane (electricity); yard handling equipment includes gantry crane (electricity) and tire crane (diesel); workshop handling equipment including overhead crane (electricity); yard handling equipment includes tire crane (diesel); horizontal and external transportation equipment includes automobiles (diesel). Also, for postal service, some means of transportation will be used, such as truck (diesel), train (diesel) and plane (kerosene). The brackets indicate the main energy types required by the tools, and the energy consumption will cause corresponding carbon dioxide emissions.

2.2. Explanation of Splitting Method of the Non-competitive Input-output Table

Taking the split of final use as an example, final use consists of consumption expenditures, capital formation, and export, which are satisfied by domestic production and import. The self-sufficiency rate of domestic demand is the ratio of the final use of domestic production to the total final use of any demand. Let the domestic demand self-sufficiency rate of sector i be z_{di}. Accordingly, its import demand rate is z_{mi} . The ratio of c_i^d and c_i^m is equal to the ratio of the total domestic output X_i of the sector after deducting the domestic export volume ex_i^d to the import volume M_i . Eventually, we obtain the formula for calculating the final import demand rate and the domestic demand self-sufficiency rate.

$$\frac{c_i^d}{c_i^m} = \frac{X_i - ex_i^d}{M_i} \tag{1}$$

$$z_{mi} = \frac{M_i}{X_i - ex_i^d + M_i} \tag{2}$$

$$z_{di} = \frac{X_i - ex_i^d}{X_i - ex_i^d + M_i} \tag{3}$$

This paper divides intermediate use in the same manner. According to two articles (Liu et al., 2010; Yin and J, 2014), Customs Statistics does not provide the import and export of sub-sectors, and their proportion of the total import has been very small over the years, so they do not break down the export. At this point, intermediate use and final use have been separated, and the non-competitive input-output table for 2018 has been derived from the competitive input-output table for 2018. This will serve as the basis for our transport industry carbon dioxide emissions calculation.

2.3. Methods for Estimating Indirect Carbon Dioxide Emissions From Transport

According to the transformed non-competitive input-output table for 2018, we can calculate the total indirect carbon dioxide emissions of the transport industry as well as the indirect carbon dioxide emissions generated by various forms of energy consumption (coal, coke, gasoline, kerosene, diesel oil, fuel oil, natural gas) (National Bureau of Statistics of China, 2020). From the transformed 2018 non-competitive input-output table, a complete consumption coefficient matrix can be obtained, which can be used to reveal the direct and indirect relationships between sectors. The data on carbon dioxide emission intensity (emissions per unit of output) and final use can be used to calculate the associated carbon dioxide emissions. Refer to Appendices A, B, C, and D for information on the carbon dioxide emission intensity of 45 industries.

$$C_{indirect} = \sum_{i=1}^{45} \sum_{j=1}^{8} E_i b_{ij} \sum_m^{m=1,\,2,\,3} y_{mj} \tag{4}$$

$$C_{kindirect} = \sum_{i=1}^{45} \sum_{j=1}^{8} E_{ik} b_{ij} \sum_m^{m=1,\,2,\,3} y_{mj} \tag{5}$$

$$C_{total} = C_{indirect} + C_{direct} \tag{6}$$

$C_{indirect}$ is the total indirect carbon dioxide emissions of 45 sectors caused by eight transport activities, while $C_{kindirect}$ is the indirect carbon dioxide emissions of k energy of the 45 sectors caused by eight transport activities. E_i represents the carbon dioxide emission intensity of i sector, E_{ik} denotes the carbon dioxide emission intensity of k energy sources in i sector, b_{ij} refers to the complete consumption coefficient matrix of elements in row i and column j, entailing that when transport activity j produces one unit of final use including consumption expenditure, capital formation and export, sector i requires provide unit output value. y_{mj} is the final use of j transport activity including consumption expenditure, capital formation and export, where 1 represents consumption expenditure, 2 represents capital formation, and 3 represents export.

2.4. Decomposition of Carbon Dioxide Emission Structure Based on Input-output Method

The concept of input-output decomposition analysis improves and perfects the conventional input-output analysis used to determine the energy consumption behavior of a particular sector and its subsector, which is of great importance to the study of pollution emission and energy consumption of relevant sectors in their production processes (Alcántara and Padilla, 2009). A sector's carbon dioxide emissions can be divided into twelve parts using the input-output method: own internal one component, own internal two component, own internal three component, feed-back one component, feed-back two component, feed-back three component, spillover one component, spillover two component, spillover three component, final use one component, final use two component, and final use three component. The specific formula is shown below, and the method of derivation is described in detail in Appendix E.

$$\begin{aligned}
C_j = {} & \underbrace{E_j\left[(1-a_{jj})^{-1}-1\right]\sum_m^{m=1,2,3} y_{mj}}_{\text{own internal component}} \\
& + \underbrace{E_j(1-a_{jj})^{-1}\sum_{i\neq j} a_{ji} d_{ij} \sum_m^{m=1,2,3} y_{mj}}_{\text{feed - back component}} + \underbrace{\sum_{i\neq j} E_i d_{ij} \sum_m^{m=1,2,3} y_{mj}}_{\text{spillover component}} \\
& + \underbrace{E_j \sum_m^{m=1,2,3} y_{mj}}_{\text{final use component}} \\
= {} & \underbrace{E_j\left[(1-a_{jj})^{-1}-1\right] y_{1j}}_{\text{own internal one}} + \underbrace{E_j\left[(1-a_{jj})^{-1}-1\right] y_{2j}}_{\text{own internal two}} \\
& + \underbrace{E_j\left[(1-a_{jj})^{-1}-1\right] y_{3j}}_{\text{own internal three}} + \underbrace{E_j(1-a_{jj})^{-1}\sum_{i\neq j} a_{ji} d_{ij} y_{1j}}_{\text{feed - back one}} \\
& + \underbrace{E_j(1-a_{jj})^{-1}\sum_{i\neq j} a_{ji} d_{ij} y_{2j}}_{\text{feed - back two}} + \underbrace{E_j(1-a_{jj})^{-1}\sum_{i\neq j} a_{ji} d_{ij} y_{3j}}_{\text{feed - back three}} \\
& + \underbrace{\sum_{i\neq j} E_i d_{ij} y_{1j}}_{\text{spillover one}} + \underbrace{\sum_{i\neq j} E_i d_{ij} y_{2j}}_{\text{spillover two}} + \underbrace{\sum_{i\neq j} E_i d_{ij} y_{3j}}_{\text{spillover three}} + \underbrace{E_j y_{1j}}_{\text{final use one}} \\
& + \underbrace{E_j y_{2j}}_{\text{final use two}} + \underbrace{E_j y_{3j}}_{\text{final use three}}
\end{aligned} \tag{7}$$

C_j represents the carbon dioxide emissions of the sector j, and 1, 2, 3 denote consumption expenditure, capital formation, and export in final use, respectively. Own internal component indicates the internal need of industry j for its own production to obtain its final demand. Feed-back component represents the output from industry j required to produce inputs that it demands from the other industries. It is the own production of industry j induced through the requirement of inputs from the other industries. Spillover component denotes the emission generated by the rest of the sectors in producing the inputs sold to sector j. Final use component presents that the emissions directly related with the magnitude of the final use (Alcántara et al., 2017).

This method is currently applied primarily to the study of pollutant emissions, and the proposed decomposition provides a useful tool for analyzing the production structure of each sector based on its relationship with other economic sectors. The relative correlation of different components reveals the relationship between different economic sectors and the optimal solution to the emission problem in each case (Alcántara et al., 2017). This decomposition method provides two dimensions for analyzing the carbon dioxide emissions of China's transport industry: the first is to consider the impact of the transport industry or other industries, and the second is to clarify the contribution of the three final parts to the carbon dioxide emissions. By combining these two dimensions, it is possible to analyze and compare which of the twelve components constitutes a significant proportion. Based on the preceding comparison, the two dimensions can be considered comprehensively when formulating specific policies to make the policies more targeted.

2.5. Data and Sources

Transport activities' direct and indirect carbon dioxide emissions can be calculated using China's Input-Output Table (National Bureau of Statistics of China, 2020b). In 2018, the direct consumption coefficient, total consumption coefficient, and final use are derived from the non-competitive input-output table that has been converted. The China Energy Statistics Yearbook provides the energy consumption of various energy types by industry (National Bureau of Statistics of China, 2020a). Through a series of mergers and modifications, we can obtain the final data required for 45 industries. The required carbon dioxide emission coefficient is obtained from the website (Carbon Emissions Trading Network, 2014), and the specific data and calculation method can be found in Appendix F.

3. Results and Discussion

3.1. Analysis of Direct and Indirect Carbon Dioxide Emissions and Carbon Dioxide Emission Structure of the Transport Industry in 2018

There are differences between the direct carbon dioxide emissions calculated using the input-output method and those calculated using energy data published by the State Statistical Bureau. The specific differences in the data are depicted in Fig. 1. We divide them into two categories: carbon dioxide emissions caused by the total output of the transport industry and carbon dioxide emissions caused by the transport industry to meet its own final use. Thus, the results derived from our data differ from those derived from official data.

Fig. 2 depicts the direct and indirect carbon dioxide emissions of China's transport industry in 2018. In 2018, the direct and indirect carbon dioxide emissions reached 197,314 and 217,950 kt CO_2, respectively, representing 2 % of the total domestic carbon dioxide emissions. The final total of carbon dioxide emissions consists of rural consumption, urban consumption, government consumption, capital formation, and export, but excludes the portion attributable to imported goods and services. In 2018, the proportions of direct and indirect carbon dioxide emissions for consumption expenditure (including rural consumption, urban consumption, and government consumption), capital formation, and export are 55 %, 15 %, and 30 % for direct carbon dioxide emissions, and 56 %, 14 %, and 31 % for indirect carbon dioxide emissions, respectively. It is evident that most of the direct and indirect carbon dioxide emissions produced by the transport industry in 2018 are the result of consumption expenditures, while the proportion of capital formation is relatively small. This is because investment in consumption expenditure represents the largest proportion of these three components.

As depicted in Fig. 3, a comparison of specific values reveals that, among the direct carbon dioxide emissions of China's transport industry in 2018, the direct carbon dioxide emissions from road transport are the highest, accounting for 53 % of the total direct carbon dioxide emissions. Then came multimodal transport and transport agents, which caused a direct emission of 29,288 kt CO_2 of carbon dioxide. However, the direct carbon dioxide emissions from road transport are four times higher than those from multimodal transport and transport agents. Consequently, controlling the final use of road transport can reduce

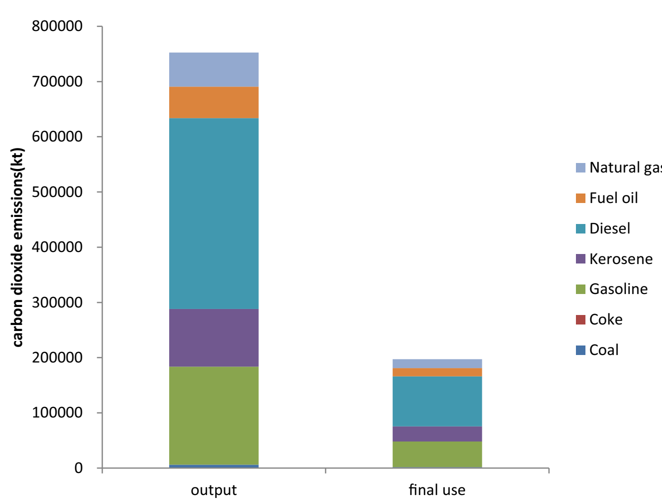


Fig. 1. Comparison of differences in direct carbon dioxide emissions.

