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Decomposition Analysis of Energy-Related CO_2 Emissions and Decoupling Status in China's Logistics Industry

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Received: 26 March 2018; Accepted: 19 April 2018; Published: 25 April 2018

Abstract: The logistics industry is one of the major fossil energy consumers and CO_2 emitters in China, which plays an important role in achieving sustainable development as well as China's emission reduction targets. To identify the key influencing factors regarding the logistics of CO_2 reductions and ensure that the development of China's logistics industry becomes less dependent on CO_2 emissions, this paper built an extended log-mean Divisia index model (LMDI) to decompose the logistics of CO_2 changes between 1985 and 2015. Then, we introduced a decoupling model that combined the decomposition results to analyze the decoupling state and identify the main factors that influenced the decoupling relationship. The results show the following. (1) The urbanization effect was the decisive factor in CO_2 emissions increases, followed by structural adjustment effects, while technological progress effects played a major role in inhibiting CO_2 emissions. Particularly, the energy structure showed great potential for CO_2 emissions reduction in China. (2) Highways appeared to have dominant promoting roles in increasing CO_2 emissions regarding transportation structure effects; highways and aviation proved to have the largest impact on CO_2 emission reduction. (3) There has been an increase in the number of expansive negative decoupling states between 2005 and 2015, which implies that the development of the logistics industry has become more dependent on CO_2 emissions. Finally, this paper puts forward some policy implications for CO_2 emission reductions in China's logistics industry.

Keywords: energy-related CO_2 emissions; extended LMDI model; decoupling analysis; logistics industry

1. Introduction

Climate change has posed a severe threat to the sustainable development of human society, the economy, and the environment [1]. The greenhouse gases (GHG) produced by burning fossil fuels has been proven to be one of the leading cause of global warming [2]. In particular, energy-related CO_2 emissions, which are an essential environmental pollutant, has greatly contributed to global climate change [3]. CO_2 emissions may have triggered a chain reaction for some natural disasters, such as certain glacier melting, sea level rise, and extreme climate. Since its reform and opening up, China's economy has experienced spectacular growth, which has been accompanied by a substantial increase in energy consumption as well as CO_2 emissions. In 2006, China's carbon dioxide emissions exceeded the United States', and it became the largest carbon dioxide emitter in the world. Moreover, its external dependence on net imports of oil increased from 7.5% in 1993 to 64.4% in 2016, which seriously endangered China's energy security. In order to cope with the challenges posed by the rising greenhouse gas emissions, the Chinese government promised a target to the world in 2015 at the Paris Climate Change Conference that by 2030, China's CO_2 emission per unit of gross domestic product (GDP) would drop by 60–65% compared with 2005, and that total CO_2 emissions have reached their peak.

Logistics is a primary industry that supports the development of China's economy, and should be given priority to develop. However, alongside the process of industrialization and urbanization in China, the demand for logistics services has continuously increased, which has made the logistics industry the second largest oil consumption sector, with the highest CO_2 emissions growth rate. In 2014, the consumption of gasoline, diesel, and fuel oil in the logistics industry respectively accounted for 47.72%, 94.89%, and 64.33% of the total gasoline, diesel, and fuel oil consumption in China, which would undoubtedly pose a more significant threat to the sustainable development of China's society, economy, and environment.

In order to achieve nationally determined contribution targets and sustainable development in China, the logistics industry should assume a critical responsibility for energy saving and emission reduction [4]. Identifying the determinants of CO_2 emissions and coordinating the contradiction between the logistics industry development and CO_2 emission reduction are essential ways to achieve the emission reduction targets and sustainable development. The growth of logistics output is often accompanied by a series of dynamic adjustments, such as the improvement of energy utilization efficiency, the advancement of equipment technology levels, and the maturity of the carbon market. It indicates that the relationship between the logistics development and CO_2 emissions has space to adjust, and the contradiction between the two is not irreconcilable. Therefore, in order to ensure the development of China's logistics industry while achieving the mitigation of logistics CO_2 emissions, the purposes of this paper are to solve the following questions: (1) What are the key factors affecting CO_2 emissions in the logistics industry? (2) Does the increasing output of the logistics industry become less dependent on energy consumption and CO_2 emissions? If not, what is the dynamic relationship between the development of the logistics industry and its CO_2 emissions? (3) How can policy be used to make logistics development less dependent on CO_2 emissions?

Since the reform and opening up of China, urbanization has developed rapidly. The urbanization rate increased from 17.9% in 1978 to 57.35% in 2016, which in turn has had a meaningful impact on CO_2 emissions in the logistics industry [5,6]. On the one hand, urbanization leads to the concentration of the population in urban areas and industrial agglomeration, which promotes the achievement of scale effects in logistics operation and the reduction of logistics CO_2 emissions. Meanwhile, the scale development of the logistics enterprises (e.g., the alliance of small and medium logistics enterprises, and the construction of logistics parks) caused by the urbanization are beneficial for accelerating the unification of the standards of logistics equipment and exerting knowledge spillover effects, which improves fuel efficiency. On the other hand, urbanization brings about the expansion of urban areas and the spatial separation of the residence and workplaces, which increases transportation distance and leads to traffic congestion. Moreover, the expansion results in an increase in the distance between production and marketing, which consequently promotes CO_2 emissions in the logistics industry. Therefore, urbanization has influenced CO_2 emissions complexity in both positive and negative ways. Simultaneously, the decomposition of the impacts of urbanization on logistics CO_2 emissions is conducive to clarifying the influencing mechanism and identifying the dominant influencing factors for CO_2 emissions.

