International Journal of
Geo-Information

Article

Analysis of Decoupling Effects and Influence Factors in Transportation: Evidence from Guangdong Province, China

Hualing Bi, Shiying Zhang and Fuqiang Lu *

School of Economic and Management, Yanshan University, Qinhuangdao 066004, China; bihualing081@126.com (H.B.)
* Correspondence: fuqiang_lu@126.com

Abstract: In recent years, global environmental issues have become increasingly prominent. The transportation industry, as the fundamental sector of national economic development, is also characterized by high energy consumption and carbon emissions. Therefore, it is imperative to conduct research on the carbon emission problem within this industry. In light of the Tapio decoupling model, an analysis of the correlation between traffic carbon emissions and economic development in Guangdong province during 1999–2019 was carried out. With the aim of encouraging Guangdong province's low-carbon transportation development, the factors affecting the transportation industry are analyzed utilizing the generalized Divisia index model (GDIM). We also introduced passenger and freight turnover as an influencing factor for analysis. The findings indicate that (1) Guangdong province's traffic carbon emissions increased from 1999 to 2019; (2) the traffic carbon emissions' decoupling effect is mainly "weakly decoupled", and the overall decoupling effect is not strong in Guangdong province; (3) among the traffic carbon emissions' factors, the effects of the production value of traffic and the turnover volume are at the forefront, and the effect of turnover volume has gradually exceeded the production value of traffic in recent years. The suppression of the intensity of carbon emissions is relatively large, while the suppression of the intensity of energy consumption and transport is relatively weak. Based on this, strategies were proposed to promote a cleaner energy mix, improve energy use efficiency, create energy savings, develop green technologies, and foster the restructuring of transportation.

Keywords: transportation; carbon emissions; Tapio decoupling model; generalized Divisia index model; decomposition of influencing factors

check for updates

Citation: Bi, H.; Zhang, S.; Lu, F. Analysis of Decoupling Effects and Influence Factors in Transportation: Evidence from Guangdong Province, China. *ISPRS Int. J. Geo-Inf.* **2024**, *13*, 404. https://doi.org/10.3390/ijgi13110404

Academic Editors: Wolfgang Kainz, Andriani Skopeliti, Anastasia Stratigea, Vassilios Krassanakis and Apostolos Lagarias

Received: 4 September 2024
Revised: 6 November 2024
Accepted: 7 November 2024
Published: 8 November 2024

1. Introduction

The steady rise in the standard of living has been accompanied by a significant increase in the consumption of mineral fuels like coal and oil, which not only causes global climate change but also impacts energy, resources, and the ecological environment. The growing "greenhouse effect" has become a major barrier to achieving sustainable social and economic progress.

In 2015, the 193 member states of the United Nations formally adopted 17 Sustainable Development Goals at the summit. These include the goal of Sustainable Cities and Communities, which aims to render cities and human settlements inclusive, safe, resilient, and sustainable, and the goal of Climate Action, which intends to undertake urgent actions to combat climate change and its impacts. Numerous nations have begun to focus on reducing their carbon emissions in the context of global warming. In July 2021, the European Commission published a set of recommendations known as "Fit for 55", which put forward a wide range of initiatives in energy, industry, transportation, and buildings [1]. In March 2023, the EU and its member states reached a provisional agreement on the revision of the Renewable Energy Directive, reaffirming the EU's determination to achieve energy independence [2]. The United Kingdom has released its Net Zero strategy, which comprehensively sets out how the United Kingdom will achieve its net zero emissions commitment to climate change by 2050 [3]. The U.S. government released the first blueprint for decarbonizing the transportation sector in January 2023, aiming to decarbonize transportation by 2050 [4]. In February 2023, the Cabinet of Ministers approved the "Basic Policy for Realizing the Green Transition", which aims to realize the green transition and simultaneously decarbonize the country, stabilizing the energy supply [5]. In March 2023, the Korean government issued an outline of a basic plan for carbon neutral and green growth and a concrete implementation plan to achieve the 2030 greenhouse gas reduction target and 2050 carbon neutrality [6]. China is also concerned about the negative effects of carbon emissions. The "Fourteenth Five-Year Plan" and the Central Economic Work Conference have made it fairly evident that carbon neutrality objectives should be met before 2060 and carbon peaking targets by 2030 [7]. The 20th National People's Congress also shows that it is necessary to "aggressively and consistently advance carbon peaking and carbon neutrality", enhance the system of market-oriented resource and ecological component allocation, and cultivate low-carbon and green industries.

Transport is an indispensable basic industry for the national economy and people's lives. However, its energy consumption is huge, especially the elevated CO_2 emissions represented by fossil fuels. In this context, transport is a key driver for achieving the objectives of carbon peak and carbon neutrality.

Guangdong is situated at the hub of the maritime transportation routes between the Pacific, Indian, and Atlantic Oceans, with its back leaning on the vast hinterland of China and its front facing Southeast Asia. It is one of China's important maritime traffic chokepoints, with its communication channels to the outside world and major ports for foreign trade. The length of expressways open to traffic in Guangdong is about 11,500 km, ranking first in China for the 10th consecutive year. The operating mileage of the high-speed railway is about 2838 km, and the operating mileage of the urban rail transit system is about 1373 km. China has built about 400 10,000-ton berths and seven 10,000-ton ports. It has opened more than 400 international container liner routes, covering the world's major trading ports. Its inland waterways cover 1479 km of high-grade waterways, ranking first in China. Nine airports, including Guangzhou Baiyun and Shenzhen Baoan, have been built, and 36 general aviation airports have been registered, forming the initial system for the general aviation industry. The geographical location of Guangdong province is shown in Figure 1.

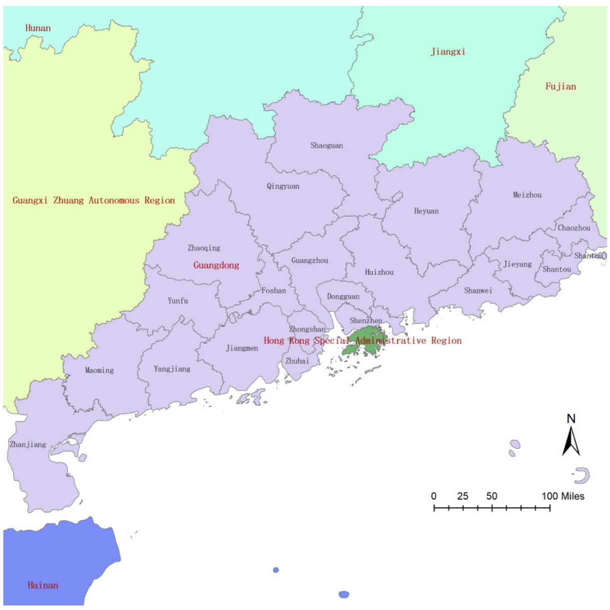

Figure 1. The geographical position of Guangdong province.

At present, Guangdong is still in the midst of a period of high-speed development, with a growing population and increased demand for travel and cargo transportation by residents, posing a serious challenge to China's goals of reducing emissions and conserving energy. By calculating China's transportation-related carbon emissions across all provinces, Guangdong ranked first in transportation emissions, with 84,645,700 metric tons, surpassing second-ranked Shanghai by about 48 percent. The total amounts of the import and export of goods, passenger and freight transportation, and turnover volume of Guangdong province are all ranked first in China, and it produces more carbon emissions while developing continuously. Thus, it is imperative to investigate the factors impacting Guangdong province's traffic carbon emissions.