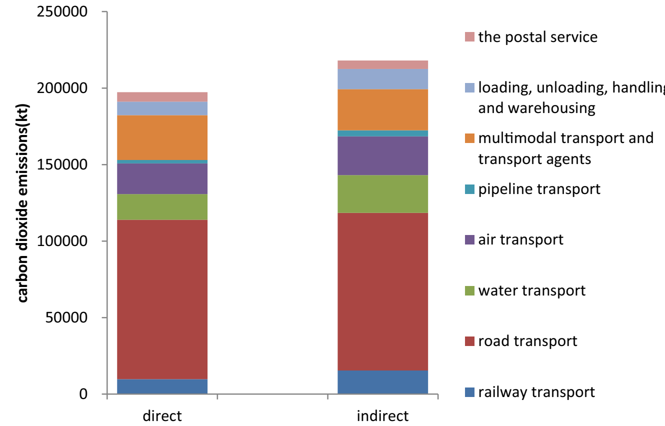


Fig. 2. Direct and indirect carbon dioxide emissions in China's transport industry in 2018.

the direct carbon dioxide emissions of the transport industry. Moreover, pipeline transportation resulted in the lowest direct carbon dioxide emissions, at just 2175 kt CO_2, primarily because its final use is less. As for indirect carbon dioxide emissions, those caused by road transport are the highest, with a total of 103,018 kt CO_2. The indirect carbon dioxide emissions from water transport, air transport, multimodal transport, and transport agents are equivalent at 24,651, 25,389, and 26,929 kt CO_2. At 3978 kt and 5424 kt CO_2 respectively, the indirect carbon dioxide emissions caused by pipeline transport and the postal service are relatively low. People's inclination to choose road transport as their primary mode of transport is understandable. Since the road transport network can cover the greatest transport, its carbon dioxide emissions are the greatest.

According to the final use classification, the direct and indirect carbon dioxide emissions of eight transport activities under consumption expenditure, capital formation, and export are calculated, allowing for a comparison of the differences between the direct and indirect carbon dioxide emissions of eight transport activities under various uses. The outcomes are depicted in Figs. 4(a), 4(b), and 4 (c). With 72,096 and 74,629 kt CO_2, the direct and indirect carbon dioxide emissions caused by road transportation are the highest in terms of consumption expenditure. The least amount of CO_2 is produced by pipeline transport, which produces between 1123 and 2054 kt. Similarly, in terms of capital formation, the direct and indirect carbon dioxide

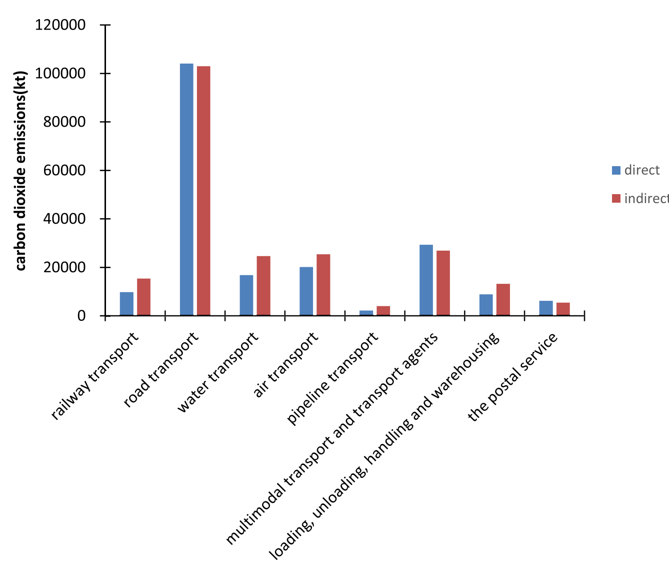
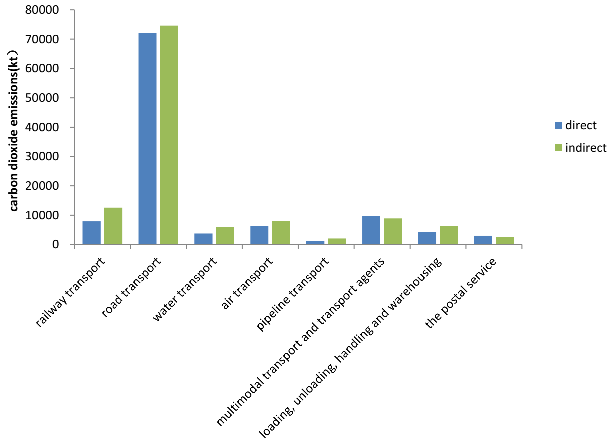
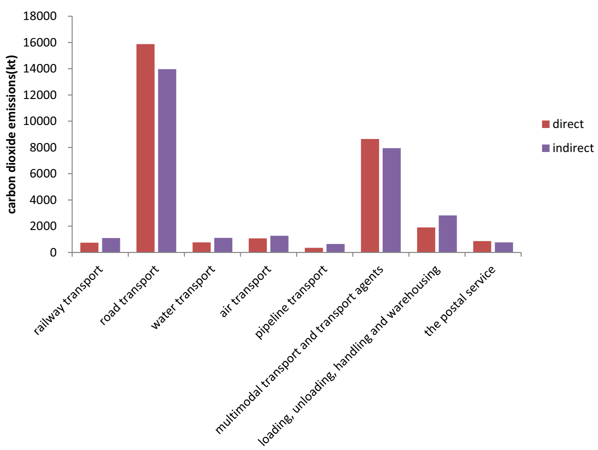


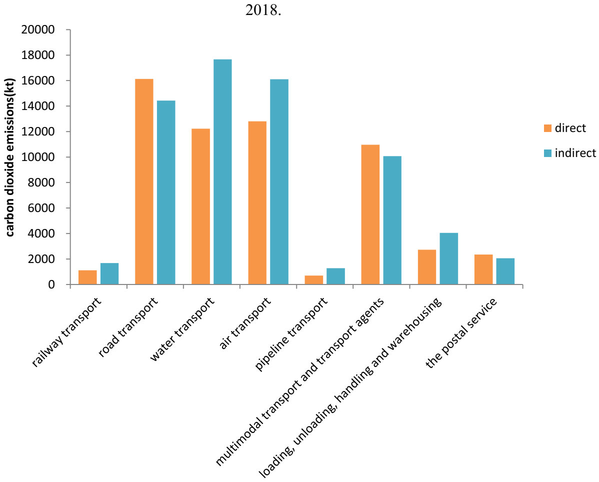
Fig. 3. Specific comparison of direct and indirect carbon dioxide emissions in China's transport industry in 2018.



(a) Direct and indirect carbon dioxide emissions from consumption expenditure in 2018.



(b) Direct and indirect carbon dioxide emissions from capital formation in 2018.



(c) Direct and indirect carbon dioxide emissions from export in 2018.

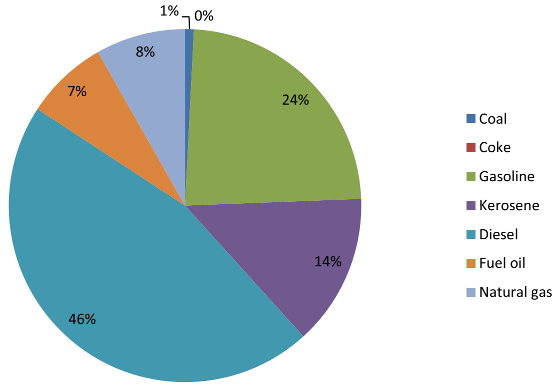
Fig. 4. (a) Direct and indirect carbon dioxide emissions from consumption expenditure in 2018.
(b) Direct and indirect carbon dioxide emissions from capital formation in 2018.
(c) Direct and indirect carbon dioxide emissions from export in 2018.

emissions attributable to road transport remain elevated, reaching 15,881 and 13,963 kt CO_2 respectively. At 352 and 645 kt CO_2, the carbon dioxide emissions caused by pipeline transport are still the lowest. This resembles the structure of total direct and indirect carbon dioxide emissions, suggesting that if consumption expenditure and capital formation are altered, the structure of total direct and indirect carbon dioxide emissions can be altered in a more consistent manner. In terms of capital formation, however, the direct and indirect carbon dioxide emissions caused by multimodal transport and transport agents are more significant than those caused by the remaining six transport activities, which is also an important consideration. On the export side, road transport remains the leading source of direct carbon dioxide emissions. Nonetheless, indirect carbon dioxide emissions have changed somewhat. The indirect carbon dioxide emissions caused by water transport and air transport rank first and second, with 17,666 and 16,110 kt CO_2 respectively, surpassing road transport's 14,425 kt CO_2. This pertains to the application's transport mode activities. At the level of export, water and air transport are utilized more frequently, resulting in relatively high indirect carbon dioxide emissions.

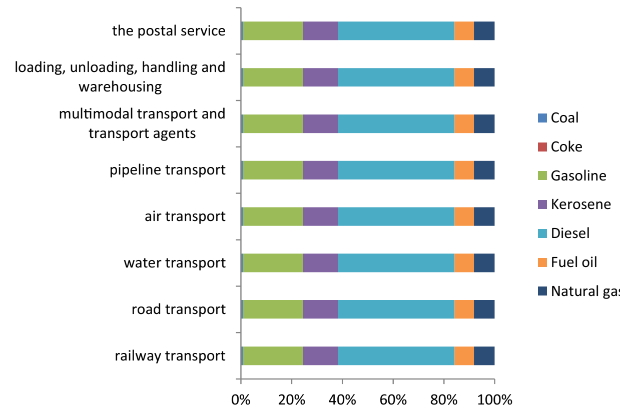
To compare energy types in 2018, we have also calculated the direct and indirect carbon dioxide emissions of various energy sources. We use the product of the carbon dioxide emission intensity of various energy sources and final use in the calculation of direct carbon dioxide emissions from different energy consumption. When applied to various transport activities, it is sufficient to replace the final use with the final use of each transport activity. In addition, we use the formula (5) to calculate the indirect carbon dioxide emissions from various energy consumptions. For the calculation of indirect carbon dioxide emissions from various transport activities, it is sufficient to replace the final use in formula (5) with the final use for each transport activity. Figs. 5(a), 5(b), 5(c), and 5(d) present the results. They demonstrate that direct carbon dioxide emissions from diesel oil consumption account for 46 % of total carbon dioxide emissions from total energy consumption (coal, coke, gasoline, kerosene, diesel oil, fuel oil, natural gas). Around 24 % of the total is the direct carbon dioxide emissions caused by gasoline consumption. These proportional structures are also evident in various modes of transport. Certainly, we should focus more on the structure of indirect carbon dioxide emissions. The indirect carbon dioxide emissions caused by the consumption of coal are relatively high, accounting for 73 % of the indirect carbon dioxide emissions caused by the consumption of all forms of energy (coal, coke, gasoline, kerosene, diesel oil, fuel oil, natural gas). The indirect carbon dioxide emissions caused by coal consumption account for 85 % and 89 %, respectively, of the indirect carbon dioxide emissions caused by total energy consumption in transport and pipeline transport. This pertains to the structure of China's energy consumption. Coal has always been China's primary energy source and an important industrial raw material, which has strongly supported the growth of the national economy, ensured its security, and made significant contributions to the nation's economic development. However, the transport industry does not directly consume coal, resulting in the highest indirect carbon dioxide emissions. Diesel oil has always been the primary raw material for vehicles and ships, resulting in the highest direct carbon dioxide emissions. To reduce direct and indirect carbon dioxide emissions to a certain extent, it is necessary to focus on controlling and reducing the use of diesel oil and coal, and if possible, to seek out reasonable clean energy alternatives. The optimal solution should combine energy types and transport modes, which may be more conducive to energy conservation and emission reduction.

3.2. Twelve-parts Structural Decomposition Analysis

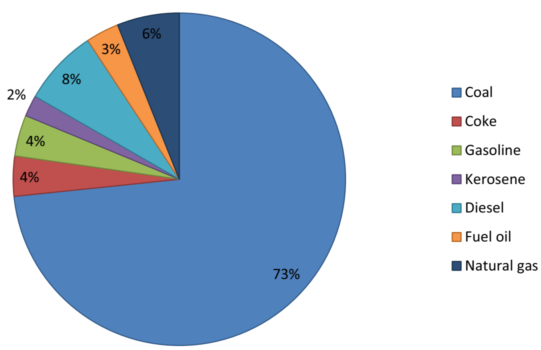
From Fig. 6 and Appendix G, it can be deduced that a significant proportion of carbon dioxide emissions result from spillover one component, which means that the majority of carbon dioxide emissions from energy consumption are generated by other sectors in order to meet the consumption expenditures of transport. The proportion of final use in one component is also substantial, indicating that the direct carbon dioxide emissions produced by the transport industry to satisfy its own demand for consumption expenditures are not insignificant. The spillover one and final use one components of railway transport account for 50 % and 32 %, respectively; the spillover one and final use one



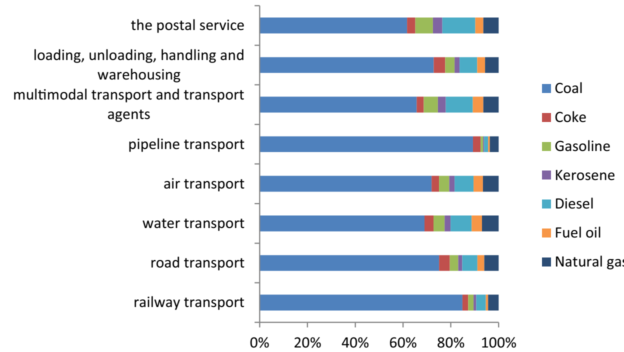
(a) Direct carbon dioxide emissions of different energy types in 2018.