Domestic and overseas scholars mainly utilized an econometric approach and decomposition model to reveal CO_2 changes and investigate the underlying factors of logistics CO_2 emissions. The econometric approach mainly includes multiple regression analysis (e.g., Stochastic Impacts by Regression on Population, Affluence, and Technology model (STIRPAT), ridge regression), spatial panel data models (e.g., spatial Durbin model, spatial error model, and geographical weighted regression). For example, Du et al. [7] investigated spatial clustering characteristics and the influencing factors of carbon emission intensity in China's province-level construction industry by utilizing Moran's I and geographical weighted regression. Wang et al. [8] proposed an extended STIRPAT model to examine the determinants of energy-related CO_2 emissions in Xinjiang by analyzing the effect of population scale, urbanization, technical progress, and industrial structure. The paper mainly focused on three periods, namely, before China's reform and opening up (1954–1977), after China's reform and opening up (1978–2000), and the western development period (2001–2014).

The decomposition model is also a conventional method to analyze the dominating factors of carbon emissions. There are two major categories of the primary decomposition models: the structural decomposition analysis (SDA) and the index decomposition analysis (IDA). The SDA model is based on the input–output table, and has a higher requirement for data compared with index decomposition analysis (IDA) [1,9–11]. Mi et al. [9] employed the SDA model to analyze the major contributors to China's carbon emission growth, and argued that the global financial crisis has influenced the driving forces of carbon emission in China. Malik et al. [11] decomposed the change in CO_2 emissions into six determinants based on a global input–output database, and indicated that affluence and population growth were significant determinants. The IDA approach includes the Laspeyres decomposition method and the Divisia index decomposition method; the Divisia index decomposition method contains the log-mean Divisia index (LMDI) and the arithmetic mean Divisia index (AMDI). The LMDI is simple to operate, and fully quantifies the contribution of potential influencing factors to carbon emission change over time. Compared to the traditional Laspeyres index decomposition method, the LMDI can realize complete decomposition of no residuals. Compared to the arithmetic mean Divisia index (AMDI), it can handle zero-value problems that may occur in eight cases [12–14]. Therefore, the LMDI is widely used and considered to be the preferred method [13]. Ang et al. [13] compared diverse index decomposition analysis approaches, and pointed out that the LMDI method is the "best" decomposition method. Zhang et al. [15] adopted the LMDI to analyze the influencing factors of carbon emissions and carbon emission intensity in China from the perspective of energy and industrial structures. The results showed that the economic growth and production activities of the secondary industry are the main driving factors for the growth of carbon emissions. Akbostancı et al. [16] decomposed the CO_2 emissions of the manufacturing industry covering 57 sub-industries in Turkey into five parts, e.g., industrial activity, activity structure, sectoral energy intensity, and sectoral energy mix. It was found that industrial activity and energy intensity are the main factors determining the changes in CO_2 emissions. Moreover, some scholars have decomposed the energy and carbon emissions in the transportation industry. Mraihi et al. [17] used the LMDI decomposition method to analyze the impacts of the fuel efficiency of road vehicles, vehicle intensity, economic growth, and urbanization on road transport-related energy consumption in Tunisia. The results indicated that the fuel efficiency of road vehicles and vehicle intensity are the main inhibiting factors of energy consumption growth. Zhu et al. [18] decomposed the carbon emissions from the transport sector in the Beijing–Tianjin–Hebei region by employing the modified LMDI approach, and pointed out that energy structure and energy intensity played negative roles regarding increases in CO_2 emissions. A few studies focused on an analysis of the influencing factors of the CO_2 emissions of the logistics industry. For example, Dai and Gao [19] analyzed the critical factors of energy consumption from China's logistics industry, and found that logistics activities and freight transport intensity have promoted the increase of the logistics industry' energy consumption. As for the transportation links of the logistics industry, Bauer et al. [20] introduced an integer program model for transportation planning to minimize the carbon emissions from freight transportation activities.

The relationship between economic growth and CO_2 emissions is an essential issue that we face in the 21st century, and it is of wide concern to scholars worldwide. Research on the relationship between energy consumption/CO_2 emissions and economic growth is usually carried out from the following four aspects. The first is generally applying Kuznets curve theory to study the fluctuation of energy consumption in relation to economic growth [21,22]. The second involves adopting Granger causality analysis and a cointegration test to investigate the causality of energy consumption and economic growth [23–25]. Bloch et al. [24] examined the relationship between coal consumption and economic growth in China from the perspective of both the supply and demand sides, and argued that there is a unidirectional causality between coal consumption and income both in the short and long run. The third aspect involves employing the OECD decoupling index and elastic decoupling model to analyze the dependence of economic growth on energy consumption [18,26,27]. Tapio [27] put forward a new theoretical framework for decoupling, and further broke the decoupling index down into eight kinds of decoupling states in order to investigate the decoupling relationship between GDP, traffic volumes, and CO_2 emissions of the transport sector in the EU15 countries between 1970 and 2001. Finally, the vector autoregressive model can be used to analyze the long-term dynamic relationship between the output and carbon emissions [28]. Among these methods, the elastic decoupling model can quantitatively analyze the dependence of economic growth on energy year by year, and has an important advantage in measuring the relationship [27].

Existing research has made some achievements in studying the determinants of CO_2 emissions and the relationship between economic growth and carbon emissions, but there are still some deficiencies. Firstly, there has been little research on CO_2 emissions in the logistics industry [19,29]. The existing research about the sector level mainly focuses on the low-carbon development of the secondary industry and the construction industry. Although some scholars have been devoted to investigating the carbon emission reductions of an individual link of the logistics process [16], achieving carbon emission reduction in a single link does not mean achieving the minimization of carbon emissions in the whole logistics industry, because there is a "trade-off" phenomenon in the logistics sector [19,29–31]. Secondly, the traditional LMDI model based on Kaya identities was adopted to analyze the dominating factors of CO_2 emissions through examining the factors of economic growth, technical progress, and population size [16,17,19,32]. There are still few observations at present taking into account urbanization effects as influencing factors when analyzing the impacts on logistics CO_2 emissions. However, with the rapid progress of urbanization in China, urbanization is bound to have a significant and complicated effect on carbon emission changes in the logistics industry. Thirdly, previous studies that examined the determinants of logistics CO_2 emissions were mostly from the macroscopic perspective, which lacks analysis regarding the impacts of freight transportation modes (i.e., highways, railways, waterways, and aviation) on CO_2 emissions. It is not conducive to analyzing the emission reduction potential and formulating emission reduction policies from the perspectives of different freight modes.