The following are the fundamental contributions of this paper:

(1) The "up-bottom" method is applied to calculate each province's carbon emissions from traffic. Guangdong's transport carbon emissions are then measured from 1999 to 2019.
(2) Utilizing the Tapio decoupling model as a basis, the research investigates traffic carbon emissions' decoupling status in Guangdong province.
(3) The GDIM model is integrated with the passenger and freight turnover data to conduct a thorough analysis of the current Guangdong province traffic carbon emission issue, and corresponding countermeasures are proposed to lessen carbon emissions.

The reminder of this paper is organized as follows. Section 2 includes a literature review, Section 3 provides a methodology, Section 4 shows the data and results, and Section 5 presents conclusions and recommendations.

2. Literature Review

The Organization for Economic Co-operation and Development (OECD) formulated the decoupling theory first, which expects to effectively solve the problems of resource depletion and environmental contamination. Carbon emission decoupling is an ideal process in which the relationship between economic growth and greenhouse gas emissions constantly weakens and even disappears. That is, there is a gradual reduction of energy consumption on the basis of economic growth. At present, the methods used by scholars are the OECD or Tapio decoupling models. Tapio developed a novel decoupling model that was derived from the OECD decoupling model, investigating the European region's decoupling state [8]. Wang and Zhang investigated trade liberalization's impact, with the results indicating that wealthy countries gain from trade liberalization as it helps to separate economic expansion from carbon emissions. However, it negatively affects developing nations [9]. Wang et al. studied information and communication technology investment and the connection with carbon emissions and found that its decoupling state gradually improved [10]. Shi et al. assessed carbon emissions' decoupling status [11]. Nima used the Tapio model to ascertain the decoupling situation in the Middle East [12]. Zhao et al. revealed that different countries' decoupling states at different times differ in different periods. The U.S. was the best performer [13]. Lu et al. introduced fair preference into the distribution and improved the use requirements [14]. The Tapio decoupling model's benefit is that it does not need to choose the base period when calculating, and it will not be limited by the statistical outline over the OECD decoupling model. It also has a complete decoupling indicator system. As a result, the Tapio decoupling model was implemented to examine Guangdong province's traffic decoupling situation.

The influential factors for the identification and decomposition of transport carbon emissions are useful for encouraging the implementation of related policies and specific measures for subsequent low-carbon transportation development. At present, most scholars combine STIRPAT models, Kaya constant equations, and their expansion forms using index decomposition methods or factor decomposition to decompose factors. Shahbaz et al. examined Pakistan through the application of the STIRPAT model, finding that energy use and urbanization are causally related in a one-way manner [15]. Wang et al. broke down the carbon emissions factors in Chinese passenger and cargo industries between 1990 and 2015 by using the LMDI [16]. Solaymani determined the primary causes that impact carbon emissions by applying the average Divisia index to use seven carbon dioxide emissions countries as a test case [17]. Mine and Kemal evaluated the variables that impact the carbon emissions from Turkish traffic in 2000–2017 and determined that the population and economic factors are the primary drivers [18]. Li et al. integrated the threshold effect model with the decoupling index to assess the transportation departments in 30 provinces in China from 2005 to 2019 [19]. Zhang et al. examined the variables driving urban carbon emissions using the LMDI, which verified that the positive drivers included population growth and GDP per capita, with energy intensity being a negative driver [20]. Lu et al. introduced risk factors into the auction mechanism to improve the higher utility [21]. In terms of decomposition and the influencing factors of traffic carbon emissions, most scholars therefore decompose the factors affecting traffic carbon emissions by index decomposition, factor decomposition, and other methods, combined with the STIRPAT model, Kaya identity, and their extended forms. The exponential decomposition method can only consider one absolute factor at most, which may lead to unrealistic decomposition results. Consequently, this paper uses the GDIM model to discover the variables contributing to Guangdong province's traffic carbon emissions.

Currently, the GDIM model is widely used in the manufacturing industry, manufacturing's high-emission subsectors [22], the construction industry [23], the mining sector [24], and other fields, and used less in the transportation industry. This paper uses the GDIM model to study the transportation industry, which not only helps to expand the application field of the model but also provides new ideas and methods for the sustainable development of the transportation industry. While previous studies mainly approached the issue from the aspects of energy, the economy, and a population change analysis of carbon emissions, Tang and Jiang introduced the urbanization effect, however passenger and freight turnover rarely factor into the influences of the transportation sector [25]. This paper introduces passenger and freight turnover as influencing factors, contributing to a more comprehensive understanding of the transportation industry's carbon decoupling target.

3. Methodology

3.1. Carbon Emissions Calculation

According to the "Publications 2006 IPCC Guidelines for National Greenhouse Gas Inventories", there are two methods to calculate carbon emissions, including the "up-bottom" approach based on traffic fuel consumption and the "bottom-up" approach centered around traffic mileage [26]. The essence of the "up-bottom" approach is an excellent method based on fuel consumption statistics, which can avoid the difficulty of obtaining data. Consequently, this paper uses the "up-bottom" approach to calculate Guangdong province's transport carbon emissions. The formula of the calculation is as follows:

$$C = \sum_{i=1}^{n} (E_i \times F_i) \tag{1}$$

$$F_i = N_i \times M_i \tag{2}$$

where C is traffic carbon emissions, i is a specific kind of energy, E_i is the entire transportation's class i usage of energy, F_i is the carbon emissions coefficient (ton carbon/ton) of sector i, N_i is the average lower heating value (TJ/10,000 tons), and M_i is the carbon emissions factor of sector i (ton carbon/TJ).

The calculation formula for the carbon emissions of electricity is as follows:

$$E = \sum_{i}^{n} A \times B \times J \tag{3}$$

where E is the amount of carbon dioxide produced by electricity, A is the amount of electricity used, B is the standard coal coefficient of converting power, and J is the carbon emissions coefficient of power.

Carbon emissions in transportation refer to the traffic energy consumption, warehousing, and postal industry. This paper mainly uses energy, including the eight categories of electricity, natural gas, liquefied petroleum gas, fuel oil, diesel, kerosene, gasoline, and raw coal.

3.2. Tapio Decoupling Model

Decoupling reveals the regional relation of carbon emissions to economic growth. The Tapio decoupling model was chosen because of its less limited base period and clear judgment criteria, which can eliminate errors due to the base selection. Therefore, this paper builds on the Tapio decoupling model, measuring Guangdong province's transportation decoupling index. The following is the computation procedure:

$$t = \frac{\%\Delta C}{\%\Delta G} = \frac{\Delta C/C}{\Delta G/G} \tag{4}$$

where t represents the decoupling elastic index of the gross value of transportation and carbon emissions, ΔC symbolizes the change in traffic carbon emissions, and ΔG represents the change in the total value of transportation. According to different elastic index values, the decoupling state is divided into eight types [8], as shown in Table 1.

Table 1. Decoupling state classification.

Decoupling State Classification	Decoupling State	△C/C	△G/G	Decoupling Elastic
Decoupling	weak decoupling	>0	>0	0 < t < 0.8
	strong decoupling	<0	>0	t < 0
	recessive decoupling	<0	<0	t > 1.2
Coupling	expansive coupling	>0	>0	0.8 < t < 1.2
	recessive coupling	<0	<0	0.8 < t < 1.2
Negative decoupling	weak negative decoupling	<0	<0	0 < t < 0.8
	strong negative decoupling	>0	<0	t < 0
	expansive negative decoupling	>0	>0	t > 1.2

3.3. The Generalized Divisia Index

Japanese scholar Yoichi Kaya proposed a model for the quantitative analysis of carbon dioxide emissions [27], which linked carbon emissions with the population, economy, energy, and other factors, called the Kaya identity, and the expression is as follows:

$$C = \frac{C}{E} \times \frac{E}{G} \times \frac{G}{P} \times P \tag{5}$$

where C is carbon emissions, E is energy consumption, C/E is the energy carbon emissions factor, G is the GDP in China, E/G is energy strength, G/P is the economy, and P is the population.