(b) Direct carbon dioxide emissions of different energy types in 2018.



(c) Indirect carbon dioxide emissions of different energy types in 2018.



(d) Indirect carbon dioxide emissions of different energy types in 2018.

Fig. 5. (a) Direct carbon dioxide emissions of different energy types in 2018.
(b) Direct carbon dioxide emissions of different energy types in 2018.
(c) Indirect carbon dioxide emissions of different energy types in 2018.
(d) Indirect carbon dioxide emissions of different energy types in 2018.

components of road transport account for 34 % and 35 %, respectively. The remainder is not listed individually. The subsequent step is the separation of the three final-use components. The outcomes are displayed in Appendix H. However, for various transport activities, the proportion of the four components to the total of 12 components varies. Nonetheless, it is evident that the spillover and final use components account for much of the proportion.

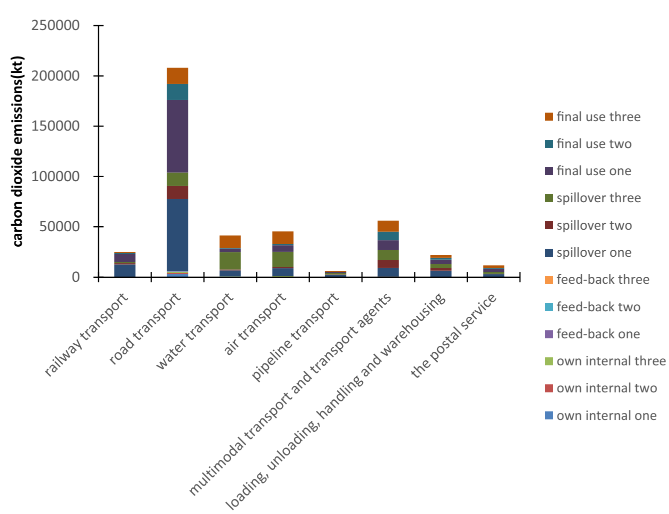


Fig. 6. The decomposed twelve parts of the total carbon dioxide emissions in 2018.

In addition, for the twelve-part decomposition analysis, we have chosen coal with the highest proportion of indirect emissions and diesel oil with the highest proportion of direct emissions. According to the carbon dioxide emissions from coal consumption shown in Fig. 7 and Appendix I, the twelve components of the eight activities in 2018 are extremely close, particularly the spillover one, spillover two, and spillover three components. The total proportion of these three components in the eight activities is close to 100 %, indicating that special attention should be paid to an input from other sectors when utilizing coal energy. Compared to other transport activities, the road transport spillover one component remains the largest at 56,556 kt CO_2. Fig. 8 and Appendix J clearly illustrate diesel oil's decomposition. Final use one component and final use three component account for much of the total amount, which is typically much larger than the remaining ten components. This is consistent with reality. Since final use one component and final use three component can be viewed as direct carbon dioxide emissions from energy consumption, and because diesel oil has the highest proportion of direct carbon dioxide emissions among all energy types, its final use one component and final use three component will account for a relatively larger proportion than those of other components. Compared to other modes of transport, road transport still merits consideration, as the total amount of these two components is still greater than that of other modes of transport.

This method of decomposition highlights the significance of decomposing direct and indirect carbon dioxide emissions for developing the most effective mitigation policies. This demonstrates that when analyzing carbon dioxide emissions in the transportation industry, we must not only consider the industry itself, but also the influence of other industries. Clearly, we should develop precise and specific

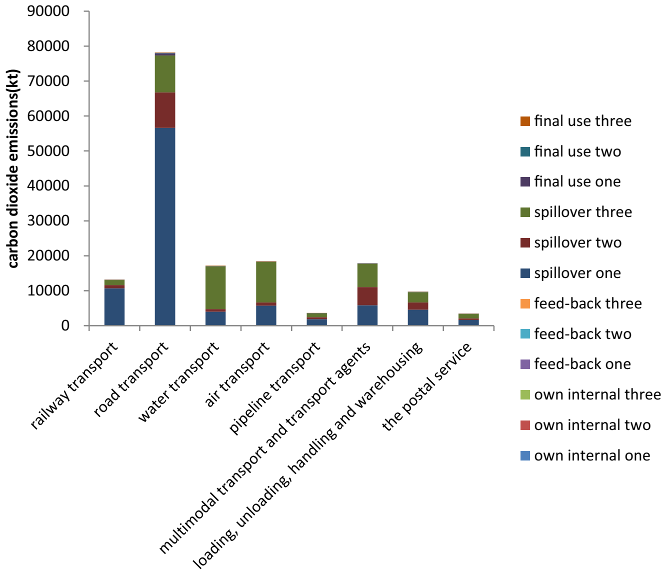


Fig. 7. The decomposed twelve parts of the carbon dioxide emissions from coal consumption in 2018.

measures. For instance, the final use of one component, the final use of two components, and the final use of three components can represent direct impacts that may necessitate macro-control and technological innovation, whereas the remaining nine components must reduce the consumption and inputs of other sectors.

3.3. Industry Association Analysis

To illustrate the relationship between indirect carbon dioxide emissions in transport and other industries, we have created two Sanki diagrams, which depict the flow of indirect carbon dioxide emissions from other industries into transport. In addition to the total indirect carbon dioxide emissions, we selected coal, which accounted for the largest share of indirect carbon dioxide emissions and drew a second Sanki diagram.

As shown in Fig. 9, the five industries most impacted by indirect carbon dioxide emissions from transport should be on the left, while the eight corresponding transport activities should be on the right. In addition, we merged and renamed the remaining industries. The thickness of the line indicating the flow of carbon dioxide emissions from an

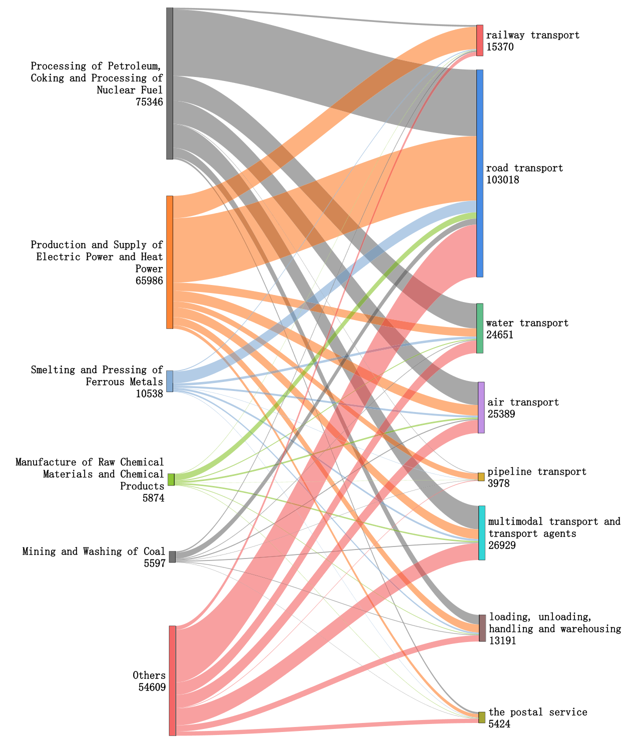


Fig. 9. Carbon dioxide emissions flow from industrial sectors to transport activities in 2018 (unit: kt CO_2).

industry to a transport activity corresponds to the amount of carbon dioxide emissions. To meet the final demand for transport, we ordinarily rank the sectors on the left by the carbon dioxide emissions produced by the industry. After calculation, the indirect carbon dioxide emissions generated by five industries account for 75 % of the indirect carbon

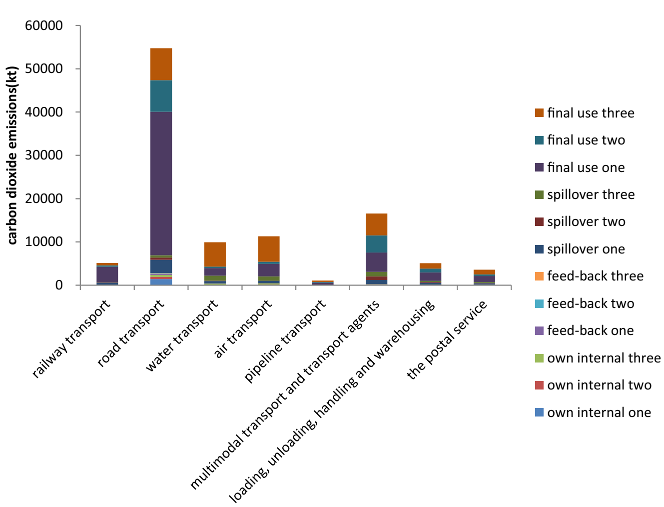


Fig. 8. The decomposed twelve parts of the carbon dioxide emissions from diesel oil consumption in 2018.

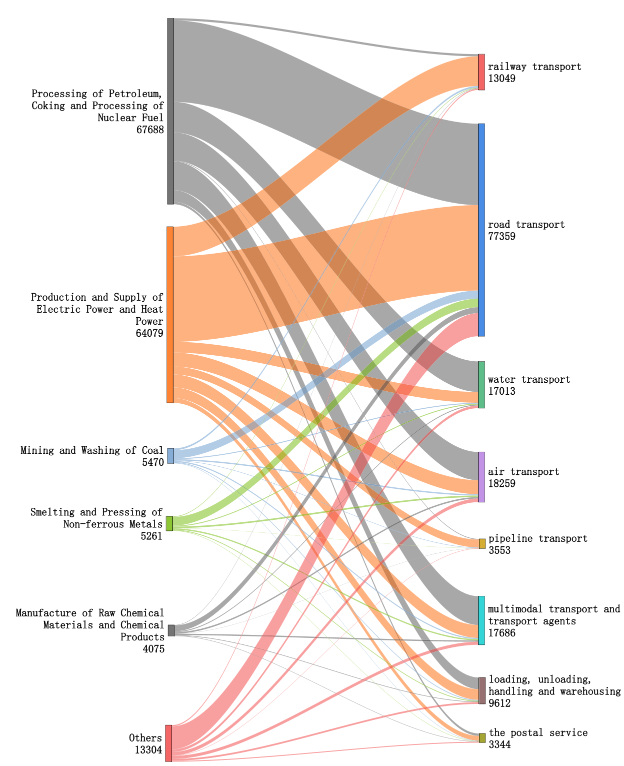


Fig. 10. The coal carbon dioxide emissions flow from industrial sectors to transport activities in 2018 (unit: kt CO_2).

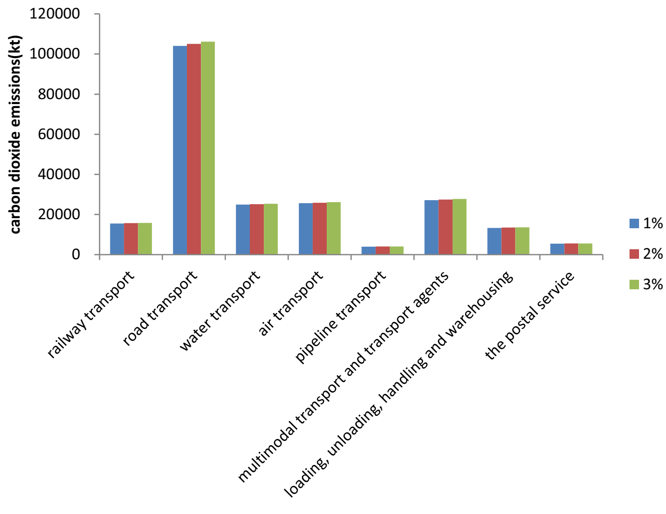


Fig. 11. Increasing change of 1 %–2 %–3 % in final use in 2018.