Therefore, as for a research objective, we focus on China's logistics industry. This paper analyzes the influencing mechanism and decomposes energy-related CO_2 emissions between 1985 and 2015 (from the early stage of the reform and opening up to the end of the 12th five-year plan, which is the Chinese government's plan for the national economy and social development of China) that witnessed the rapid development of the urbanization and the logistics industry in China. It is conducive for the government to formulate scientific energy-saving policies in the logistics industry. This is the first contribution of this paper. Simultaneously, as for methodology, this paper extends the traditional LMDI model to quantify the impact of influencing factors on logistics CO_2 emissions from the perspective of freight transportation modes and energy types through examining the effect of technological progress, structural adjustment, and urbanization. The decomposition index is more comprehensive and more in-depth, and this is the second contribution of this paper. In order to coordinate the relationship between the logistics development and carbon emissions and realize logistics activities that can have less dependence on carbon emissions, in addition to decomposing CO_2 emissions change, we also put forward a decoupling approach based on LMDI decomposition results to study what decoupling status has occurred and what factors have affected the decoupling relationship. To date, few studies have combined the decoupling approach with decomposition results to identify and explore the primary factors that have influenced the decoupling relationship in the logistics industry. This is another contribution of this paper.

2. Materials and Methods

2.1. Estimation Approach of CO_2 Emissions from the Logistics Industry

The two methods that are widely used to estimate CO_2 emissions in the logistics industry are the top–down and the bottom–up approach. Applying the bottom–up approach, we need to collect data relating to the mileage, energy consumption, and CO_2 emissions coefficients of various types of vehicles at different speeds, as well as the number of each vehicle. These statistical data on logistics activities are difficult to obtain, while the top–down approach is only based on terminal energy consumption. Therefore, the top–down approach is more accurate for estimating the CO_2 emissions of the logistics industry in China. In this paper, we utilized the top–down approach to calculate CO_2 emissions based on energy consumption such as raw coal, crude oil, natural gas, and electricity [33–35]. The CO_2 emissions can be calculated as follows:

$$C^t = \sum_i \sum_j E_{ij}^t \times f_j = \sum_i \sum_j E_{ij}^t \times ALV_j \times v_j \times o_j \times \frac{44}{12} \quad (1)$$

where C^t means total CO_2 emissions from the logistics industry in the year t, which are quoted in 10,000 tons; i represents freight transportation mode; $i = 1,2,3,4$ denotes highways, railways, waterways, and aviation, respectively; and j represents the energy type. E_{ij}^t denotes energy consumption of the ith transport mode of energy type j in year t; ALV_j means the average low calorific value of energy type j; v_j implies carbon content per unit calorific value of energy type j; o_j denotes carbon oxidation rate; and f_j is the CO_2 emissions coefficient of energy type j. The calculation equation of f_j is shown as follows:

$$f_j = ALV_j \times v_j \times o_j \times \frac{44}{12} \quad (2)$$

where $44/12$ denotes the molecular weight ratio of carbon dioxide to carbon.

2.2. Extended CO_2 Emissions Decomposition Model

The traditional Kaya identity is used to decompose CO_2 emissions into technological progress, affluence, and population scale through examining the effect of energy intensity per capita GDP and population [36]. However, the Kaya identity does not analyze the impacts of structural adjustment and technological progress from the perspective of freight transportation modes, and does not comprehensively consider urbanization effects. The impact of urbanization on CO_2 emissions in the logistics industry has many channels, and the influencing mechanisms are very complex [6,37]. In brief, urbanization affects the logistics industry's CO_2 emissions through economic growth, population, and urban spatial expansion effects. The specific influencing mechanisms are as follows. (1) The development of urbanization often leads to the rapid development of the economy and the improvement of people's living standards, and this directly results in the change of the lifestyle of the residents (e.g., the rapid popularization of e-commerce and intracity logistics distribution), accordingly influencing the CO_2 emissions in the logistics industry. (2) As for the influencing mechanism of the population urbanization effect, on the one hand, there is a large number of people who move into urban areas from rural areas, which leads to an increase in logistics demands (such as cold chain logistics, commodity logistics, and trade logistics) and an increase in logistics energy consumption. On the other hand, the concentration of the population results in the scale effect of logistics operation and the reduction of CO_2 emissions. Meanwhile, with extensive publicity and advocacy of low-carbon logistics and the notion of a green lifestyle, residents' awareness of energy-saving and emission reductions has improved, which leads to a reduction in per capita logistics CO_2 emissions. (3) The other significant characteristic of the development of urbanization is the rapid expansion of urban areas. The rapid expansion increases the transportation distance and the complexity of the logistics network, which consequently has increased logistics CO_2 emissions. Moreover, the development of urbanization in China brings about a spatial separation between residences and workplaces, and consequently a substantial increasing demand for cars. Accordingly, this phenomenon leads to commuter traffic and traffic congestion, which leads to an increase in CO_2 emissions. Ultimately, taking into account the characteristics of the logistics industry (such as the improvement of energy utilization efficiency and the advancement of equipment technology levels accompanied by logistics development) and the urbanization effect, we decompose logistics CO_2 emissions change through examining the impacts of structural adjustment, technological progress, and urbanization. The extended Kaya identity is shown in Equation (3):

$$C^t = \sum_i \sum_j \frac{E_{ij}^t}{E_i^t} \times \frac{T_i^t}{T^t} \times \frac{E_i^t}{T_i^t} \times \frac{T^t}{K^t} \times \frac{K^t}{P^t} \times \frac{P^t}{Area^t} \times Area^t \times f_j \tag{3}$$

where E_i^t denotes energy consumption of the transport mode i in year t; T_i^t denotes the freight turnover of the ith transport mode in year t; T^t denotes the total freight turnover of the logistics industry; K^t represents the gross domestic product in year t; p^t represents the total urban population in year t; and $Area^t$ represents the urban built-up area in year t.