This paper expands the influencing factors of the Kaya constant equation and decomposes the variables. It also constructs a factor decomposition model for Guangdong province's traffic carbon emissions. According to the GDIM [28], the following is a description of carbon emissions and related variables, and the specific meaning can be obtained from Table 2:

$$C = \frac{C}{G} \times G = \frac{C}{E} \times E = \frac{C}{T} \times T \tag{6}$$

According to $\Phi(X) = 0$:

$$C = \frac{C}{G} \times G, \frac{C}{G} \times G - \frac{C}{E} \times E = 0, \frac{C}{G} \times G - \frac{T}{C} \times C = 0, T - \frac{T}{G} \times G = 0, E - \frac{E}{G} \times G = 0 \tag{7}$$

For convenience, eight factors in turn are replaced by $X_1, X_2, \ldots, X_8$:

$$C = X_1 \times X_2, X_1 \times X_2 - X_3 \times X_4 = 0, X_1 \times X_2 - X_5 \times X_6 = 0, X_5 - X_1 \times X_7 = 0, X_3 - X_1 \times X_8 = 0 \tag{8}$$

Table 2. The specific meaning of various factors.

Factor	Symbol	Name	Meaning
X_1	G	the added value of transportation	A standard for measuring the level of the transportation industry in a region
X_2	C/G	carbon emission intensity	The level of reflecting economic development, technological progress, and the efficiency of energy utilization
X_3	E	energy consumption	Considering how energy affects carbon emissions
X_4	C/E	carbon intensity from energy consumption	Considering how clean energy affects carbon emissions
X_5	T	turnover volume	The product of the tonnage of cargo or the number of passengers transported and the distance they traveled
X_6	C/T	carbon emission efficiency	Reflecting the low-carbon level of the transportation method
X_7	T/G	transportation intensity	Reflecting a high or low transportation efficiency
X_8	E/G	energy consumption intensity	Representing the reliance of economic growth on energy

The factor X is written as the function C(X), and a Jacobian matrix composed of the various factors is constructed based on the above equation Φ_X:

$$\Phi_X = \begin{pmatrix} X_2 & X_1 & -X_4 & -X_3 & 0 & 0 & 0 & 0 \\ X_2 & X_1 & 0 & 0 & -X_6 & -X_5 & 0 & 0 \\ -X_1 & 0 & 0 & 0 & 1 & 0 & -X_1 & 0 \\ -X_8 & 0 & 1 & 0 & 0 & 0 & 0 & -X_1 \end{pmatrix} \tag{9}$$

According to the principle of GDIM, ΔC is decomposed into the form of the contribution sum of each influencing factor:

$$\Delta C[X|\Phi] = \int_L \nabla C^T (I - \Phi_X \Phi_X^+) dX, \nabla C^T = (X2, X1, 0, 0, 0, 0, 0, 0)^T \tag{10}$$

For the absolute quantity factors X_1, X_3, and X_5, the exponential function is defined as follows:

$$Q(t) = (Q_1/Q_0)^t \tag{11}$$

4. Data and Results

4.1. Analysis of Carbon Emissions Results in Transportation

4.1.1. Data

The data are given in Tables 3 and 4, including the carbon emission coefficient, power conversion standard coal coefficient, and carbon emission coefficient of petrochemical energy:

Table 3. Net heating value, carbon content, and emission coefficient of various energy sources.

Energy Type	Raw Coal	Gasoline	Kerosene	Diesel Oil	Fuel Oil	Liquefied Petroleum Gas	Natural Gas
Net heating value/(TJ.(10^3 t)$^{-1}$)	20.9	44.3	43.8	43.0	40.4	47.3	44.2
Carbon content /t.(TJ)$^{-1}$	26.37	18.9	19.6	20.2	21.2	17.2	17.5
Carbon oxidation rate/%	0.94	0.98	0.98	0.98	0.98	0.98	0.99
Emission coefficient of unit energy CO_2/t.t^{-1}	1.9	2.925	3.017	3.096	3.171	3.101	2.667

Table 4. Electricity coal folding coefficient and carbon emission coefficient.

Energy	Conversion of the standard coal coefficient (kg equivalent of coal. (kW·h)$^{-1}$)	Carbon emission coefficient (carbon. (t equivalent of coal)$^{-1}$)
Electricity	0.1229	8.12

The carbon emission coefficient is calculated according to the average low calorific of various energy sources given in the China Energy Statistical Yearbook and the carbon emission factor in the IPCC [26]. To completely mitigate the epidemic's effect on traffic carbon emissions, the 2019 data were used to calculate the carbon emissions in 30 provinces and cities.

4.1.2. Results

The "top-down" method was adopted to calculate the carbon emissions of various provinces in China, and the results are shown in Figure 2 below. From the figure, it is obvious that the carbon emissions of the transportation industry in Guangdong province rank first, reaching 84.6457 million tons, about 48% more than those of Shanghai, which is located in second place. Guangdong province's total import and export of goods, passenger and freight traffic, turnover, etc. are ranked first in China, while development has produced more carbon emissions, so it is urgent to study the influencing factors of Guangdong province's traffic carbon emissions.

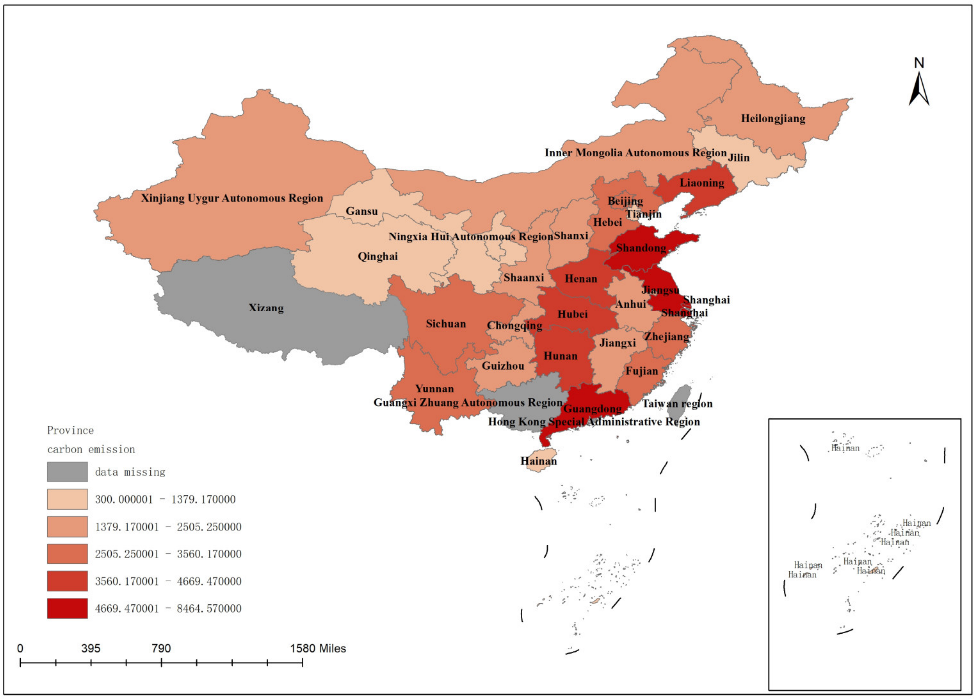

Figure 2. Carbon emissions of transport industry in China by province.

As a result, this paper uses the "up-bottom" method to calculate Guangdong province's carbon from 1999 to 2019, and Table 5 displays the outcomes. It is evident that Guangdong's traffic carbon emissions indicate a rising tendency. In 2003, the traffic carbon emissions increased significantly, mainly because the growth of port transportation demand this year increased the amount of water transportation, which led to the transportation's carbon emissions rising noticeably. In 2013, the traffic carbon emissions prematurely decreased first and then rose annually.