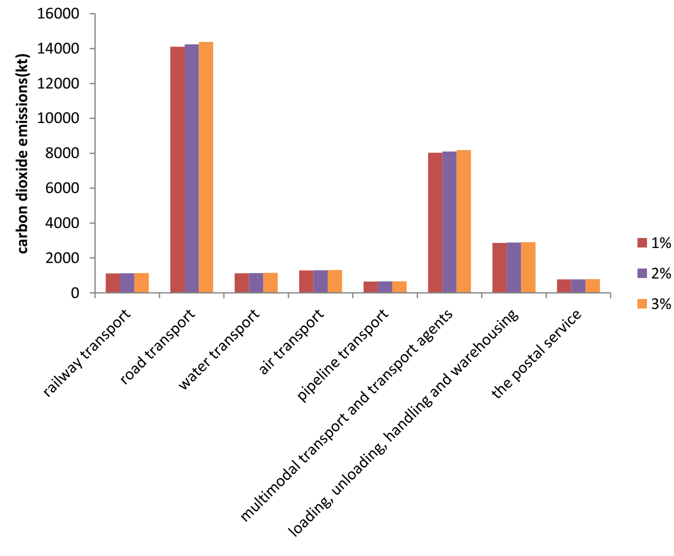


Fig. 13. Increasing change of 1 %–2 %–3 % in capital formation in 2018.

dioxide emissions generated by 45 industries as a whole; thus, the selected five industries are somewhat representative. Processing of Petroleum, Coking and Processing of Nuclear Fuel industry ranks first. The rest of the representative industries are Production and Supply of Electric Power and Heat Power, Smelting and Pressing of Ferrous Metals, Manufacture of Raw Chemical Materials and Chemical Products, and Mining and Washing of Coal.

Fig. 10 depicts the flow of indirect carbon dioxide emissions resulting from the consumption of coal energy by specific industries and transport activities. In terms of carbon dioxide emissions from coal consumption in 2018, the industry most affected by the transport sector is still Processing of Petroleum, Coking and Processing of Nuclear Fuel industry. The distinction is that the ranking of Mining and Washing of Coal has increased. Meanwhile, the remaining industries are Production and Supply of Electric Power and Heat Power, Smelting and Pressing of Nonferrous Metals, and Manufacture of Raw Chemical Materials and Chemical Products. In conclusion, based on the indirect relationship between industries and carbon dioxide emissions, the energy-saving and emission-reduction effects of the transport industry can be achieved by adjusting the demand pattern of the transport industry. The correlation analysis presented previously provides us with a way of thinking. When regulating carbon dioxide emissions in the transport industry, we must pay particular attention to the impact of heavy industry. Controlling the transport industry's carbon dioxide emissions through industry transformation.

3.4. Sensitivity Analysis

To comprehend the effect of related changes in various transport activities on energy conservation and emission reduction, we analyzed sensitivity using an input-output table and considered all related behaviors. We have assumed that by increasing final use by 1 %, 2 %, and 3 %, indirect carbon dioxide emissions will increase to quantify the emission reduction potential of various transport activities, thereby assisting the government in implementing more targeted special control policies. The following explains why this ratio was chosen: On the one hand, we calculated the average annual growth rate of the value-added index for the transport, warehousing, and postal industries from 1998 to 2021. The exact percentage is 0.813 %. To avoid setting the ratio too large or too small, we believe that it is reasonable to base the increasing ratio on 1 %. On the other hand, existing studies assume that the energy-saving potential of various consumption patterns can be quantified by reducing consumer spending on goods or services by 1–4 % (Liu et al., 2021b), and the activities of the transport industry are also dependent on consumption expenditure, which has statistical significance. The results of the sensitivity analysis are shown below.

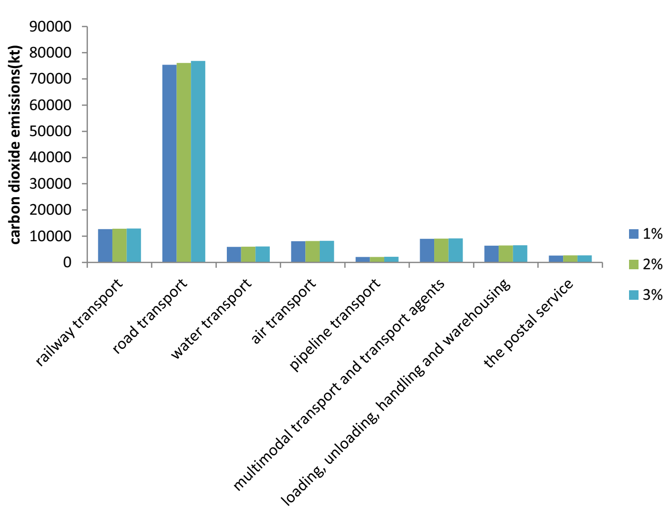


Fig. 12. Increasing change of 1 %–2 %–3 % in consumption expenditure in 2018.

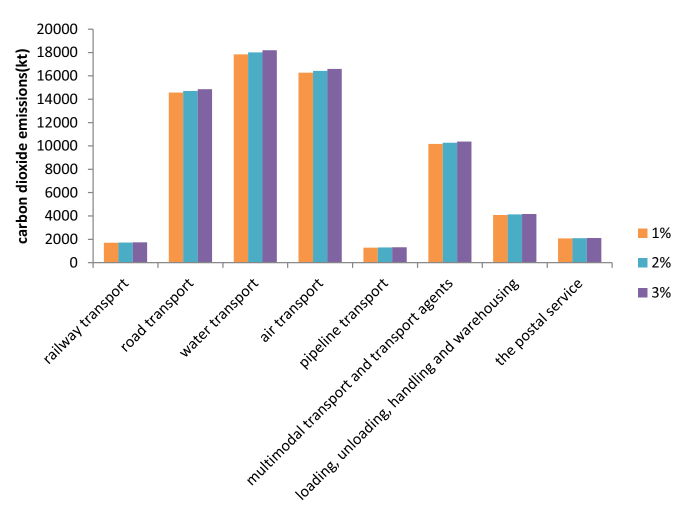


Fig. 14. Increasing change of 1 %–2 %–3 % in export in 2018.

Table 1
Scenario settings of transport industry before 2035.

Scenario	Final demand change (y_j)	Energy structure and intensity adjustment (E_k)
Baseline scenario (BL scenario)	Average annual growth rate before 2025 Railway passenger transport:4.3 % Railway freight transport and transport support activities:2.3 % Urban public transport and road passenger transport:4.3 % Road cargo transport and transport support activities:2.3 % Passenger transport by sea:4.3 % Water cargo transport and transport support activities:2.3 % Air passenger transport:4.3 % Air cargo transport and transport support activities:2.3 % Pipeline transport:5.5 % Multimodal transport and transport agents:2.3 % Loading, unloading, handling and warehousing:2.3 % The postal service: 7.1 % Average annual growth rate between 2025 and 2030 Railway passenger transport:3.2 % Railway freight transport and transport support activities:2 % Urban public transport and road passenger transport:3.2 % Road cargo transport and transport support activities:2 % Passenger transport by sea:3.2 % Water cargo transport and transport support activities:2 % Air passenger transport:3.2 % Air cargo transport and transport support activities:2 % Pipeline transport:4.7 % Multimodal transport and transport agents:2 % Loading, unloading, handling and warehousing:2 % The postal service: 6.3 % Average annual growth rate between 2030 and 2035 Railway passenger transport:2.1 % Railway freight transport and transport support activities:1.7 % Urban public transport and road passenger transport:2.1 % Road cargo transport and transport support activities:1.7 % Passenger transport by sea:2.1 % Water cargo transport and transport support activities:1.7 % Air passenger transport:2.1 % Air cargo transport and transport support activities:1.7 % Pipeline transport:3.9 % Multimodal transport and transport agents:1.7 % Loading, unloading, handling and warehousing:1.7 % The postal service: 5.5 %	Same as 2018
Structural optimization scenario (SO scenario)	Same as the BL scenario	The proportion of non- fossil energy in primary energy consumption will reach about 22 %, 25 % and 40 % in 2025, 2030 and 2035 respectively
Technological progress scenario (TP scenario)	Same as the BL scenario	In 2025, 2030 and 2035, the energy consumption per unit of GDP will decrease by 13.5 %, 30 % and 30.88 % compared with that in 2020

Fig. 11 demonstrates that when the final use increases by 1 %, 2 %, and 3 %, respectively, the indirect carbon dioxide emissions caused by road transport change substantially. Figs. 12 and 13 illustrate how indirect carbon dioxide emissions from eight transportation activities change when final consumption expenditures and capital formation increase by 1 %, 2 %, and 3 %, respectively. The trends depicted in Figs. 12, 13, and 11 are relatively consistent, and the indirect carbon dioxide emissions caused by road transport have changed relatively dramatically compared to those caused by other modes of transport. For instance, when consumption expenditures increase by 1 %, indirect carbon dioxide emissions from road transport rise by 144 kt CO_2, indicating that reducing the final use of road transport will have a significant impact on reducing indirect carbon dioxide emissions from transport. Fig. 14 illustrates the changes in indirect carbon dioxide emissions resulting from eight transport activities when the export in final use increases by 1 %, 2 %, and 3 %. Road transport, water transport, air transport, multimodal transport, and transport agents have all changed, so the change in export structure will influence the reduction of indirect carbon dioxide emissions from various transport activities. This demonstrates that the regulation of certain major transport activities, such as road transport, can have a significant effect on energy conservation and emission reduction. The final use structure must be considered. Depending on the structure, various transport activities can be regulated to achieve superior results.

In addition, we must monitor and pay special attention to the changes of nine components (own internal one component, own internal two component, own internal three component, feed-back one component, feed-back two component, feed-back three component, spillover one component, spillover two component, spillover three component), which comprise the indirect carbon dioxide emissions of the transport industry. It is estimated that the spillover one, spillover two, and spillover three components change the most, indicating that the input from other sectors has the greatest indirect impact among the nine components. To determine the precise changes in total indirect carbon dioxide emissions, we can use 1 % as the quantitative index and increase each of the nine components of each activity by 1 %. The results indicated that CO_2 emissions increased by 40, 15, 28, 7, 2, 3, 1170, 281, and 645 kt for each of the nine components. This demonstrates that a 1 % reduction in final use can reduce a substantial amount of indirect carbon dioxide emissions, and that the small actions of everyone in China can lead to a reduction in final use that is significantly greater than 1 %. Consequently, everyone can be encouraged to prepare for energy conservation and emission reduction.

3.5. Scenario Prediction

To analyze the indirect carbon dioxide emissions of the transport industry in 2030 based on the various influencing factors of the transport industry, three different scenarios were developed to predict the varying degrees of impact of the changes of various factors of the transport industry on the future indirect carbon dioxide emissions. Table 1 displays the scenario settings.

On February 24, 2021, the Central Committee of the Communist Party of China and the State Council released the Outline of National Comprehensive Three-Dimensional Transportation Network Planning, which outlined the construction objective and realization path for China's integrated three-dimensional transport network over the next 15 years. From 2021 to 2035, the average annual growth rate of passenger trips (including car trips) is projected to be approximately 3.2 %. The annual growth rate of freight volume in the entire society is approximately 2 %, and the annual growth rate of the postal express business is approximately 6.5 % (China's State Council, 2021a). Here, we have assumed that the average annual growth rate of all activities during 2018–2020 is the same as previously stated, which serves as the foundation for establishing the baseline scenario. In addition, because there is almost no literature or data available to predict pipeline transport at this time, we have calculated the average annual growth rate of the total pipeline transport from 2010 to 2018 (National Bureau of Statistics of China, 2020c), which will serve as the basis for future predictions.