In order to measure the contribution of the above factors to CO_2 emissions, Equation (3) can be rewritten as follows:

$$C^t = \sum_i \sum_j es_{ij}^t \times ts_i^t \times ei_i^t \times tgdp^t \times pgdp^t \times ps^t \times s^t \times f^t \tag{4}$$

where:

$es_{ij}^t = E_{ij}^t / E_i^t$ is energy mix of the jth energy type in the ith transport mode, which implies an energy structure change effect; $ts_i^t = T_i^t / T^t$ is the freight transportation turnover share of ith transport mode in year t, which reflects the impacts of mode shift in freights transportation on CO_2 emissions; $ei_i^t = E_i^t / T_i^t$ is the energy intensity of the ith transport mode, which implies the efficiency of energy utilization and technology application effects in the logistics industry; $tgdp^t = T^t / K^t$ is the freight transportation intensity measured by the freight transportation turnover per unit of gross domestic product, which indicates the transportation efficiency effect on logistics CO_2 emissions; $pgdp^t = K^t / P^t$ is the per capita gross domestic product, which reflects the urbanization effect of economic growth; $ps^t = P^t / Area^t$ is the urban population per unit of urban built-up area, which implies the urbanization effect of population density; $s^t = Area^t$, which represents the urbanization effect of space expansion; es_{ij}^t and ts_{ij}^t both indicate the structural adjustment effect; ei_i^t and $tgdp^t$ both indicate the impacts of logistics technology development on CO_2 emissions; and $pgdp^t$, ps^t, and s^t reflect the urbanization effect. Meanwhile, f^t and $44/12$ are constant, and thus their contribution to CO_2 change is zero.

According to the additive decomposition proposed by Ang et al. [12–14,38] and Zhang et al. [32], we can rewrite Equation (4) to decompose the contribution of the above factors to logistics CO_2 emissions change from the base year *0* to the year t, as shown in the Equations (5)–(13):

$$\Delta C = C^t - C^0 = \Delta es + \Delta ts + \Delta ei + \Delta tgdp + \Delta pgdp + \Delta ps + \Delta s \tag{5}$$

$$\Delta es = \textstyle\sum_{ij} w(C_{ij}^t, C_{ij}^0) \ln(\frac{es_{ij}^t}{es_{ij}^0}) \tag{6}$$

$$\Delta ts = \textstyle\sum_{ij} w(C_{ij}^t, C_{ij}^0) \ln(\frac{ts_i^t}{ts_i^0}) \tag{7}$$

$$\Delta ei = \textstyle\sum_{ij} w(C_{ij}^t, C_{ij}^0) \ln(\frac{ei_i^t}{ei_i^0}) \tag{8}$$

$$\Delta tgdp = \textstyle\sum_{ij} w(C_{ij}^t, C_{ij}^0) \ln(\frac{tgdp^t}{tgdp^0}) \tag{9}$$

$$\Delta pgdp = \textstyle\sum_{ij} w(C_{ij}^t, C_{ij}^0) \ln(\frac{pgdp^t}{pgdp^0}) \tag{10}$$

$$\Delta ps = \sum_{ij} w(C_{ij}^t, C_{ij}^0) \ln(\frac{ps^t}{ps^0}) \tag{11}$$

$$\Delta s = \sum_{ij} w(C_{ij}^t, C_{ij}^0) \ln(\frac{s^t}{s^0}) \tag{12}$$

$$w(C_{ij}^t, C_{ij}^0) = \frac{C_{ij}^t - C_{ij}^0}{\ln C_{ij}^t - \ln C_{ij}^0} \tag{13}$$

where $\Delta es, \Delta ts, \Delta ei$, and $\Delta tgdp$ represent the energy structure effect, freight transportation structure effect, energy intensity effect, and transportation intensity effect on variations of logistics CO_2 emissions, respectively. Meanwhile, $\Delta pgdp, \Delta ps$, and Δs represent the economic growth effect, population density effect, and urban built-up area expansion effect on the logistics CO_2 emissions, and they are all used to measure the contribution of urbanization to CO_2 emissions. It is worth noting that the freight transportation structure effect (Δts) and energy intensity effect (Δei) can be further decomposed according to the transport mode, i.e., highways, railways, waterways, and aviation.

2.3. Decoupling Model

In order to realize China's emission reduction targets and low-carbon development in the logistics industry, it is necessary to explore the decoupling relationship between logistics development and CO_2 emissions. In this paper, we build a decoupling model, which combines the Tapio decoupling model with the LMDI decomposition results. The total decoupling index of the logistics development and CO_2 emissions can be expressed in Equation (14):

$$D^t = \Delta CO_2\% / \Delta IGDP\% = (\frac{C^t - C^0}{C^0}) \Big/ (\frac{IGDP^t - IGDP^0}{IGDP^0}) \tag{14}$$

where D^t represents the total decoupling index; $\Delta CO_2\%$ means the growth rate of CO_2; $\Delta IGDP\%$ implies the growth rate of $IGDP$; and $IGDP$ means the GDP in the logistics industry. According to the definition of decoupling state put forward by Tapio [27], the decoupling degrees can be divided into eight types (see Table 1). However, China's logistics industry has experienced rapid development since the reform and opening up. Thus $\Delta IGDP\% > 0$, and only four decoupling degrees may occur.