Table 5. Traffic carbon emissions in Guangdong province from 1999 to 2019.

Year	Carbon Emissions	Year	Carbon Emissions
1999	1787.91	2010	5815.64
2000	2057.68	2011	6063.79
2001	2254.24	2012	6346.04
2002	2457.78	2013	6157.36
2003	2940.33	2014	6446.25
2004	3422.06	2015	7044.92
2005	4066.47	2016	7562.99
2006	4192.19	2017	7827.27
2007	4635.13	2018	8111.29
2008	4990.32	2019	8464.57
2009	5267.83	—	—

4.2. Empirical Analysis of Carbon Emissions Decoupling Effects

On the basis of Guangdong province's economic development and carbon emission decoupling elastic index, the result is shown in Table 6, and the changing trend of the decoupling elastic index is shown in Figure 3.

Table 6. 1999–2019 Guangdong province's decoupling index and status judgment form.

Year	△C/C	△G/G	Decoupling Index	Decoupling Status
1999–2000	0.15	0.26	0.59	weak decoupling
2000–2001	0.10	0.22	0.43	weak decoupling
2001–2002	0.09	0.10	0.86	expansive negative decoupling
2002–2003	0.20	0.03	6.47	expansive negative decoupling
2003–2004	0.16	0.12	1.32	expansive negative decoupling
2004–2005	0.19	0.19	0.99	expansive coupling
2005–2006	0.03	0.16	0.19	weak decoupling
2006–2007	0.11	0.16	0.66	weak decoupling
2007–2008	0.08	0.14	0.55	weak decoupling
2008–2009	0.06	−0.04	−1.57	strong negative decoupling
2009–2010	0.10	0.12	0.84	expansive coupling
2010–2011	0.04	0.13	0.32	weak decoupling
2011–2012	0.05	0.11	0.42	weak decoupling
2012–2013	−0.03	0.06	−0.46	strong decoupling
2013–2014	0.05	0.11	0.42	weak decoupling
2014–2015	0.09	0.07	1.34	expansive negative decoupling
2015–2016	0.07	0.08	0.91	expansive coupling
2016–2017	0.03	0.10	0.35	weak decoupling
2017–2018	0.04	0.06	0.58	weak decoupling
2018–2019	0.04	0.09	0.50	weak decoupling

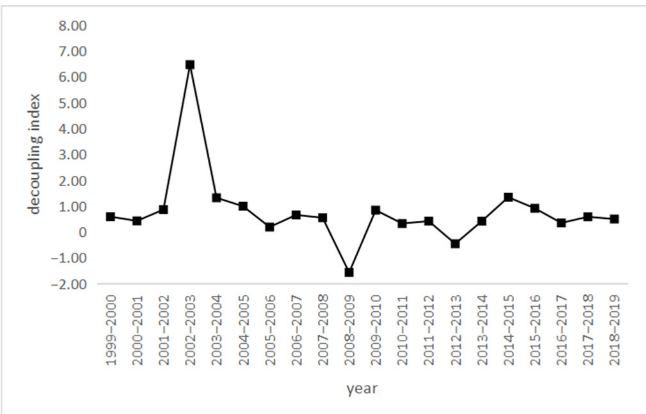

Figure 3. Guangdong province's transportation decoupling index change tracker.

From 1999 to 2005, Guangdong province's traffic decoupling status appeared as expansive coupling, expansive negative decoupling, and weak decoupling. The decoupling situation of the last few years is not optimal. In a great period of economic development, the quick expansion of various industries has increased the demand for logistics and transportation in Guangdong province. Moreover, because of the weakness of transportation infrastructure and the weak awareness of emissions reductions, it has caused a lot of consumption of transportation energy.

From 2006 to 2010, weak decoupling was the outstanding characteristic at this stage. During this period, the economy outpaced the rise in carbon emissions primarily because Guangdong attached great importance to infrastructure construction, forming a relatively complete comprehensive transportation system. Railway construction has achieved historic leaps, high-speed railway roads have considerably developed, and freight capacity has been considerably improved. In addition, Guangdong province has a lengthy coastal line on the coast. The rapid development of ports has led Guangdong's container throughput to increase to almost one-third of the country's.

From 2011 to 2014, the traffic carbon emissions growth rate during this period was lower than the rate of economic expansion, and Guangdong's economy was in a sustainable development state. Guangdong province attaches great importance to low-carbon development. Followed by Shenzhen in 2011, it was identified as a low-carbon transportation system construction pilot, and green transportation gradually entered into people's thoughts. In 2013, there was a state of strong decoupling, which is an ideal state. Guangdong province issued transportation energy conservation projects and kept pushing for energy saving, carrying out pilots, demonstration projects, and a transportation month and increasing the transportation of energy saving and technology applications, as well as creating and applying sustainable renewable energy, which has received excellent results.

From 2015 to 2019, there were three states where the traffic carbon emissions' decoupling state occurred, suggesting that it is still unstable. In 2015, the number of Guangdong civilian cars increased from 7.835 million in 2010 to 14.7233 million; by 2019, this had reached 23.2695 million vehicles, with an average growth rate of about 73%. With the swift expansion of the number of urban automobiles and the swift advancement of passenger transportation, freight business and the transportation industry's "carbon reduction" pressure is increasingly great; in the field of transportation, the situation is still grim.

On the whole, the economic development of China's transportation from 1999 to 2019 has not entirely rid itself from dependence on carbon emissions, and the environmental problems are still extremely serious. As China's economy continues to grow quickly, the road to low-carbon transformation is still lengthy. For this reason, it is essential to research the reasons that affect traffic carbon emissions.

4.3. Carbon Emissions' Influencing Factors Decomposition Results

4.3.1. Data

This paper selects the overall data on Guangdong's transportation from 1999 to 2019 as a research sample. Related data mainly come from the Chinese Energy Statistical Yearbook [29] and the Guangdong Statistical Yearbook [30,31].

In order to facilitate the calculations, the passenger turnover volume is converted into a freight turnover calculation through a certain transformation. The conversion coefficient is shown in Table 7 below:

Table 7. The conversion coefficient of each transportation method.

Transportation	Railway	Highway	Waterway	Aviation
conversion coefficient	1	0.2	0.3	0.83

4.3.2. Results

This paper breaks down the influential factors of the GDIM with R language. The contribution rate and contribution of different factors are presented in Tables 8 and 9.

Table 8. The influencing factors' contribution rate.

Year	G	C/G	E	C/E	T	C/T	T/G	E/G
2000	0.0854	−0.0298	0.0496	0.0000	0.0149	0.0363	−0.0049	−0.0007
2001	0.0739	−0.0369	0.0286	0.0027	0.0194	0.0123	−0.0028	−0.0017
2002	0.0353	−0.0045	0.0275	0.0025	0.0071	0.0233	−0.0010	0.0000
2003	0.0105	0.0565	0.0500	0.0162	0.0381	0.0274	−0.0007	−0.0018
2004	0.0418	0.0126	0.0519	0.0030	0.0485	0.0062	0.0000	−0.0001
2005	0.0640	−0.0005	0.0976	−0.0310	0.0002	0.0656	−0.0055	−0.0021
2006	0.0532	−0.0394	0.0097	0.0004	0.0228	−0.0130	−0.0008	−0.0021
2007	0.0534	−0.0168	0.0342	0.0007	0.0328	0.0021	−0.0004	−0.0003
2008	0.0467	−0.0192	0.0256	−0.0003	0.0075	0.0183	−0.0017	−0.0003
2009	−0.0119	0.0322	0.0170	0.0018	0.0270	−0.0076	−0.0020	−0.0009
2010	0.0405	−0.0063	0.0352	−0.0008	0.0623	−0.0263	−0.0007	−0.0001
2011	0.0424	−0.0275	0.0090	0.0052	0.0573	−0.0415	−0.0005	−0.0017
2012	0.0353	−0.0211	0.0124	0.0030	0.0970	−0.0726	−0.0061	−0.0014
2013	0.0205	−0.0309	−0.0099	0.0003	0.0617	−0.0663	−0.0032	−0.0020
2014	0.0363	−0.0211	0.0159	−0.0005	0.0678	−0.0490	−0.0017	−0.0009
2015	0.0236	0.0075	0.0321	−0.0008	−0.0053	0.0372	−0.0013	−0.0002
2016	0.0253	−0.0024	0.0221	0.0022	0.1351	−0.0906	−0.0178	−0.0002
2017	0.0321	−0.0212	0.0065	0.0052	0.0807	−0.0629	−0.0040	−0.0015
2018	0.0207	−0.0082	0.0080	0.0041	0.0083	0.0038	−0.0002	−0.0002
2019	0.0292	−0.0137	0.0063	0.0083	0.0087	0.0058	−0.0004	−0.0006