General Secretary Xi Jinping delivered an important speech at the Climate Ambition Summit on December 12, 2020, announcing that China's carbon dioxide emissions per unit of GDP will decrease by more than 65 % compared to 2005 by 2030, and that non-fossil energy will account for 25 % of primary energy consumption (The Xinhua News Agency, 2020). In addition, Shan Baoguo, deputy chief economist of the State Grid Energy Research Institute, stated that based on preliminary estimates, China's energy consumption per unit GDP is anticipated to decrease by 30 % in 2030, compared to that of 2020, due to the continuous advancement of technological energy saving, structural energy saving, and management energy saving (The Xinhua News Agency, 2021). The State Council's action plan for reaching the carbon dioxide peak before 2030 proposes that the proportion of non-fossil energy consumption will reach approximately 20 % by 2025, and energy consumption per unit of GDP will be 13.5 % lower than in 2020. By 2030, non-fossil energy consumption will account for approximately 25 % (China's State Council, 2021b). According to China Power Grid's (2020) analysis on the development law of energy consumption per unit GDP from a global perspective and the study and judgment of five southern provinces and regions, China's energy consumption per unit GDP is expected to decrease by approximately 40 % by 2035, compared to China's level in 2015. Combining the above-mentioned national policies and significant projections, after a series of adjustment calculations, the basis for the respective scenario setting is obtained, as shown in Table 1.

Fig. 15 depicts the scenario prediction's outcomes. The scenario analysis reveals that, under the baseline scenario, the ever-increasing demand in the future has become an impediment to the energy conservation and emission reduction processes in the transport industry. Indirect carbon dioxide emissions in 2035 will be 122,060 kt CO_2 higher than in 2018. In Fig. 15, the indirect carbon dioxide emissions under the SO and TP scenarios are less than those under the BL scenario, which reflects in part that the national policy is risky, but also demonstrates our nation's resolve to improve the climate and environment. This is the objective for which we must continually overcome obstacles and strive. Under the SO scenario, the transportation industry is expected to reach its carbon dioxide peak in 2030, whereas under the TP scenario, the carbon dioxide peak will occur in 2025, which is consistent with the national goal. Certain policy interventions can play an important role in reducing carbon dioxide emissions from the transport sector. If the transport industry is left unchecked, the industry's low-carbon goal will be extremely difficult to achieve. Moreover, as evidenced by the ER and BR scenarios, the accelerated decline of energy intensity and the modification of energy structure contribute to the reduction of indirect carbon dioxide emissions.

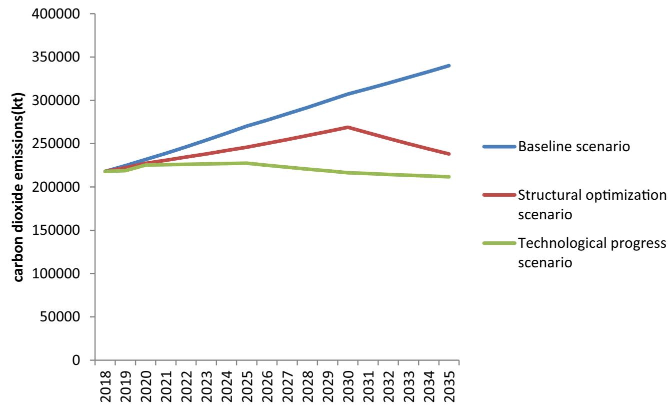


Fig. 15. Annual change of indirect carbon dioxide emissions caused by transport activities under three scenarios.

3.6. Discussion

In the previous section, this paper combines input-output and structural decomposition, divides carbon dioxide emissions from energy consumption in transport activities into twelve parts, and builds a transmission network from transport activities to carbon dioxide emissions based on the input-output table data for 2018. Currently, a number of studies have utilized the input-output subsystem method to examine the structure decomposition of pollutants, demonstrating the viability of this technique (Alcántara and Padilla, 2009). Existing research uses the input-output subsystem method to divide each sector into four parts, three of which represent the emissions generated in the sector's production process (scale, own internal, and feed-back components), and one of which represents the emissions generated by activities induced in other economic fields (spillover component). The results demonstrated that, based on the magnitude of the spillover component, more than half of the nitrogen oxide emissions in the economy are caused by different sectors that influence the rest of the economy when intermediate inputs are required. Architecture is the primary source of pollution in total emissions because it produces pollution from other industries (Alcántara et al., 2017). Through the decomposition effect, Butnar and Llop (2011) demonstrated that between 2000 and 2005, technological changes led to a decrease in carbon dioxide emissions, while an increase in demand for final services led to an increase in emissions. Another study used the structural decomposition analysis method based on the input-output subsystem model to investigate the source of China's power industry's emission increase between 2007 and 2015. The results demonstrated that consumption is the primary driver of the increase in carbon dioxide emissions. Additionally, cleaner energy can reduce carbon dioxide emissions (Ma et al., 2019).

Scholars have also made relevant research on the calculation of carbon dioxide emissions from China's transport industry in 2018. According to the energy consumption data of the transport industry, Le and Haiyan (2021) used the top-down method to calculate that the carbon dioxide emissions of China's transport industry in 2018 will reach 695,110 kt. The carbon dioxide emission of China's transport industry increased from 306,850 kt in 2004 to 859,640 kt in 2018, an increase of 1.8 times (Xia et al., 2022). Based on the LMDI method, Liu et al. (2021c) studied the carbon dioxide emissions of China's transport industry from 2001 to 2018, and the calculation result in 2018 is 884,660 kt. The carbon dioxide emissions of the transport industry calculated in the existing research is based on the perspective of the total output of the industry. From this perspective, our calculation result is 752,609 kt, which is between 695,110 kt and 884,660 kt obtained by previous studies. It can be seen that our results are reasonable to a certain extent if we follow the previous research model. However, we focused on the final demand of the transport industry. Our calculation result is 415,264 kt, which is the carbon dioxide emissions generated by the transport industry itself and other industries to meet the final demand of the transport industry.

In our study, road transport had the highest carbon dioxide emissions of all modes of transport, a finding that is consistent with previous research. Liu et al. (2015b) analyzed the carbon dioxide emission differences of China's four major transportation subindustries (highway, waterway, aviation, and railway) and found that roads and waterways are the primary sources of China's transportation carbon dioxide emissions, with road transport being the relative largest carbon dioxide emitter. By calculating the carbon dioxide emissions of the transport sector from 1985 to 2009, Wang et al. (2011) determined that road transport is the largest source of carbon dioxide emissions. In addition, we have calculated the twelve components of transport activities that contribute to carbon dioxide emissions, with the spillover component contributing the most. The multiplier effects were greater than the spillover effects, which were greater than the feedback effects between regions (Chen et al., 2021). The calculation and twelve-part decomposition of indirect carbon dioxide emissions comprise the core of all calculations in this paper, and the analysis is also intended to inform policy recommendations.

In terms of carbon dioxide emissions from the transport industry, our research reveals that we cannot focus solely on the transport industry, but must conduct correlation analysis with other industries. On the supply side of the transport sector, the majority of energy was embodied in the petroleum refining, coking, etc. sector (S11), the electricity and hot water production and supply sector (S22), the other services sector (S27), and the transport equipment sector (S28). From the transport sector's demand side, the other services sector (S27), the construction sector (S24), the wholesale, retail, and hotel and restaurant sectors (S26), and the chemical sector (S12) receive the majority of their embodied energy (Li et al., 2021).

In the scenario prediction, we measured the impact of various factors on the transportation industry's carbon dioxide emissions. Consistent with previous research, the results indicate that the accelerated decline of energy intensity and the modification of energy structure contribute to the reduction of indirect carbon dioxide emissions. By analyzing the comprehensive impact of carbon emissions from the transportation sector in the six central provinces of China from 2005 to 2016, it is shown that the change in carbon dioxide emission efficiency is primarily attributable to technological advancement (Sun et al., 2019). Wang and Wang (2021) demonstrated that China must improve its energy structure and promote electricity substitution in tandem with the rate of urbanization to achieve carbon dioxide emission reduction in the transport industry. Carbon dioxide emissions are reduced by technology state effects and other factors related to technology state effects, such as transportation intensity effects and energy intensity effects. Additionally, the decline in traffic intensity and energy intensity is a result of technological advancement. Therefore, increasing the level of technological advancement will cause other factors related to technological advancement to inhibit carbon dioxide emission (Liu et al., 2021c).

4. Conclusions and Implications

In this paper, the input-output analysis is combined with eight transport activities in order to examine the direct and indirect carbon dioxide emissions caused by transport on energy consumption in 2018, with the following key conclusions and implications:

(1) Road transport contributes significantly

Because its indirect carbon dioxide emissions account for the largest proportion of the transport industry's indirect carbon dioxide emissions, road transport has become the most crucial area for reducing emissions. Therefore, road transport is the focus of energy conservation and emission reduction in China's transport industry. The direction of road transport development should shift from a traditional mode of development to a low-carbon structure adjustment. It is suggested that the department of road transport should improve the technical performance of vehicles and the quality of petroleum products, as well as formulate carbon dioxide emission standards, in order to lessen the impact of released exhaust gases on the environment and on human health. Second, increase investments in information technology, such as information platform construction, cloud computing, radio frequency identification, and path optimization technology, in order to effectively reduce convoluted transportation and traffic congestion.

(2) The spillover one component proportion is the highest

Among the twelve components, spillover from one component accounts for the largest proportion of total carbon dioxide emissions in 2018. Under the premise of not affecting economic growth, we should therefore accelerate the optimization and upgrading of industrial structures and the reform of industries with high energy consumption; focus on the development of strategic emerging industries and high-tech industries (such as advanced manufacturing industries); and accelerate the transformation of low-end traditional manufacturing industries.

(3) Consumption expenditure is a crucial link

In 2018, from the perspective of final use, consumption expenditures were the most influential factor in indirect carbon dioxide emissions in the transport industry, surpassing capital formation and export. Consequently, it is necessary to vigorously develop public transport, improve transport structure, increase road network density, optimize transport network layout, improve public transport accessibility and service level, and gradually establish a low-carbon transport system centered on public transport. Regarding modes of transportation, residents should actively contribute to the construction of public infrastructure, increase investment in public transport facilities and non-motorized transport, continue to improve the public transport system, enhance the comfort and accessibility of public transport, and increase its utilization rate. Simultaneously, develop high-capacity public transport, enhance the punctuality and convenience of public transport, and increase resident satisfaction with public transport travel. And maintain focus on the construction of rail transit and the development of a rail transit line network. We should maximize the carbon emission efficiency of public electric vehicles and rail transit, utilize the complementary benefits of public electric vehicles and rail transit, and increase the travel occupancy of public transport.

(4) Energy adjustment is highly advantageous

Under the SO and TP scenarios, the carbon dioxide peak is anticipated to occur in 2030 and 2025, respectively, indicating that the adjustment of intensity and structure is conducive to emission reduction. Therefore, the government can promote technology research and development in energy exploitation, conversion and utilization (e.g., clean coal and biofuel technologies), encourage the application of new clean energy like natural gas and solar energy, and strive to increase the proportion of non-fossil energy in industrial energy consumption through financial subsidies and carbon trading policies. In addition, accelerating the promotion of new energy vehicles (such as pure electric and plug-in hybrid vehicles) is crucial for reducing carbon emissions in the transportation industry. Considering the current practical issues, such as the high operating costs of new energy vehicles, the insufficiency of charging stations, and the immaturity of the technology, central cities can be used as pilot cities and promoted further once the experience has matured.