Table 1. Evaluation criteria for decoupling degree of the total decoupling index.

$\Delta CO_2\%$	$\Delta IGDP$	D^t	Decoupling Degree	Meaning
< 0		$D^t < 0$	Strong decoupling	CO_2 declines and logistics output increases.
> 0	> 0	$0 \;\; D^t \leq 0.8$	Weak decoupling	CO_2 grows and logistics output increases, while the $\Delta CO_2\%$ is less than the $\Delta IGDP\%$.
> 0		$0.8 \;\; D^t \leq 1.2$	Expansive coupling	CO_2 grows and logistics output increases, while the $\Delta CO_2\%$ is almost the same as the $\Delta IGDP\%$.
> 0		$D^t > 1.2$	Expansive negative decoupling	CO_2 grows and logistics output increases, while the $\Delta CO_2\%$ is higher than the $\Delta IGDP\%$.
> 0		$D^t < 0$	Strong negative decoupling	CO_2 grows and logistics output declines.
< 0	< 0	$0 \;\; D^t \leq 0.8$	Weak recessive decoupling	CO_2 and logistics output both decline, while the $\Delta CO_2\%$ is less than $\Delta IGDP\%$.
< 0		$0.8 \;\; D^t \leq 1.2$	Recessive coupling	CO_2 and logistics output both decline, while the $\Delta CO_2\%$ is almost the same as the $\Delta IGDP\%$.
< 0		$D^t > 1.2$	Recessive decoupling	CO_2 and logistics output both decline, while the $\Delta CO_2\%$ is higher than the $\Delta IGDP\%$.

Note: logistics output is measured by the value added in the logistics industry.

Equation (14) can be further expressed as Equation (15):

$$\begin{aligned} D^t &= (\frac{C^t - C^0}{C^0}) \Big/ (\frac{IGDP^t - IGDP^0}{IGDP^0}) = \frac{C^t - C^0}{IGDP^t - IGDP^0} \times \frac{IGDP^0}{C^0} \\ &= \frac{\Delta C^t}{\Delta IGDP^t} \times \frac{IGDP^0}{C^0} = \frac{\Delta es + \Delta ts + \Delta ei + \Delta tgdp + \Delta pgdp + \Delta ps + \Delta s}{\Delta IGDP^t} \times \frac{IGDP^0}{C^0} \\ &= \left(\frac{\Delta es}{\Delta IGDP^t} + \frac{\Delta ts}{\Delta IGDP^t} + \frac{\Delta ei}{\Delta IGDP^t} + \frac{\Delta tgdp}{\Delta IGDP^t} + \frac{\Delta pgdp}{\Delta IGDP^t} + \frac{\Delta ps}{\Delta IGDP^t} + \frac{\Delta s}{\Delta IGDP^t} \right) \times \frac{IGDP^0}{C^0} \\ &= D_{es}^t + D_{ts}^t + D_{ei}^t + D_{tgdp}^t + D_{pgdp}^t + D_{ps}^t + D_s^t \end{aligned} \tag{15}$$

where $\Delta IGDP^t = IGDP^t - IGDP^0$. The total decoupling index (D^t) can be further decomposed into seven sub-decoupling indices to explore what factors affected the decoupling relationship between the logistics development and CO_2 emissions. D^t_{es} represents the energy structure decoupling index; D^t_{ts} represents the freight transportation structure decoupling index; D^t_{ei} means the energy intensity decoupling index; D^t_{tgdp} implies the transportation intensity decoupling index. Meanwhile, D^t_{pgdp}, D^t_{ps}, and D^t_s respectively indicate the influence of economic growth, population density, and urban built-up area expansion on the decoupling relationship. The evaluation of criteria for the influencing effect of the sub-decoupling index on the total decoupling relationship is displayed in Table 2, where ΔD^t_x represents the sub-decoupling index.

Table 2. The evaluation of the impacts of the sub-decoupling index on the total decoupling relationship.

$\Delta IGDP\%$	ΔD^t_x	The Impacts of the Sub Decoupling Index
> 0	> 0	The sub-index plays an inhibiting role in the decoupling relationship. The higher the value of the sub-decoupling index, the stronger the inhibiting effect of the index on the decoupling relationship.
	< 0	The sub-index plays a promoting role in the decoupling relationship. The smaller the value of the sub-decoupling index (i.e., the higher the absolute value of ΔD^t_x), the stronger the promoting effect of the index on the decoupling relationship.

2.4. Data Sources

The research period in this paper ranged from 1985 to 2015, which is from the early stage of reform and opening up to the end of the 12th five-year plan, and has witnessed the rapid development of the logistics industry in China. As for energy data, energy statistics in the logistics industry are limited in the China Statistical Yearbook. From previous literature, some studies argued that transport, storage, and communications are important parts of the logistics industry, and used data from transport, storage, and communications to estimate logistics CO_2 emissions. Moreover, other studies indicated that transport, storage, and communications accounted for about 90% of the output of logistics in China [19,39–42]. Therefore, in this paper, we use data from transport, storage, and communications to estimate and analyze the influencing factors of logistics CO_2 emissions. Energy includes eight kinds of terminal energy, such as raw coal, crude oil, gasoline, kerosene, diesel oil, and fuel oil, which can be collected from the energy balance sheet in the China Energy Statistics Yearbook 1986–2016 and are measured in 10,000 tons.

To make the estimation more in line with the actual situation of China's CO_2 emissions in the logistics industry, we utilized data that has the local characteristics of China instead of IPCC data [35,43,44]. The average low calorific value (ALV_j), carbon content per unit calorific value (v_j), carbon oxidation rate (o_j), and the CO_2 emissions coefficient of electricity have been obtained from the Guidelines for the Compilation of China Provincial Greenhouse Gas Inventories published by the National Bureau of Statistics [45]. Except for electricity, the CO_2 emissions coefficient is calculated by the multiplication of the ALV_j, the v_j, the o_j, and the molecular weight ratio of carbon dioxide to carbon in this paper; the results of the coefficient calculations are shown in Table 3.