Table 9. The influencing factors' contribution.

Year	G	C/G	E	C/E	T	C/T	T/G	E/G
2000	152.68	−53.25	88.73	0.06	26.70	64.90	−8.72	−1.31
2001	152.03	−75.88	58.89	5.58	39.91	25.33	−5.77	−3.51
2002	79.57	138.94	122.80	39.91	93.72	67.43	−1.68	−4.42
2003	25.87	16.01	119.51	41.02	91.47	69.23	−1.31	−0.18
2004	122.92	36.98	152.53	8.80	142.71	18.22	−0.11	−0.32
2005	219.06	−1.54	333.89	−106.21	0.77	224.63	−18.93	−7.24
2006	216.24	−160.02	39.31	1.75	92.90	−52.99	−3.13	−8.34
2007	306.00	−141.68	142.11	3.12	136.25	9.09	−6.24	−5.68
2008	216.61	−88.97	118.62	−1.22	34.96	84.70	−8.05	−1.45
2009	−59.16	160.67	84.79	8.86	134.91	−38.00	−10.06	−4.50
2010	213.45	−32.95	185.55	−4.00	328.18	−138.31	−3.67	−0.45
2011	246.39	−160.08	52.49	30.04	333.51	−241.12	−2.98	−10.08
2012	214.19	−128.16	74.90	18.43	588.43	−440.40	−36.90	−8.23
2013	130.23	−196.00	−63.06	1.85	391.58	−420.75	−20.06	−12.47
2014	223.47	−129.63	97.67	−2.97	417.58	−301.61	−10.35	−5.26
2015	152.23	48.49	207.03	−5.13	−34.33	239.73	−8.09	−1.23
2016	177.92	−17.22	155.58	15.46	951.69	−638.25	−125.56	−1.54
2017	242.44	−160.28	49.20	39.24	610.52	−475.83	−29.96	−11.04
2018	162.37	−64.53	62.31	32.17	64.78	29.67	−1.31	−1.41
2019	237.24	−111.33	50.83	67.17	70.73	46.80	−3.45	−4.67

From the data in the table, carbon emissions have risen tremendously due to the production value of traffic (G). Although they have gradually decreased from the overall point of view, their contribution value is still increasing. Energy consumption (E) has an enhancive effect and is also at the forefront, and there is the overall presence of a rising first then moving downward trend. The turnover volume (T) promotes the increase in carbon emissions, with its impact gradually increasing first and then gradually weakening.

Moreover, the maximum value in 2016 reached 13.51%, mainly because the waterway freight remained rapidly developing in 2016, accounting for 22.7% of the total cargo volume and 82.4% of the cargo turnover.

In most cases, carbon emission intensity (C/G) has suppressed carbon emissions. Moreover, its degree of suppression is relatively large, indicating that the level of energy utilization has improved due to the ongoing advancements in technology development, thus playing an inhibitory role. The impact of carbon intensity from energy consumption (C/E) is mostly promoted, and the inhibitory effect is minor. The promotion and suppression effect of carbon emission efficiency (C/T) is equivalent, which shows that the low carbonization of energy in transportation is low.

Although the transportation intensity (T/G) and energy consumption intensity (E/G) have an inhibition effect, it was not more than 1%, and the inhibitory effect is weak. Therefore, transportation efficiency still needs to be continuously improved, and there should be a progressive reduction in the extent to which the economy depends on energy.

Divided from 1999 to 2019 into four sub-stages—from 1999 to 2004, 2004 to 2009, 2009 to 2014, and 2014 to 2019—the driving factor decomposition results were calculated, as shown in Figures 4 and 5.

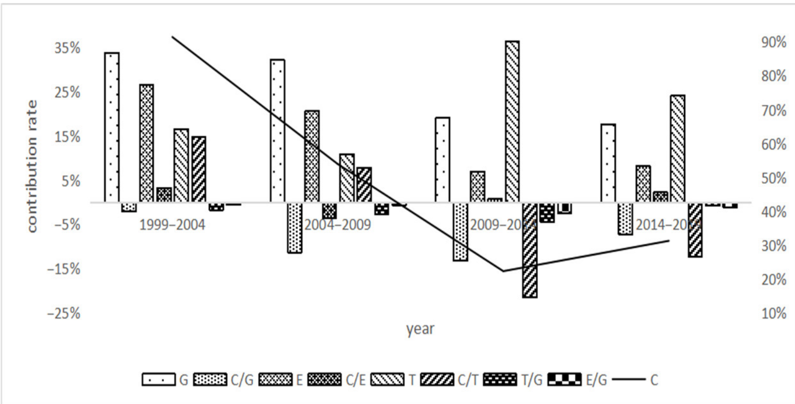

Figure 4. The various factors' contribution rates.

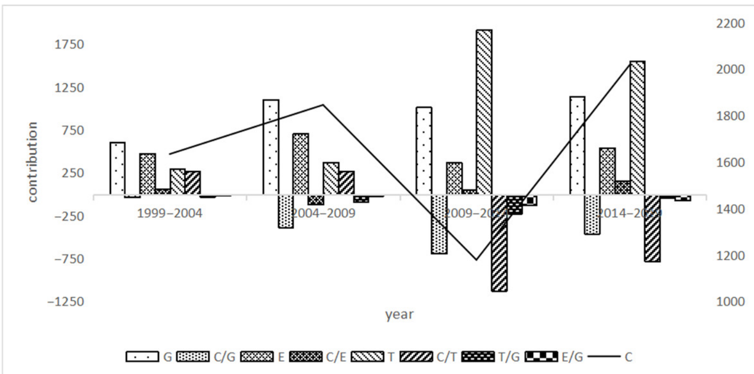

Figure 5. The various factors' contributions.

(1) The production value of traffic (G) is the end result of the production activities undertaken by the transportation industry throughout a specific time. It is evident that from 1999 to 2009, the effect of G was extremely obvious, and the contribution rate and contribution volume always ranked first. Owing to the national economy's explosive growth throughout this period, Guangdong province has also begun to attach importance to the transportation industry's development and investments. Various highways have been completed and used. Various transportation networks, such as railways, water transportation, civil aviation, and pipelines, are continuously improved. Motor vehicles

and transportation demands continue to increase, and numerous nonrenewable energies are consumed, resulting in increasing carbon emissions.