Reducing energy consumption and carbon dioxide emissions is a lengthy process, and China has a long way to go. In China, the generation of electricity mainly depends on coal. Considering the problem of repeated calculation, we do not take the electricity into account. Inaccurate industry classification and uncertain scenario assumptions are also this paper's flaws. These can be considered in the follow-up study to generate more accurate conclusions and solid evidence for policy improvement.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. The names of 45 sectors and their carbon dioxide emission intensity in 2018

	Sector	Carbon emission intensity (kt/10000yuan)
1	Agriculture, Forestry, Animal Husbandry, Fishery and Water Conservancy	9.06658E-05
2	Mining and Washing of Coal	0.001994661
3	Extraction of Petroleum and Natural Gas	0.000297919
4	Mining and Processing of Ferrous Metal Ores	0.00016182
5	Mining and Processing of Non-Ferrous Metal Ores	7.10181E-05
6	Mining and Processing of Nonmetal Ores	0.000211192
7	Support Activities for Mining and Mining of Other Ores	0.000913936
8	Processing of Food from Agricultural Products	7.03253E-05
9	Manufacture of Foods	0.000146769
10	Manufacture of Liquor, Beverages and Refined Tea	9.151E-05
11	Manufacture of Tobacco	6.38087E-06
12	Manufacture of Textile	6.90486E-05
13	Manufacture of Textile, Wearing Apparel and Accessories	1.19526E-05
14	Manufacture of Leather, Fur, Feather and Related Products and Footwear	7.87265E-06
15	Processing of Timber, Manufacture of Wood, Bamboo, Rattan, Palm, and Straw Products	1.79551E-05
16	Manufacture of Furniture	6.70057E-06
17	Manufacture of Paper and Paper Products	0.000468393
18	Printing and Reproduction of Recording Media	2.99726E-05
19	Manufacture of Articles for Culture, Education, Arts and Crafts, Sport and Entertainment Activities	2.24825E-05
20	Processing of Petroleum, Coking and Processing of Nuclear Fuel	0.002280213
21	Manufacture of Raw Chemical Materials and Chemical Products	0.000759446
22	Manufacture of Medicines	7.31007E-05
23	Manufacture of Chemical Fibers	0.000347287
24	Manufacture of Rubber and Plastics Products	4.10315E-05
25	Manufacture of Non-metallic Mineral Products	0.000720933
26	Smelting and Pressing of Ferrous Metals	0.002433122
27	Smelting and Pressing of Non-ferrous Metals	0.000908303
28	Manufacture of Metal Products	6.5487E-05
29	Manufacture of General Purpose Machinery	3.4499E-05
30	Manufacture of Special Purpose Machinery	1.62637E-05
31	Manufacture of Automobiles	1.50121E-05
32	Manufacture of Railway, Ship, Aerospace and Other Transport Equipments	0.000151161
33	Manufacture of Electrical Machinery and Apparatus	6.95246E-06
34	Manufacture of Computers, Communication and Other Electronic Equipment	9.62641E-06
35	Manufacture of Measuring Instruments and Machinery	4.77334E-06
36	Other Manufacture	2.19997E-05
37	Utilization of Waste Resources	5.24302E-05
38	Repair Service of Metal Products, Machinery and Equipment	1.85348E-05
39	Production and Supply of Electric Power and Heat Power	0.005833704
40	Production and Supply of Gas	0.000459578
41	Production and Supply of Water	2.88124E-05
42	Construction	1.7314E-05
43	Transport, Storage and Post	0.000668165
44	Wholesale, Retail Trade and Hotel Restaurants	4.47252E-05
45	Others	2.72132E-05

Appendix B. The coal intensities, coke intensities, gasoline intensities of 45 sectors in 2018

	Sector	Coal carbon emission intensity (kt/10000yuan)	Coke carbon emission intensity (kt/10000yuan)	Gasoline carbon emission intensity (kt/10000yuan)
1	Agriculture, Forestry, Animal Husbandry, Fishery and Water Conservancy	4.03571E-05	2.64788E-06	6.38613E-06
2	Mining and Washing of Coal	0.001949192	4.11636E-06	7.61418E-07
3	Extraction of Petroleum and Natural Gas	1.79136E-05	0	1.75616E-06
4	Mining and Processing of Ferrous Metal Ores	7.2083E-05	6.25597E-05	5.84769E-07
5	Mining and Processing of Non-Ferrous Metal Ores	5.00156E-05	2.19811E-06	1.0621E-06
6	Mining and Processing of Nonmetal Ores	0.000183671	3.3044E-06	5.6319E-07
7	Support Activities for Mining and Mining of Other Ores	0.000622156	0	6.18063E-06
8	Processing of Food from Agricultural Products	5.52925E-05	6.09421E-06	4.50346E-07
9	Manufacture of Foods	0.000127026	1.181E-07	5.79704E-07
10	Manufacture of Liquor, Beverages and Refined Tea	7.18493E-05	0	6.65181E-07
11	Manufacture of Tobacco	3.12072E-06	0	1.40908E-07
12	Manufacture of Textile	4.65296E-05	1.47294E-07	5.28694E-07
13	Manufacture of Textile, Wearing Apparel and Accessories	4.71648E-06	0	7.33641E-07
14	Manufacture of Leather, Fur, Feather and Related Products and Footwear	4.08708E-06	0	6.84404E-07
15	Processing of Timber, Manufacture of Wood, Bamboo, Rattan, Palm, and Straw Products	1.24153E-05	0	3.78675E-07
16	Manufacture of Furniture	9.3322E-07	2.80943E-07	9.13608E-07
17	Manufacture of Paper and Paper Products	0.000434517	0	4.85351E-07
18	Printing and Reproduction of Recording Media	1.5134E-05	0	1.44362E-06
19	Manufacture of Articles for Culture, Education, Arts and Crafts, Sport and Entertainment Activities	4.39797E-06	4.01211E-07	8.49293E-07
20	Processing of Petroleum, Coking and Processing of Nuclear Fuel	0.002048444	3.5591E-06	1.28296E-06
21	Manufacture of Raw Chemical Materials and Chemical Products	0.000526785	0.000126308	6.47551E-07
22	Manufacture of Medicines	6.20669E-05	2.04656E-07	6.09019E-07
23	Manufacture of Chemical Fibers	0.000310294	6.32119E-06	2.87296E-07
24	Manufacture of Rubber and Plastics Products	2.74346E-05	0	1.06712E-06
25	Manufacture of Non-metallic Mineral Products	0.000624476	3.7335E-05	6.75058E-07
26	Smelting and Pressing of Ferrous Metals	0.000823655	0.001571614	1.50974E-07
27	Smelting and Pressing of Non-ferrous Metals	0.000855729	2.37159E-05	2.57568E-07
28	Manufacture of Metal Products	1.37545E-05	2.66955E-05	7.94106E-07
29	Manufacture of General Purpose Machinery	3.79027E-06	1.9292E-05	1.04657E-06
30	Manufacture of Special Purpose Machinery	2.6011E-06	1.63136E-06	1.17196E-06
31	Manufacture of Automobiles	4.53893E-06	1.18322E-06	1.08391E-06
32	Manufacture of Railway, Ship, Aerospace and Other Transport Equipments	9.51956E-06	1.91056E-07	1.46142E-06
33	Manufacture of Electrical Machinery and Apparatus	1.09837E-06	8.93678E-08	7.97371E-07
34	Manufacture of Computers, Communication and Other Electronic Equipment	3.59888E-06	0	3.09206E-07
35	Manufacture of Measuring Instruments and Machinery	7.9196E-07	0	1.27391E-06
36	Other Manufacture	1.77002E-06	0	5.99402E-07
37	Utilization of Waste Resources	1.33104E-05	1.03515E-05	1.50248E-07
38	Repair Service of Metal Products, Machinery and Equipment	0	0	8.45965E-07
39	Production and Supply of Electric Power and Heat Power	0.005665117	1.72996E-06	8.65041E-07
40	Production and Supply of Gas	0.000423961	9.68378E-07	1.29727E-06
41	Production and Supply of Water	1.65764E-05	0	3.1375E-06
42	Construction	4.61615E-06	1.17588E-07	5.52036E-06
43	Transport, Storage and Post	5.41554E-06	0	0.00015757
44	Wholesale, Retail Trade and Hotel Restaurants	2.84896E-05	3.03346E-07	4.49801E-06
45	Others	9.13155E-06	2.72992E-08	1.00666E-05

Appendix C. The kerosene intensities, diesel oil intensities, residual fuel oil intensities of 45 sectors in 2018

	Sector	Kerosene carbon emission intensity(kt/10000yuan)	Diesel oil carbon emission intensity(kt/10000yuan)	Residual fuel oil carbon emission intensity(kt/10000yuan)
1	Agriculture, Forestry, Animal Husbandry, Fishery and Water Conservancy	1.33174E-07	4.08524E-05	3.6473E-08
2	Mining and Washing of Coal	8.55829E-08	2.138E-05	3.48906E-08
3	Extraction of Petroleum and Natural Gas	0	9.77432E-06	6.15877E-06
4	Mining and Processing of Ferrous Metal Ores	0	2.65287E-05	2.70867E-08
5	Mining and Processing of Non-Ferrous Metal Ores	2.26116E-07	1.44708E-05	9.68473E-07
6	Mining and Processing of Nonmetal Ores	7.74743E-09	2.07752E-05	1.22088E-08
7	Support Activities for Mining and Mining of Other Ores	0	0.000232684	1.51778E-06
8	Processing of Food from Agricultural Products	6.57057E-09	1.23205E-06	7.74101E-08
9	Manufacture of Foods	0	1.21688E-06	2.77516E-07
10	Manufacture of Liquor, Beverages and Refined Tea	9.92218E-09	1.03992E-06	1.02502E-07
11	Manufacture of Tobacco	0	5.62648E-07	0
12	Manufacture of Textile	1.55404E-09	5.8029E-07	3.9591E-07
13	Manufacture of Textile, Wearing Apparel and Accessories	0	7.3469E-07	7.1788E-08

(continued on next page)

(continued)

	Sector	Kerosene carbon emission intensity(kt/10000yuan)	Diesel oil carbon emission intensity(kt/10000yuan)	Residual fuel oil carbon emission intensity(kt/10000yuan)
14	Manufacture of Leather, Fur, Feather and Related Products and Footwear	1.9669E-09	4.43902E-07	7.64551E-08
15	Processing of Timber, Manufacture of Wood, Bamboo, Rattan, Palm, and Straw Products	1.82565E-09	1.07501E-06	5.56209E-08
16	Manufacture of Furniture	2.96413E-09	1.1646E-06	4.98241E-08
17	Manufacture of Paper and Paper Products	0	2.53366E-06	1.00971E-06
18	Printing and Reproduction of Recording Media	3.64161E-09	1.63625E-06	1.18598E-07
19	Manufacture of Articles for Culture, Education, Arts and Crafts, Sport and Entertainment Activities	2.11651E-08	9.59678E-07	9.78356E-08
20	Processing of Petroleum, Coking and Processing of Nuclear Fuel	4.69385E-09	4.20501E-06	0.000132316
21	Manufacture of Raw Chemical Materials and Chemical Products	6.834E-08	1.47954E-06	2.12956E-05
22	Manufacture of Medicines	2.15925E-09	1.10088E-06	2.4499E-07
23	Manufacture of Chemical Fibers	7.41028E-09	7.75384E-07	5.60518E-07
24	Manufacture of Rubber and Plastics Products	3.4786E-09	1.47468E-06	3.84635E-07
25	Manufacture of Non-metallic Mineral Products	3.34373E-08	1.18495E-05	6.34918E-06
26	Smelting and Pressing of Ferrous Metals	8.92631E-10	2.34374E-06	4.17306E-08
27	Smelting and Pressing of Non-ferrous Metals	5.21545E-08	2.33819E-06	1.35675E-06
28	Manufacture of Metal Products	3.50502E-08	1.51786E-06	1.78852E-07
29	Manufacture of General Purpose Machinery	1.21009E-07	1.59594E-06	5.0199E-08
30	Manufacture of Special Purpose Machinery	6.71264E-08	1.47964E-06	8.22741E-08
31	Manufacture of Automobiles	1.61081E-08	1.23974E-06	2.28455E-08
32	Manufacture of Railway, Ship, Aerospace and Other Transport Equipments	2.63258E-06	3.51122E-06	9.06369E-07
33	Manufacture of Electrical Machinery and Apparatus	2.07435E-08	6.50479E-07	1.01037E-07
34	Manufacture of Computers, Communication and Other Electronic Equipment	7.29011E-09	2.53373E-07	2.35889E-08
35	Manufacture of Measuring Instruments and Machinery	5.0309E-08	4.77386E-07	3.96397E-08
36	Other Manufacture	5.62199E-08	9.22767E-07	2.21485E-08
37	Utilization of Waste Resources	3.17076E-08	1.83598E-06	3.47914E-07
38	Repair Service of Metal Products, Machinery and Equipment	1.08689E-06	7.99068E-06	5.88223E-07
39	Production and Supply of Electric Power and Heat Power	6.03726E-08	2.33713E-06	1.93226E-07
40	Production and Supply of Gas	0	8.28004E-07	5.90349E-08
41	Production and Supply of Water	0	2.08044E-06	1.02431E-07
42	Construction	1.94779E-07	6.28676E-06	3.77145E-07
43	Transport, Storage and Post	9.27711E-05	0.000306927	5.05447E-05
44	Wholesale, Retail Trade and Hotel Restaurants	2.60587E-07	3.6594E-06	1.77849E-07
45	Others	4.98328E-07	5.45359E-06	4.55898E-08