Table 3. The CO_2 emissions coefficient results of main energy.

Energy	Raw Coal	Crude Oil	Gasoline	Kerosene	Diesel Oil	Fuel Oil	Natural Gas	Electricity
Unit	($kg \cdot kg^{-1}$)	($kg \cdot kg^{-1}$)	($kg \cdot kg^{-1}$)	($kg \cdot kg^{-1}$)	($kg \cdot kg^{-1}$)	($kg \cdot kg^{-1}$)	($kg \cdot m^{-3}$)	$t \cdot (10^4\ kW \cdot h)^{-1}$
coefficient	1.9003	3.0202	2.9251	3.0179	3.0960	3.1705	2.16219	9.7402

Note: The calculation results are similar to the previous literature [35,43,44], and therefore have strong reliability.

The unit of freight turnover of each transport mode is 100 million ton-km, which can be obtained from the Yearbook of China Transportation and Communications 1986–2016. The unit of GDP and the value added of the logistics industry is 100 million yuan in 1978 (constant price), which can be collected from the China Statistical Yearbook 1986–2016. The urban population and urban built-up area are measured in 10^4 persons and km^2, which are obtained from the China Statistical Yearbook 1986–2016.

3. Empirical Results and Discussion Analysis

3.1. Decomposition Analysis of CO_2 from China's Logistics Industry

The decomposition results of the logistics CO_2 emissions changes from 1985 to 2015 are listed in Table 4. The total CO_2 change is attributed to the effect of technological progress, structural adjustment, and urbanization, and some findings are as follows.

First, CO_2 emissions in the logistics industry increased by a factor of 8.4 (737.55 million tons), with an annual rate of 7.86%. Specifically, the urbanization effect is the dominating contributor to the increase of CO_2 emissions; it accounted for 828.41 million tons of total logistics CO_2 change, which is consistent with the results of Zhang et al. [6]. The structural adjustment effect comes next, which explains about 205.58 million tons, or 27.87% of the increase of CO_2 emissions. However, the technological progress effect appears to be the primary inhibiting contributor to CO_2 emissions, which can explain 40.19% of the changes in CO_2 emissions.

Table 4. The decomposition of energy-related CO_2 emissions from China's logistics industry.

Time Period	Δes	Δts	Δei	$\Delta tgdp$	$\Delta pgdp$	Δps	Δs	ΔC
1985–1986	−98.88	15.10	−151.74	85.89	329.77	−241.43	691.10	629.81
1986–1987	27.95	502.16	−1178.98	−97.59	597.43	−166.79	630.38	314.56
1987–1988	70.13	474.40	−822.51	−366.24	716.23	−761.91	1110.29	420.38
1988–1989	37.14	−204.25	−194.04	342.31	114.06	2.77	310.05	408.03
1989–1990	8.92	−112.03	−114.37	−147.98	174.62	−96.87	328.90	41.19
1990–1991	−25.10	−262.46	−0.88	−230.95	605.26	−575.60	930.73	441.00
1991–1992	21.98	324.64	−241.04	−1010.70	1163.28	−393.87	741.38	605.66
1992–1993	−149.32	213.14	330.20	−991.62	1217.16	−887.42	1259.48	991.63
1993–1994	218.81	−36.71	−1050.50	−440.87	1197.72	−624.29	1003.31	267.49
1994–1995	−201.67	−212.81	94.27	−408.04	992.72	−557.88	940.60	647.19
1995–1996	60.57	287.51	−416.87	−1027.36	488.24	145.23	656.02	193.34
1996–1997	48.38	−10.68	2813.51	−611.02	501.04	429.64	435.68	3606.55
1997–1998	−330.75	388.90	1591.12	−1524.60	403.58	459.97	505.66	1493.88
1998–1999	−451.15	−162.21	1481.40	−198.97	465.24	866.34	134.84	2135.48
1999–2000	−32.99	−217.63	−139.63	189.49	716.34	142.60	909.19	1567.38
2000–2001	157.72	−631.39	−488.13	−124.36	778.54	−515.55	1572.35	749.18
2001–2002	22.74	183.26	101.26	−636.44	1048.86	−828.71	1889.35	1780.32
2002–2003	56.16	−58.04	1971.91	−942.96	1434.56	−1181.42	2316.73	3596.96
2003–2004	−373.38	−2812.94	178.72	4987.26	1875.97	−1112.82	2226.35	4969.17
2004–2005	−736.76	−856.57	−281.33	1245.88	2555.57	−1137.83	2367.51	3156.47
2005–2006	−196.04	162.44	385.53	−847.39	3230.46	71.41	1337.24	4143.65
2006–2007	67.16	80.16	−1062.23	−56.64	4043.32	−560.21	2268.94	4780.49
2007–2008	−468.00	22,494.18	−21,671.00	−342.03	3030.90	276.96	1105.49	4426.50
2008–2009	163.49	337.66	−4026.62	751.05	2825.92	−793.86	2498.43	1756.07
2009–2010	458.81	360.53	−3257.04	2732.72	3495.84	−683.18	2748.32	5856.01
2010–2011	322.72	1764.65	−3349.17	1395.47	3632.39	−3277.67	5155.33	5643.71
2011–2012	−292.45	2180.18	−1000.56	803.35	2987.76	−939.62	2947.17	6685.84
2012–2013	158.60	−1198.57	8621.78	−8023.00	3440.61	−1620.94	3565.75	4944.23
2013–2014	−40.33	−3403.15	916.05	374.02	3514.97	−1143.51	3015.83	3233.90
2014–2015	−10.92	2474.68	3477.07	−7039.37	3038.94	−1351.41	3679.52	4268.51
1985–2015	−1506.43	22,064.13	−17,483.83	−12,160.70	50,617.31	−17,057.85	49,281.93	73,754.55

Note: The unit is 10,000 tons.