(2) Carbon emission intensity (C/G) is the economic output of the carbon emissions per unit. It continually acts as a brake on carbon emissions. In November 2010, Guangdong officially launched its national low-carbon provincial pilot work and established a number of programs and initiatives. In 2011, the low-carbon concept gradually permeated the transportation sector, from the construction of infrastructure to its promotion and application. It is clear that the contribution increased between 1999 and 2014. This suggests that the creation and efficient application of diverse low-carbon technologies during this period has improved the degree of low carbonization and the energy utilization efficiency of transportation. As a result, the suppression of the intensity of carbon emissions is relatively large. However, from 2014 to 2015, its contribution rate and contribution value decreased, indicating that the effect of carbon intensity gradually softened due to technical constraints. Between 1999 and 2019, energy consumption (E) made carbon emissions grow. The province was becoming less of an emitter of carbon from 26.6% to 8.4%, but the change in its contribution was relatively small. Between 1999–2004 and 2014–2019, carbon emissions increased less strongly than energy consumption, which shows that carbon emissions are still greatly influenced by energy consumption, and the reduction in its contribution rate is associated with other influencing factors. When other factors' contributions greatly increased, the energy consumption's contribution rate could decrease. As a result, the weakening of the positive driving effect cannot be explained only by the decrease in the contribution rate.

(3) Carbon intensity from energy consumption (C/E) has more of a promoting effect on carbon emissions than an inhibitory effect. It hardly slowed the increase in carbon emissions in 2004–2009, and its contribution rate accounts for only 3.45%, so the inhibitory effect is relatively minor. During this period, clean energy in Guangdong received unprecedented attention and development. Not only did it pay great attention to developing renewable energy sources, such as wind and water, but it also actively promoted pilot projects of solar energy and biomass energy utilization, so that the carbon intensity from energy consumption played a certain inhibitory role. Its facilitative role in 1999–2004 was due to the weak low-carbon awareness and underdeveloped technology at that time. Although its facilitative role was weak, the C/E transitioned from inhibition in 2004–2009 to growth in 2009–2019. This shows that, in the previous period, Guangdong province optimized the energy structure successfully, but the energy consumption structure is irrational in later periods, with unstable low-carbon degrees of energy and minor amounts of clean energy.

(4) Turnover volume (T) is the product of the tonnage of goods or the actual number of passengers and its transport distance, which increases carbon emissions. Its contribution rate and contribution volume first increased and then decreased, reaching a maximum of 36.41% and 19,181,010 tonnes in 2009–2014. This is a result of the increased demand for water transport during this period, with turnover increasing from 29,937.94 billion tonnes-km to 11,407.8 billion tonnes-km, resulting in a sudden increase in its contribution to carbon emissions. As a result of advancements in social and economic growth, as well as higher income levels among individuals and the rise in logistics and tourism, the demand for transportation in all walks of life was increasing. From 1999 to 2019, passenger and cargo turnover in Guangdong's rail, air, highways, and waterways increased substantially. Its impact on carbon emissions also continued to grow, and it has grown to become a significant driver of the rise in transport carbon emissions.

(5) There is less of a facilitative role due to carbon emission efficiency (C/T) on carbon emissions, which has gradually changed to being an inhibitory effect. Its contribution rate reduced from 14.9% to −12.2%, and the contribution value reduced from 18.4578 million tons to −7.867 million tons. From being the factor promoting carbon emissions' growth

to the primary obstacle, it is indicated that the increasing efficiency of carbon emissions suppresses carbon emissions. From 2009 to 2014, the greatest inhibition of carbon emission efficiency was 21.38%. Along with the development and promotion of shared bikes, Guangdong province has been trying to innovate and apply energy-saving technologies, promote current energy vehicles, strengthen public transportation, and speed up the development of a comprehensive three-dimensional transport network. Guangdong has actively developed various forms of transportation methods and increased the proportion of rail and waterways in integrated transportation, making efficiency in carbon emissions the main restraining factor.

(6) During 1999–2019, the rise in carbon emissions was restrained by transportation intensity (T/G). Transportation intensity is the ratio of transport turnover volume to the production value of traffic in a certain period of time, and low transport intensity represents an elevated transport efficiency. The contribution rate of transportation intensity is maintained at around -1% most of the time, and the overall inhibitory effect is weak. Its contribution rate reached a maximum of 5 percent from 2009 to 2014, indicating that Guangdong has strengthened its transportation infrastructure, developed advanced technological equipment, and changed its transportation structure to make it more efficient, so the inhibitory effect has become stronger. Although transportation intensity has a restraining effect, its inhibitory effect is relatively low compared with the influencing factors of promoting the growth effect, so it is still necessary to continuously improve transportation efficiency to enhance the inhibitory effect.

(7) Energy consumption intensity (E/G) influences carbon emissions in a positive way. From 1999 to 2019, energy consumption intensity prevented carbon emissions from rising, but the overall inhibitory effect was relatively tiny. Its contribution rate gradually increased to 2.22% from 2009 to 2014. During this period, the energy consumption intensity's inhibitory effect became more pronounced with Guangdong province's increased percentage of renewable energy sources. During 2014–2019, its contribution rate decreased to 0.64%; although it has a certain inhibitory effect, it is weak. Transportation development's dependence on energy is still large, and the growth of it will inevitably lead to increased energy use. There is still a need to build up the quantity of technological advancement and the implementation of clean energy.

To more accurately depict every variable's dynamic influence from 1999 to 2019, this paper adds up the contribution rate and contribution value of each factor from 1999 to calculate the cumulative contribution. In Figures 6 and 7, we can see that cumulative traffic carbon emissions rose by 69.56 million tons from 1999 to 2019. The production value of traffic (G) was a significant positive contributor. Because of the increase from 1,526,800 tons in 2000 to 2,372,400 tons in 2019, the cumulative contribution rate to the increase in carbon emissions was 75.83%. One of the key elements contributing to the rise in carbon emissions was turnover volume (T), and its contribution increased and increased dramatically, due to the increase in water transport turnover volume in 2016. From 1999 to 2019, the turnover volume increased by 45.1696 million tons of carbon emissions, and the final contribution rate reached 79.21% and exceeded the production value of traffic. After 2005, the effect of energy consumption (E) gradually became apparent, but its growth was gradual, with a 21.3365 million ton increase in total by 2019. Carbon intensity from energy consumption (C/E) also promoted carbon emissions, but the effect was tiny and less obvious, with only 1,939,500 tons by 2019.

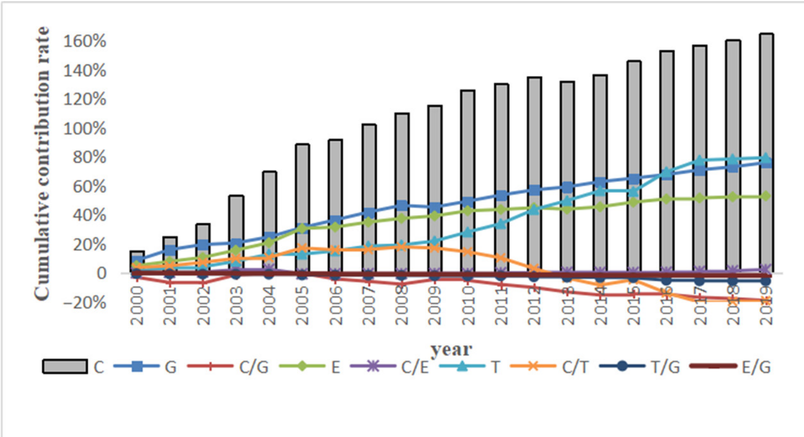

Figure 6. Cumulative contribution rate amount of each influencing factor.