Appendix D. The natural gas intensities, of 45 sectors in 2018

	Sector	Natural gas carbon emission intensity(kt/10000yuan)
1	Agriculture, Forestry, Animal Husbandry, Fishery and Water Conservancy	2.52623E-07
2	Mining and Washing of Coal	1.90905E-05
3	Extraction of Petroleum and Natural Gas	0.000262316
4	Mining and Processing of Ferrous Metal Ores	3.69448E-08
5	Mining and Processing of Non-Ferrous Metal Ores	2.07696E-06
6	Mining and Processing of Nonmetal Ores	2.85862E-06
7	Support Activities for Mining and Mining of Other Ores	5.13973E-05
8	Processing of Food from Agricultural Products	7.17227E-06
9	Manufacture of Foods	1.75511E-05
10	Manufacture of Liquor, Beverages and Refined Tea	1.78432E-05
11	Manufacture of Tobacco	2.55659E-06
12	Manufacture of Textile	2.08652E-05
13	Manufacture of Textile, Wearing Apparel and Accessories	5.69603E-06
14	Manufacture of Leather, Fur, Feather and Related Products and Footwear	2.57884E-06
15	Processing of Timber, Manufacture of Wood, Bamboo, Rattan, Palm, and Straw Products	4.02865E-06
16	Manufacture of Furniture	3.3554E-06
17	Manufacture of Paper and Paper Products	2.9847E-05
18	Printing and Reproduction of Recording Media	1.16364E-05
19	Manufacture of Articles for Culture, Education, Arts and Crafts, Sport and Entertainment Activities	1.57553E-05
20	Processing of Petroleum, Coking and Processing of Nuclear Fuel	9.04008E-05
21	Manufacture of Raw Chemical Materials and Chemical Products	8.28619E-05
22	Manufacture of Medicines	8.8721E-06
23	Manufacture of Chemical Fibers	2.90411E-05
24	Manufacture of Rubber and Plastics Products	1.06669E-05
25	Manufacture of Non-metallic Mineral Products	4.02147E-05
26	Smelting and Pressing of Ferrous Metals	3.5315E-05
27	Smelting and Pressing of Non-ferrous Metals	2.48532E-05
28	Manufacture of Metal Products	2.25112E-05
29	Manufacture of General Purpose Machinery	8.60307E-06
30	Manufacture of Special Purpose Machinery	9.23021E-06
31	Manufacture of Automobiles	6.92734E-06
32	Manufacture of Railway, Ship, Aerospace and Other Transport Equipments	0.000132939

(continued)

	Sector	Natural gas carbon emission intensity(kt/10000yuan)
33	Manufacture of Electrical Machinery and Apparatus	4.19509E-06
34	Manufacture of Computers, Communication and Other Electronic Equipment	5.43407E-06
35	Manufacture of Measuring Instruments and Machinery	2.14013E-06
36	Other Manufacture	1.86291E-05
37	Utilization of Waste Resources	2.64024E-05
38	Repair Service of Metal Products, Machinery and Equipment	8.02307E-06
39	Production and Supply of Electric Power and Heat Power	0.000163401
40	Production and Supply of Gas	3.24644E-05
41	Production and Supply of Water	6.91569E-06
42	Construction	2.01205E-07
43	Transport, Storage and Post	5.4937E-05
44	Wholesale, Retail Trade and Hotel Restaurants	7.33645E-06
45	Others	1.99031E-06

Appendix E. Carbon dioxide emissions structure decomposition and derivation based on input-output method

$$x = Ax + y \tag{1}$$

where x is a $(n \times 1)$matrix, representing total production of each production sector i, j = 1,2, …j…n; y is the$(n \times 1)$matrix of sector net output or final demand; A is the $(n \times n)$ matrix of the direct consumption coefficient, and a_{ij} represents the value of the goods or services directly consumed by the product (or industry) sector i in the production and operation process of the unit output of the product (or industry) sector j.

$$a_{ij} = \frac{x_{ij}}{x_j} \tag{2}$$

$$x = (I - A)^{-1} y \tag{3}$$

$(I - A)^{-1}$ is the inverse of Leontief, and I is the identity matrix.

$$\sum x^{(j)} = x \tag{4}$$

where $x^{(j)}$ represents the output that all sectors must produce in order to obtain the final demand of sector j.

$$Ax^{(j)} + y^{(j)} = x^{(j)} \tag{5}$$

$y^{(j)}$is a matrix in that all elements have a value of zero, except the value corresponding to the final demand of the production sector j.

$$A(I - A)^{-1} y^{(j)} + y^{(j)} = x^{(j)} \tag{6}$$

Let E be the matrix of carbon dioxide emissions directly generated by each unit of output of different industries; $y^{(j)}$ stands for final use. The following formula can be obtained:

$$EA(I - A)^{-1} y^{(j)} + Ey^{(j)} = Ex^{(j)} \tag{7}$$

$$EA(I - A)^{-1} y + Ey = Ex = E(I - A)^{-1} y \tag{8}$$

where $A(I - A)^{-1} = (I - A)^{-1} - I$ and assume $D = (I - A)^{-1}$, the simplified expression is as follows (9):

$$E[D - I]y + Ey = Ex \tag{9}$$

According to this method, the total carbon dioxide emissions caused by the final demand of an industry has no less than two components: internal component, $E_j(d_{jj} - 1)y_j$, which is given by the size of the corresponding elements of the main diagonal and shows the carbon dioxide emissions caused by the sector during the production of intermediate inputs needed to meet the final demand; Spillover component, $\sum_{i \neq j} E_j d_{jj} y_j$,which is given by the other elements in the corresponding column and represents the carbon dioxide emissions caused by other sectors in producing the inputs provided to sector j; In addition, we can obtain the final use component from Eq. (9), $E_j y_j$, which represents the carbon dioxide emissions directly related to the final demand. Formula (10) can be obtained:

$$C_j = \underbrace{E_j [d_{jj} - 1] y_j}_{\text{internal component}} + \underbrace{\sum\nolimits_{i \neq j} E_i d_{ij} y_j}_{\text{spillover component}} + \underbrace{E_j y_j}_{\text{final use component}} \tag{10}$$

$$d_{jj} = \left[(1 - a_{jj})^{-1} - 1 \right] + (1 - a_{jj})^{-1} \sum\nolimits_{i \neq j} a_{ji} d_{ij} + 1 \tag{11}$$

$$d_{jj} - 1 = \left[(1 - a_{jj})^{-1} - 1 \right] + (1 - a_{jj})^{-1} \sum\nolimits_{i \neq j} a_{ji} d_{ij} \tag{12}$$

Also due to Eqs. (11) and (12), the total (direct and indirect) carbon dioxide emissions of sector j can be divided into:

$$C_j = \underbrace{E_j\left[(1-a_{jj})^{-1}-1\right]\sum_{m}^{m=1,2,3} y_{mj}}_{\text{own internal component}} + \underbrace{E_j(1-a_{jj})^{-1}\sum_{i\neq j} a_{ji}d_{ij}\sum_{m}^{m=1,2,3} y_{mj}}_{\text{feed - back component}} + \underbrace{\sum_{i\neq j} E_i d_{ij}\sum_{m}^{m=1,2,3} y_{mj}}_{\text{spillover component}} + \underbrace{E_j\sum_{m}^{m=1,2,3} y_{mj}}_{\text{final use component}}$$

$$= \underbrace{E_j\left[(1-a_{jj})^{-1}-1\right]y_{1j}}_{\text{own internal one}} + \underbrace{E_j\left[(1-a_{jj})^{-1}-1\right]y_{2j}}_{\text{own internal two}} + \underbrace{E_j\left[(1-a_{jj})^{-1}-1\right]y_{3j}}_{\text{own internal three}} + \underbrace{E_j(1-a_{jj})^{-1}\sum_{i\neq j} a_{ji}d_{ij}y_{1j}}_{\text{feed - back one}} + \underbrace{E_j(1-a_{jj})^{-1}\sum_{i\neq j} a_{ji}d_{ij}y_{2j}}_{\text{feed - back two}}$$
$$+ \underbrace{E_j(1-a_{jj})^{-1}\sum_{i\neq j} a_{ji}d_{ij}y_{3j}}_{\text{feed - back three}} + \underbrace{\sum_{i\neq j} E_i d_{ij}y_{1j}}_{\text{spillover one}} + \underbrace{\sum_{i\neq j} E_i d_{ij}y_{2j}}_{\text{spillover two}} + \underbrace{\sum_{i\neq j} E_i d_{ij}y_{3j}}_{\text{spillover three}} + \underbrace{E_j y_{1j}}_{\text{final use one}} + \underbrace{E_j y_{2j}}_{\text{final use two}} + \underbrace{E_j y_{3j}}_{\text{final use three}} \quad (13)$$

Appendix F. Data of carbon emission coefficient

Energy name	Average low calorific value	Conversion Factor	Carbon content per calorific value (ton carbon/TJ)	Carbon oxidation rate	CO_2 emission factor
Coal	20,908 kJ/kg	0.714 3 kgce/kg	26.37	0.94	1.9003 kg-co2/kg
Coke	28,435 kJ/kg	0.971 4 kgce/kg	29.5	0.93	2.8604 kg-co2/kg
Crude Oil	41,816 kJ/kg	1.428 6 kgce/kg	20.1	0.98	3.0202 kg-co2/kg
Residual fuel Oil	41,816 kJ/kg	1.428 6 kgce/kg	21.1	0.98	3.1705 kg-co2/kg
Gasoline	43,070 kJ/kg	1.471 4 kgce/kg	18.9	0.98	2.9251 kg-co2/kg
Kerosene	43,070 kJ/kg	1.471 4 kgce/kg	19.5	0.98	3.0179 kg-co2/kg
Diesel oil	42,652 kJ/kg	1.457 1 kgce/kg	20.2	0.98	3.0959 kg-co2/kg
Natural gas	38,931 kJ/m3	1.330 0 kgce/m3	15.3	0.99	2.1622 kg-co2/m3

Explanation:
1.A fuel with a low (level) calorific value equal to 29,307 kilojoules (kJ) is called 1 kilogram of standard coal (1 kgce).
2.The first two columns of the above table are derived from the "General Principles of Comprehensive Energy Consumption Calculation" (GB/T 2589-2008)
3.The last two columns of the above table are derived from the "Guidelines for Compiling Provincial Greenhouse Gas Inventories" (Fagaiban Climate [2011] No. 1041)
4.Calculation method of "CO_2 emission coefficient": Take "raw coal" as an example
1.9003=20,908*0.000000001*26.37*0.94*1,000*3.66667

Appendix G. The decomposition of the total carbon dioxide emissions in 2018

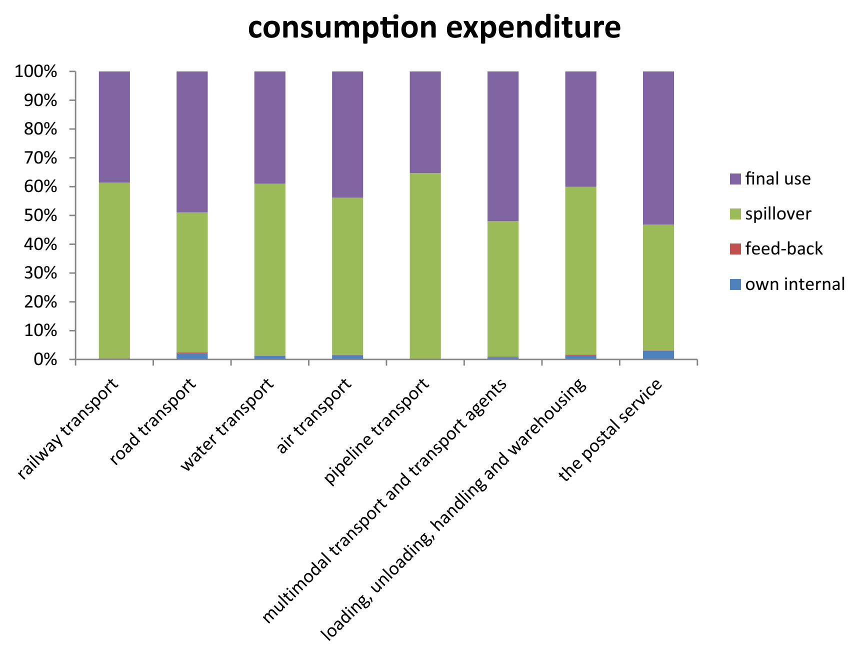
Activity	Own internal one		Own internal two		Own internal three	
	kt	%	kt	%	kt	%
Railway transport	78	0 %	47	0 %	58	0 %
Road transport	3095	1 %	1038	1 %	1019	0 %
Water transport	127	0 %	43	0 %	681	2 %
Air transport	212	0 %	123	0 %	667	1 %
Pipeline transport	3	0 %	1	0 %	2	0 %
Multimodal transport and transport agents	150	0 %	134	0 %	170	0 %
Loading, unloading, handling and warehousing	142	1 %	64	0 %	91	0 %
The postal service	170	1 %	50	0 %	135	1 %