Second, as for the urbanization effect, economic growth ($\Delta pgdp$) played the most significant role in the total increase of CO_2 emissions in the logistics industry. The effect of $\Delta pgdp$ increased by 506.17 million tons, which contributed approximately 68.63% to CO_2 change; this result is in line with Zhang et al. [15]. This is ascribed to the rapid development of China's economy, which in turn promoted the increase of logistics demand and brought about changes in the lifestyles of the residents, such as the popularization of e-commerce and an increase in demand for express delivery. The urban built-up area expansion factor (Δs), which had a promoting effect during the research period, appeared to be the second contributor to CO_2 emissions increase behind $\Delta pgdp$. During 1985–2015, the urban built-up area in China rose from 9.39 thousand km^2 to 52.10 thousand km^2, which caused 492.82 million tons (66.82%) of CO_2 changes. In fact, the urban built-up area expansion factor produced the spatial separation of residence and workplaces and the improvement of the complexity of the logistics network, which caused transportation distance increases between the place of production and consumption and the circuitous transportation problems. Moreover, population density (Δps) played the second dominating role in the reduction of logistics CO_2, which is only next to energy intensity effects (Δei). The cumulative effect of Δps was -170.58 million tons, which contributed -23.13% to the total CO_2 change. It should be noted that population density, which is the ratio of urban population and urban built-up area, almost kept declining over the research period; it dropped from 2.67 (10,000 persons per km^2) to 1.48 (10,000 persons per km^2). Alongside the fast development of urbanization in China, a large number of people moved into urban areas. However, at the same time, the rate of urban area expansion was higher than the growth rate of the population, which in turn resulted in a population density decline. In addition, as mentioned previously, the marked curbing effect of Δps is closely related to the logistics operation scale effect caused by population concentration and the improvement of residents' awareness regarding energy-saving and emission reductions.

Third, as for the structural adjustment effect, freight transportation structure (Δts) presented the third contributor to logistics CO_2 increase; this finding is also consistent with previous studies [18,19,28]. From 1985 to 2015, Δts contributed 220.64 million tons, which accounted for 29.92% of the CO_2 change. The reason is due to the shift of freight structure during the past decades, and the share of transportation turnover among the four transport modes as detailed in Figure 1. Specifically, the percentage of highways with a higher energy consumption per freight turnover increased remarkably from 9.64% in 1985 to 32.98% in 2015. At the same time, the share of aviation also appeared to have an upward trend, which increased from 0.02% in 1985 to 0.12% in 2015 due to the growing aviation logistics demand for the transportation of fresh products (e.g., flowers, seafood), precision machinery (e.g., the medical machine), business documents, and communication products. However, the proportion of railways decreased between the seventh and the 12th five-year plan periods. Energy structure (Δes) played a weak role in inhibiting the increase of CO_2 emissions, which can explain about 15.06 million tons or 2.04% of the CO_2 changes in the logistics industry. This happened mainly due to the use of clean energy and new energy, as well as changes within the energy structure over the past decades. The energy consumption structure of the logistics industry is shown in Figure 2. During the 1985–2015 periods, the proportion of coal rapidly decreased from 30.38% to 0.97%, a decrease of 29.41%. However, the share of oil has presented an upward trend, which contributed to the increase of CO_2 and offset the reduction caused by the coal effect.

Figure 1. The share of transportation turnover in the logistics industry.

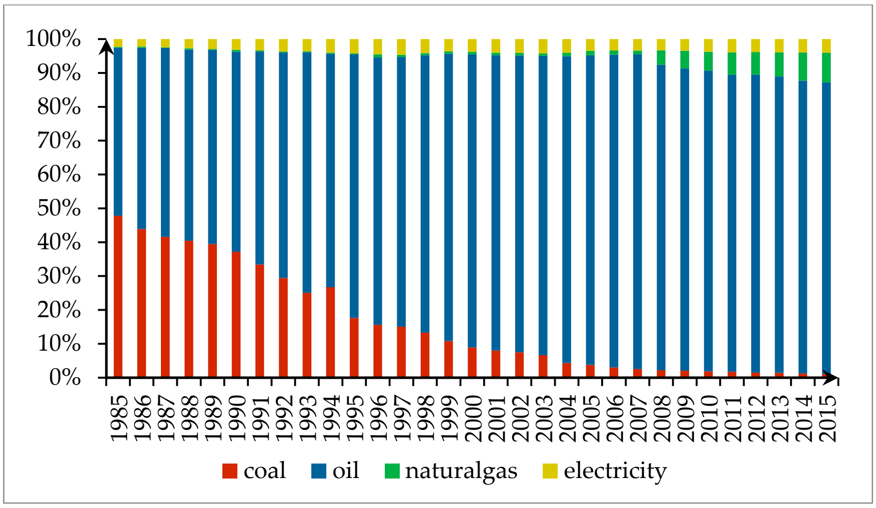

Figure 2. Energy consumption structure of the logistics industry in China.