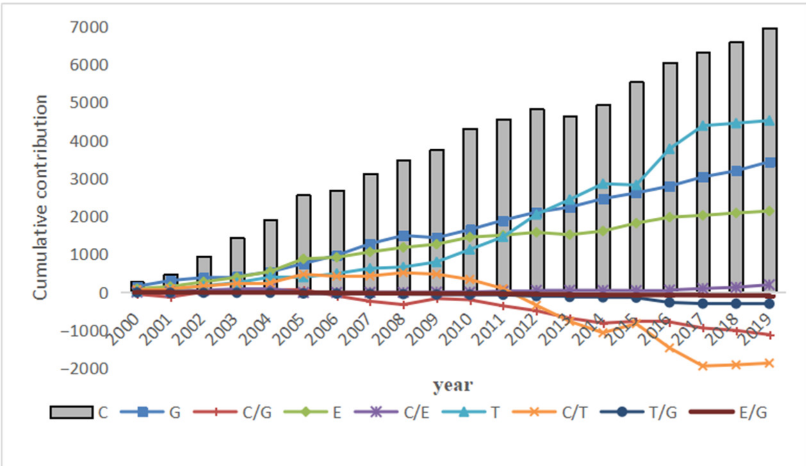

Figure 7. Cumulative contribution amount of each influencing factor.

Carbon emission intensity (C/G) and carbon emission efficiency (C/T) are the principal inhibitors, preventing an increase of 11.2044 million tons and 18.6751 million tons, respectively. However, both factors are not stable and occasionally promote carbon emissions. Carbon emission efficiency's promoting effect was slowly weakened in 1999–2011, then changed to an inhibitory effect in 2012, and gradually became an essential factor to restrain carbon emissions. The role that carbon emission intensity (C/G) inhibits is relatively tiny. There has been a gradual increase in inhibitory effects since 2011, but development has been limited. Energy consumption intensity (E/G) and transportation intensity (T/G) have relatively weak effects on carbon emissions. By 2019, carbon emissions were reduced by 933,300 tons and 3.0634 million tons, respectively. According to the needs of the "double-carbon" target, starting from the present situation and the development tendency of the transport industry, the carbon emission reduction policy of transportation should be implemented mainly by enhancing the energy economy and supporting the clean energy system.

5. Conclusions and Recommendations

5.1. Conclusions

This paper explores the traffic carbon emission's decoupling state in Guangdong province from 1999 to 2019 by using the Tapio decoupling index model. In conclusion, the decoupling state is poor, and low-carbon transformation still faces great challenges and needs long-term and arduous efforts.

(1) Through the breakdown of the contributing elements that can be obtained, one of the main causes of the rise in carbon emissions in the early stages was the production value of traffic, and its promoting effect was first enhanced and then weakened. In 2005, energy consumption's influence ranked top and then gradually weakened. However, turnover volume's steadily increasing effect grew year by year and gradually became the biggest factor. Although the carbon emission efficiency and energy consumption intensity showed an inhibitory effect for several years, they changed into a positive impact later on, indicating that the low-energy carbon degree of transportation is not stable enough and should be continuously strengthened.

(2) Among the inhibitory factors, the role of carbon emission intensity is relatively obvious. However, its inhibitory effect is unstable, which may be the bottleneck in technical aspects. Although energy consumption intensity and transportation intensity play an inhibitory role, their role is weak, indicating that the current transportation efficiency and energy structure cannot effectively inhibit carbon emissions and needs to be further improved.

5.2. Recommendations

(1) Rely on science and technology. Guangdong province should actively pursue innovation and research, as well as the promotion of cutting-edge technologies. Because of the marginal suppression of energy consumption and transportation intensity, it should give full play to its own technical advantages and talent advantages, aggressively advance environmentally friendly technologies, and enhance energy effectiveness. It is imperative to hasten clean energy technology's adoption and improve its use efficiency to promote clean production and the clean cycle of fossil energy. This can be achieved through developing energy-saving technology and innovating, introducing talents related to low-carbon transportation technology, and establishing professional talent teams. Intelligent and information management methods should be used to alleviate traffic congestion and to improve urban traffic efficiency and the degree of interconnection of highways, railways, and waterways, thereby reducing the operation time of transportation equipment. Additionally, high-performance battery technology could be developed to improve the energy density and life cycle of batteries and to reduce their cost. The research and development of battery systems for electric vehicles and hydrogen vehicles could also be promoted to improve the energy conversion efficiency and durability of batteries. Integration technology of solar and wind energy in transportation infrastructure should be strengthened to reduce the dependence on traditional energy sources. Carbon capture and sequestration technology could be developed to capture, compress, transport, and sequester the carbon dioxide generated in the transportation sector, thereby reducing carbon emissions.

(2) Accelerate the use of renewable energy. The installation of solar panels at transportation hubs, depots, and along major highways to harness solar energy for operational needs should be encouraged. There should also be the active development and use of biomass for the production of transport equipment, the strengthening of the management of transportation equipment and facilities, and the stimulation of the adoption of hybrid transportation equipment. Pilot projects showcasing the benefits of hybrid and electric transportation equipment should be developed and promoted. Charging infrastructure for electric vehicles and hydrogen fueling stations to facilitate the transition should be expanded, and the usage of clean energy vehicles to decrease fuel-powered vehicles should be aggressively encouraged, along with promoting the use of electricity-, hydrogen fuel-, and liquefied natural gas-powered heavy freight vehicles; improving the level of transport's own emissions technology; and implementing continuous control to reduce energy consumption.

(3) Optimize the transportation structure, promotion of transformation, and upgrading. There should be the improvement of the transportation structure, the optimization of urban transportation networks, and a decrease in freight turnover. Logistics hubs and

distribution centers that are strategically located to minimize transportation distances should be developed. Public transport and rail transit should be vigorously developed, along with promoting green low-carbon travel methods and raising the percentage of urban public transit, while gradually lowering the percentage of private vehicles. The development of multi-modal transport such as "railway to rail" and "railway to water could be promoted. The integration and development of green travel methods, such as rail, bus, and slow travel should be vigorously promoted, along with strengthening the construction of comprehensive transportation hubs and transportation facilities, optimizing the layout of the urban public transport line network, and promoting the coordinated development of various transportation methods. Various passenger and freight organizations should be optimized to reduce the empty load rate of each passenger transport. Partnerships between freight companies to share vehicles and reduce empty trips could be developed. The use of technology, such as load matching platforms, should be encouraged to improve the utilization of transportation assets.

(4) Increase policy support. A mechanism for rewarding energy conservation could be created. Special funds could be established, and there could be an increase in investment in research, developing improved techniques and new energy sources. The city's vehicles could be guided and encouraged to use fresh energy, replacing fuel vehicles with fresh energy vehicles, actively promoting green and low-carbon technologies, improving policies and measures, and promoting the application of new energy vehicles. For instance, a points-based system could be introduced where individuals and businesses would earn points for reducing energy consumption, which could be redeemed for various benefits such as discounts, vouchers, or even cash incentives. Green travel should be advocated, including advocating for the public to implement the concept of green travel, forming a good social style of low-carbon travel, and cultivating the public's low-carbon travel awareness. People should be guided towards using sustainable modes of transportation such as walking, cycling, and public buses. Infrastructure could be improved to make these options more convenient and appealing, such as building more bike lanes, pedestrian pathways, and efficient public transit systems.

Author Contributions: Conceptualization, Shiying Zhang; methodology, Shiying Zhang, Hualing Bi, and Fuqiang Lu; software, Shiying Zhang; validation, Shiying Zhang; formal analysis, Shiying Zhang; investigation, Shiying Zhang; resources, Shiying Zhang; data curation, Shiying Zhang; writing—original draft preparation, Shiying Zhang; writing—review and editing, Hualing Bi and Fuqiang Lu; visualization, Shiying Zhang; supervision, Hualing Bi and Fuqiang Lu; project administration, Hualing Bi and Fuqiang Lu; and funding acquisition, Hualing Bi and Fuqiang Lu. All authors have read and agreed to the published version of the manuscript.