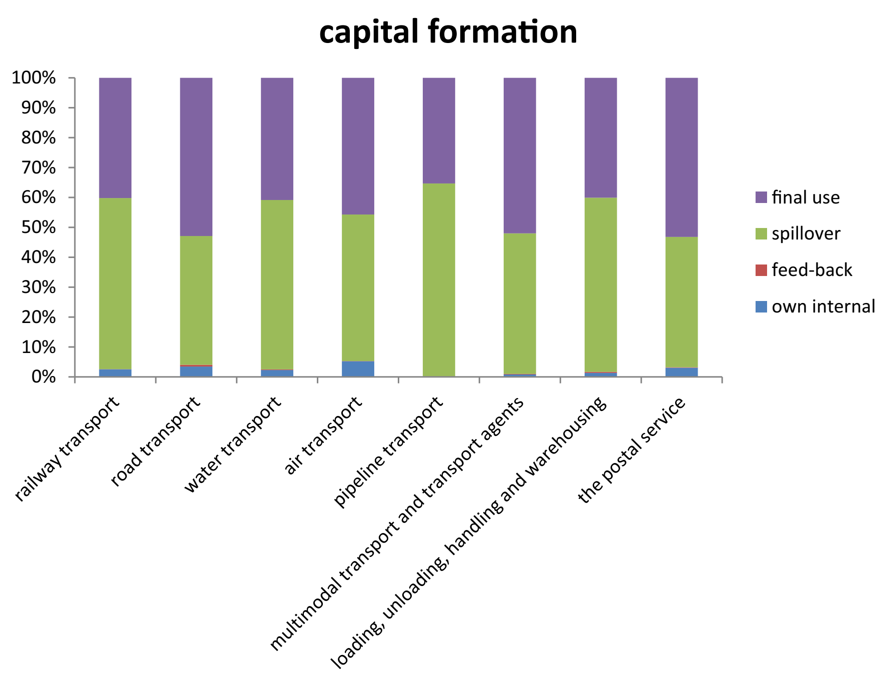
Activity	feed-back one		feed-back two		feed-back three	
	kt	%	kt	%	kt	%
Railway transport	11	0 %	1	0 %	2	0 %
Road transport	576	0 %	176	0 %	173	0 %
Water transport	12	0 %	4	0 %	66	0 %
Air transport	9	0 %	2	0 %	18	0 %
Pipeline transport	2	0 %	1	0 %	1	0 %
Multimodal transport and transport agents	35	0 %	31	0 %	39	0 %
Loading, unloading, handling and warehousing	36	0 %	16	0 %	23	0 %
The postal service	9	0 %	3	0 %	7	0 %

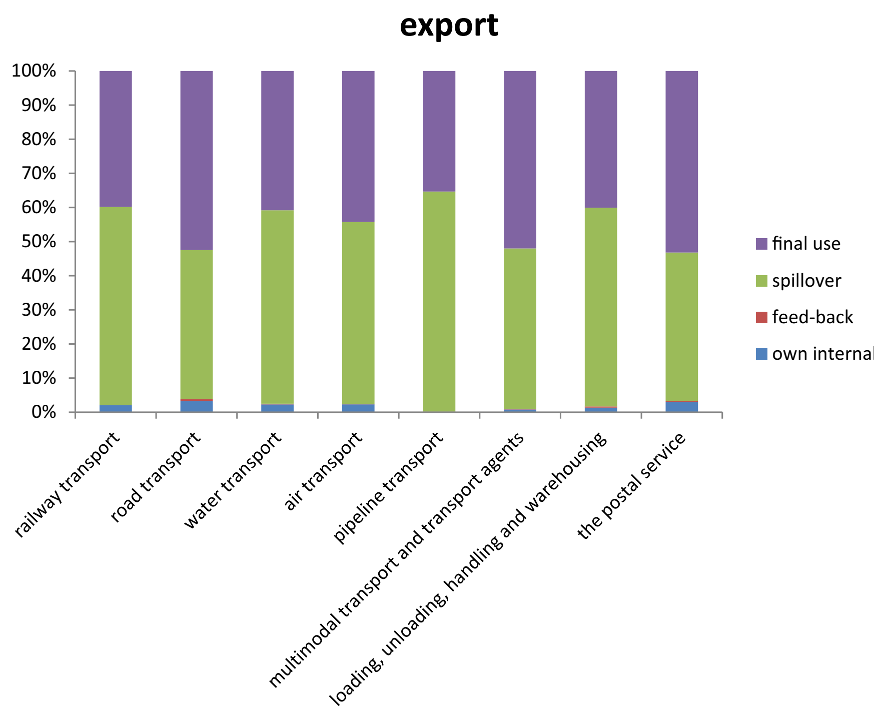
Activity	Spillover one		Spillover two		Spillover three	
	kt	%	kt	%	kt	%
Railway transport	12,505	50 %	1057	4 %	1626	6 %
Road transport	71,534	34 %	12,925	6 %	13,406	6 %
Water transport	5747	14 %	1067	3 %	16,986	41 %
Air transport	7792	17 %	1152	3 %	15,443	34 %
Pipeline transport	2051	33 %	6,44	10 %	1278	21 %
Multimodal transport and transport agents	8755	16 %	7812	14 %	9907	18 %
Loading, unloading, handling and warehousing	6172	28 %	2765	12 %	3956	18 %
The postal service	2433	21 %	7,15	6 %	1921	17 %

Activity	Final use one		Final use two		Final use three	
	kt	%	kt	%	kt	%
Railway transport	7921	31 %	743	3 %	1117	4 %
Road transport	72,096	35 %	15,881	8 %	16,126	8 %
Water transport	3766	9 %	770	2 %	12,231	29 %
Air transport	6260	14 %	1075	2 %	12,808	28 %
Pipeline transport	1123	18 %	352	6 %	700	11 %
Multimodal transport and Transport agents	9685	17 %	8642	15 %	10,960	19 %
Loading, unloading, handling and warehousing	4248	19 %	1903	9 %	2723	12 %
The postal service	2969	26 %	872	8 %	2344	20 %

Appendix H. The decomposition of consumption expenditure, capital formation and export







Appendix I. The decomposition of the carbon dioxide emissions from coal consumption in 2018

Activity	Own internal one		Own internal two		Own internal three	
	kt	%	kt	%	kt	%
Railway transport	1	0 %	0	0 %	0	0 %
Road transport	25	0 %	8	0 %	8	0 %
Water transport	1	0 %	0	0 %	6	0 %
Air transport	2	0 %	1	0 %	5	0 %
Pipeline transport	0	0 %	0	0 %	0	0 %
Multimodal transport and transport agents	1	0 %	1	0 %	1	0 %
Loading, unloading, handling and warehousing	1	0 %	1	0 %	1	0 %
The postal service	1	0 %	0	0 %	1	0 %

Activity	Feed-back one		Feed-back two		Feed-back three	
	kt	%	kt	%	kt	%
Railway transport	0	0 %	0	0 %	0	0 %
Road transport	5	0 %	1	0 %	1	0 %
Water transport	0	0 %	0	0 %	1	0 %
Air transport	0	0 %	0	0 %	0	0 %
Pipeline transport	0	0 %	0	0 %	0	0 %
Multimodal transport and transport agents	0	0 %	0	0 %	0	0 %
Loading, unloading, handling and warehousing	0	0 %	0	0 %	0	0 %
The postal service	0	0 %	0	0 %	0	0 %

Activity	Spillover one		Spillover two		Spillover three	
	kt	%	kt	%	kt	%
Railway transport	10,712	82 %	922	7 %	1413	11 %
Road transport	56,556	72 %	10,189	13 %	10,572	14 %
Water transport	3969	23 %	771	5 %	12,266	72 %
Air transport	5741	31 %	926	5 %	11,585	63 %
Pipeline transport	1834	51 %	576	16 %	1143	32 %
Multimodal transport and transport agents	5847	33 %	5218	29 %	6617	37 %
Loading, unloading, handling and warehousing	4600	48 %	2061	21 %	2949	30 %
The postal service	1604	47 %	471	14 %	1266	37 %

Activity	Final use one		Final use two		Final use three	
	kt	%	kt	%	kt	%
Railway transport	64	0 %	6	0 %	9	0 %
Road transport	584	1 %	129	0 %	131	0 %
Water transport	31	0 %	6	0 %	99	1 %
Air transport	51	0 %	9	0 %	104	1 %
Pipeline transport	9	0 %	3	0 %	6	0 %
Multimodal transport and transport agents	79	0 %	70	0 %	89	1 %
Loading, unloading, handling and warehousing	34	0 %	15	0 %	22	0 %
The postal service	24	1 %	7	0 %	19	1 %

Appendix J. The decomposition of the carbon dioxide emissions from diesel oil consumption in 2018

Activity	Own internal one		Own internal two		Own internal three	
	kt	%	kt	%	kt	%
Railway transport	36	1 %	22	0 %	27	1 %
Road transport	1422	3 %	477	1 %	468	1 %
Water transport	58	1 %	20	0 %	313	3 %
Air transport	97	1 %	57	1 %	306	3 %
Pipeline transport	1	0 %	0	0 %	1	0 %
Multimodal transport and transport agents	69	0 %	62	0 %	78	0 %
Loading, unloading, handling and warehousing	65	1 %	29	1 %	42	1 %
The postal service	78	2 %	23	1 %	62	2 %

Activity	feed-back one		feed-back two		feed-back three	
	kt	%	kt	%	kt	%
Railway transport	5	0 %	0	0 %	1	0 %
Road transport	265	0 %	81	0 %	80	0 %
Water transport	6	0 %	2	0 %	30	0 %
Air transport	4	0 %	1	0 %	8	0 %
Pipeline transport	1	0 %	0	0 %	1	0 %
Multimodal transport and transport agents	16	0 %	14	0 %	18	0 %
Loading, unloading, handling and warehousing	17	0 %	7	0 %	11	0 %
The postal service	4	0 %	1	0 %	3	0 %

Activity	spillover one		spillover two		spillover three	
	kt	%	kt	%	kt	%
Railway transport	464	9 %	23	0 %	41	1 %
Road transport	3097	6 %	511	1 %	536	1 %
Water transport	518	5 %	74	1 %	1189	12 %
Air transport	545	5 %	41	0 %	974	9 %
Pipeline transport	34	3 %	11	1 %	21	2 %
Multimodal transport and transport agents	942	6 %	840	5 %	1065	6 %
Loading, unloading, handling and warehousing	400	8 %	179	4 %	256	5 %
The postal service	280	8 %	82	2 %	221	6 %

Activity	final use one		final use two		final use three	
	kt	%	kt	%	kt	%
Railway transport	3638	71 %	341	7 %	513	10 %
Road transport	33,118	60 %	7295	13 %	7408	14 %
Water transport	1730	17 %	354	4 %	5618	57 %
Air transport	2876	25 %	494	4 %	5883	52 %
Pipeline transport	516	48 %	162	15 %	321	30 %
Multimodal transport and transport agents	4449	27 %	3970	24 %	5035	30 %
Loading, unloading, handling and warehousing	1951	38 %	874	17 %	1251	25 %
The postal service	1364	38 %	401	11 %	1077	30 %

Appendix K. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2022.06.021.

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