Funding: This work is supported by the National Key R&D Program of China under grant no. 2020YFB1712802; the Research Program of Social Science of Qinhuangdao under grant no. 2024LX026; the Science and Technology Research and Development Plan Project of Qinhuangdao under grant no. 202401A143; the Key Applied Research Program of Social Science of Qinhuangdao under grant no. 2023LX044; and the Teaching Research and Reform Cultivation Project of Yanshan University under grant no. 2023XJJG084.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments: The authors would like to gratefully acknowledge the anonymous reviewers and the members of the editorial team who helped to improve this paper through their thorough review.

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

References

1. Marten, O.; Stef, P. Cost-effective reduction of fossil energy use in the European transport sector: An assessment of the Fit for 55 Package. *Energy Policy* **2022**, *168*, 113085.
2. Jessica, S.; Beatrice, G. Forest protection in the EU's renewable energy directive and nature conservation legislation in light of the climate and biodiversity crisis—Identifying legal shortcomings and solutions. *For. Policy Econ.* **2023**, *153*, 102996.

3. Daniel, S.; Aoife, H.; Manan, S.; Sushanth, B.; Ben, J.; Manish, D.; Ryan, S.; Yann, G.; Arild, G. Comparative review of international approaches to net-zero buildings: Knowledge-sharing initiative to develop design strategies for greenhouse gas emissions reduction. *Energy Sustain. Dev.* **2020**, *71*, 291–306.
4. Erin, M.; Jesse, J.; Eric, L.; Chris, G. Labor pathways to achieve net-zero emissions in the United States by mid-century. *Energy Policy* **2023**, *177*, 113516.
5. Hiroshi, O.; Brendan, F.D. Barrett Politics of climate change and energy policy in Japan: Is green transformation likely? *Earth Syst. Gov.* **2023**, *17*, 100187.
6. Xu, G.; Wang, Y.; Rehman, H. The future trajectory of carbon emissions in the process of carbon neutrality in South Korea. *J. Environ. Manag.* **2023**, *345*, 118588. [CrossRef] [PubMed]
7. Liu, Z.; Sun, T.; Yu, Y.; Ke, P.; Deng, Z.; Lu, C.; Huo, D.; Ding, X. Near-Real-Time Carbon Emission Accounting Technology Toward Carbon Neutrality. *Engineering* **2022**, *14*, 44–51. [CrossRef]
8. Tapio, P. Towards a theory of decoupling: Degrees of decoupling in the EU and the case of road traffic in Finland between 1970 and 2001. *Transp. Policy* **2005**, *12*, 137–151. [CrossRef]
9. Wang, Q.; Zhang, F. The effects of trade openness on decoupling carbon emissions from economic growth—Evidence from 182 countries. *J. Clean. Prod.* **2021**, *279*, 123838. [CrossRef]
10. Wang, J.; Jiang, Q.; Dong, X.; Dong, K. Decoupling and decomposition analysis of investments and CO_2 emissions in information and communication technology sector. *Appl. Energy* **2021**, *302*, 117618. [CrossRef]
11. Shi, B.; Xiang, W.; Bai, X.; Wang, Y.; Geng, G.; Zheng, J. District level decoupling analysis of energy-related carbon dioxide emissions from economic growth in Beijing, China. *Energy Rep.* **2022**, *8*, 2045–2051. [CrossRef]
12. Kouyakhi, N.R. CO_2 emissions in the Middle East: Decoupling and decomposition analysis of carbon emissions, and projection of its future trajectory. *Sci. Total Environ.* **2022**, *845*, 157182. [CrossRef]
13. Zhao, Y.; Su, Q.; Li, B.; Zhang, Y.; Wang, X.; Zhao, H.; Guo, S. Have those countries declaring "zero carbon" or "carbon neutral" climate goals achieved carbon emissions-economic growth decoupling? *J. Clean. Prod.* **2022**, *363*, 132450. [CrossRef]
14. Lu, F.; Wang, L.; Bi, H.; Du, Z.; Wang, S. An Improved Revenue Distribution Model for Logistics Service Supply Chain Considering Fairness Preference. *Sustainability* **2021**, *13*, 6711. [CrossRef]
15. Shahbaz, M.; Chaudhary, A.; Ozturk, I. Does urbanization cause increasing energy demand in Pakistan? Empirical evidence from STIRPAT model. *Energy* **2017**, *122*, 83–93. [CrossRef]
16. Wang, B.; Sun, Y.; Chen, Q.; Wang, Z. Determinants analysis of carbon dioxide emissions in passenger and freight transportation sectors in China. *Struct. Chang. Econ. Dyn.* **2018**, *47*, 127–132. [CrossRef]
17. Solaymani, S. CO_2 emissions patterns in 7 top carbon emitter economies: The case of transport sector. *Energy* **2018**, *168*, 989–1001. [CrossRef]
18. Isik, M.; Ari, I.; Sarica, K. Challenges in the CO_2 emissions of the Turkish power sector: Evidence from a two-level decomposition approach. *Util. Policy* **2021**, *70*, 101227. [CrossRef]
19. Li, R.; Li, L.; Wang, Q. The impact of energy efficiency on carbon emissions: Evidence from the transportation sector in Chinese 30 provinces. *Sustain. Cities Soc.* **2022**, *82*, 103880. [CrossRef]
20. Zhang, Y.; Zhang, Y.; Zhang, Y.; Gong, C.; Kong, Y. Analysis of the carbon emission driving factors and prediction of a carbon peak scenario—A case study of Xi'an city. *Heliyon* **2022**, *8*, e11753. [CrossRef]
21. Lu, F.; Hu, Y.; Bi, H.; Feng, W.; Wang, S.; Zhang, X. A Two-Stage Auction Mechanism for 3PL Supplier Selection under Risk Aversion. *Sustainability* **2021**, *13*, 9745. [CrossRef]
22. Liu, J.; Yang, Q.; Ou, S.; Liu, J. Factor decomposition and the decoupling effect of carbon emissions in China's manufacturing high-emission subsectors. *Energy* **2022**, *248*, 123568.
23. Liu, Y.; Gan, L.; Cai, W.; Li, R. Decomposition and decoupling analysis of carbon emissions in China's construction industry using the generalized Divisia index method. *Environ. Impact Assess. Rev.* **2024**, *104*, 107321.
24. Shao, S.; Liu, J.; Geng, Y.; Miao, Z.; Yang, Y. Uncovering driving factors of carbon emissions from China's mining sector. *Appl. Energy* **2016**, *166*, 220–238. [CrossRef]
25. Tang, Y.; Jiang, H. Analysis of the decoupling effect and driving factors of carbon emissions from the transportation sector in Guangdong Province. *Sci. Rep.* **2023**, *13*, 18744. [CrossRef]
26. Intergovernmental Panel on Climate Change (IPCC). 2006 IPCC Guidelines for National Greenhouse Gas Inventories. 2006. Available online: https://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html (accessed on 1 May 2023).
27. Kaya, Y.; Yokobori, K. *Environment, Energy, and Economy: Strategies for Sustainability*; United Nations University Press: Tokyo, Japan, 1997.
28. Vaninsky, A. Factorial decomposition of CO_2 emissions: A generalized Divisia index approach. *Energy* **2014**, *45*, 389–400. [CrossRef]
29. National Bureau of Statistics of China. *China Energy Statistical Yearbook*; China Statistics Press: Beijing, China, 2000–2022.
30. Guangdong Provincial Bureau of Statistics, National Bureau of Statistics, Guangdong Survey Team. *Guangdong Statistical Yearbook*; China Statistics Press: Beijing, China, 2022.
31. Lu, F.; Hao, H.; Bi, H. Evaluation on the development of urban low-carbon passenger transportation structure in Tianjin. *Res. Transp. Bus. Manag.* **2024**, *55*, 101142.