Finally, as for the technological progress effect, energy intensity (Δei) and freight transportation intensity ($\Delta tgdp$) were both significant contributors to the reduction of logistics CO_2. Specifically, energy intensity, which is the ratio of energy consumption and freight turnover and implies energy efficiency and the application of critical technologies in energy saving [46], was the most dominating factor for the decline in logistics CO_2. During the research period, some techniques, such as the application of fuel-saving technologies, were utilized in China, which effectively improved energy efficiency in the logistics industry. Freight transportation intensity ($\Delta tgdp$), which means the freight turnover required per unit of economic output, and indicates the application of technologies that improve transport efficiency, was also the primary curbing factor of logistics CO_2 decrease. As shown in Figure 3, the curve of the growth rates of GDP had the same trend as the added value of the logistics industry, and they trace each other tightly, which indicates that the logistics industry has played a significant role in economic development from 1985 to 2015. This result is in line with the results of previous literature [17,19]. However, freight transportation intensity declined from 2.5 ton-km·yuan^{-1} in 1985 to 1.56 ton-km·yuan^{-1} in 2015, which indicates that the freight turnover required per unit of economic output has decreased, and that transport efficiency has improved. This may be attributed to measures and policies that have been taken in China, such as enhancing route optimization abilities and the standardization level of transportation equipment.

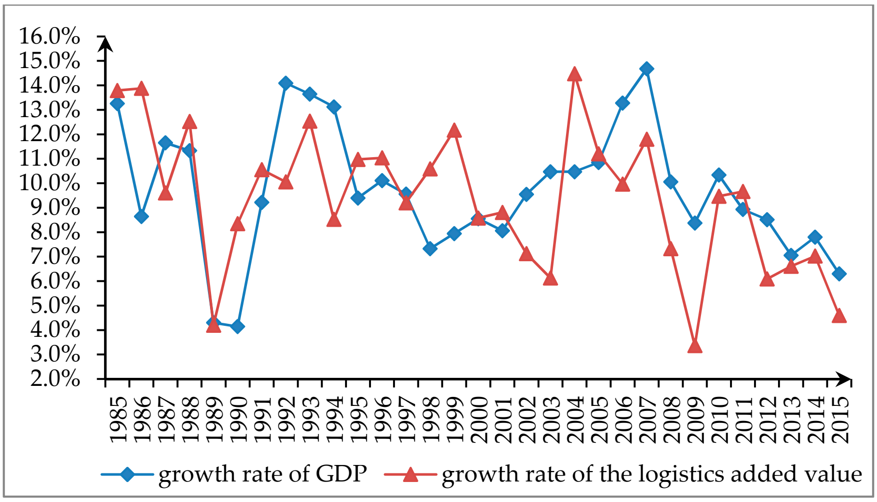

Figure 3. The growth rates of gross domestic product (GDP) and the logistics added value from 1985 to 2015.

In brief, as shown in Figure 4, economic growth and urban built-up area expansion proved to be the dominating factors for increasing CO_2 emissions. Freight transportation structure comes next, which is mainly due to a transport mode shift in China. It should be noted that technological progress effects (i.e., energy intensity and transportation intensity) played a dominant role in inhibiting CO_2 increase. Moreover, highway transportation has been proven to be a key objective for reducing CO_2 emissions in the logistics industry, and it is a significant contributor to CO_2 increase from transport structure. In addition, energy structure, which has great reduction potentials, has so far played only a small role in reducing CO_2 emissions.

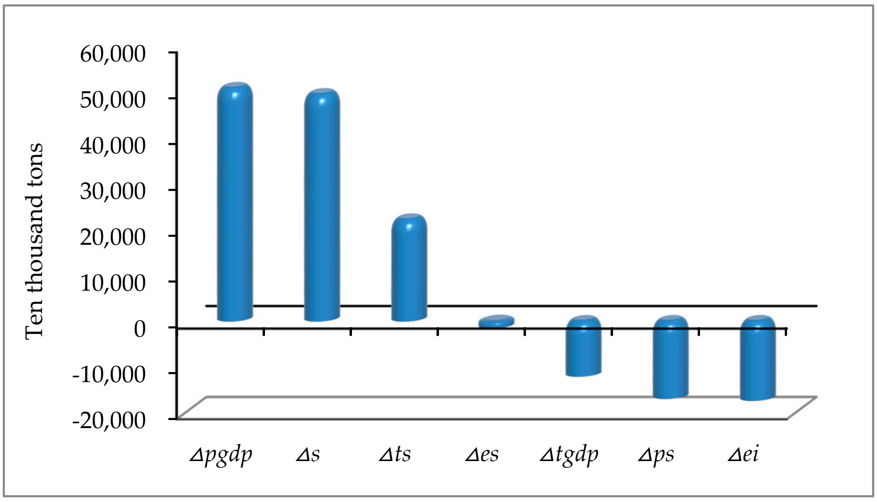

Figure 4. The energy-related CO_2 emission decomposition between 1985 and 2015.

Moreover, this paper further analyzes the decomposition results by five-year plan periods, as displayed in Table 5 and Figure 5. The five-year plan is the plan for the national economy and social development of China launched by the Chinese government. Taking five-year plan periods as intervals can better explain the impacts of the driving factors on logistics CO_2 changes over time. Some points were obtained as follows.

Table 5. The decomposition results of energy-related CO_2 emission by time periods.

Time Period	Δes	Δts	Δei	$\Delta tgdp$	$\Delta pgdp$	Δps	Δs	ΔC
1985–1990	45.26	675.38	−2461.64	−183.61	1932.11	−1264.23	3070.72	1813.97
1990–1995	−135.30	25.80	−867.95	−3082.18	5176.14	−3039.06	4875.50	2952.97
1995–2000	−705.94	285.89	5329.53	−3172.46	2574.44	2043.78	2641.39	8996.63
2000–2005	−873.52	−4175.68	1482.43	4529.38	7693.50	−4776.33	10,372.29	14,252.1
2005–2010	25.42	23,434.97	−29,631.40	2237.71	16,626.44	−1688.88	9958.42	20,962.72
2010–2015	137.62	1817.79	8665.17	−12,489.5	16,614.67	−8333.15	18,363.60	24,776.19

Note: 1985–1990, 1990–1995, 1995–2000, 2000–2005, 2005–2010, and 2010–2015 are the seventh, eighth, ninth, 10th, 11th, and 12th five-year plan periods in China, respectively. The unit is 10,000 tons.

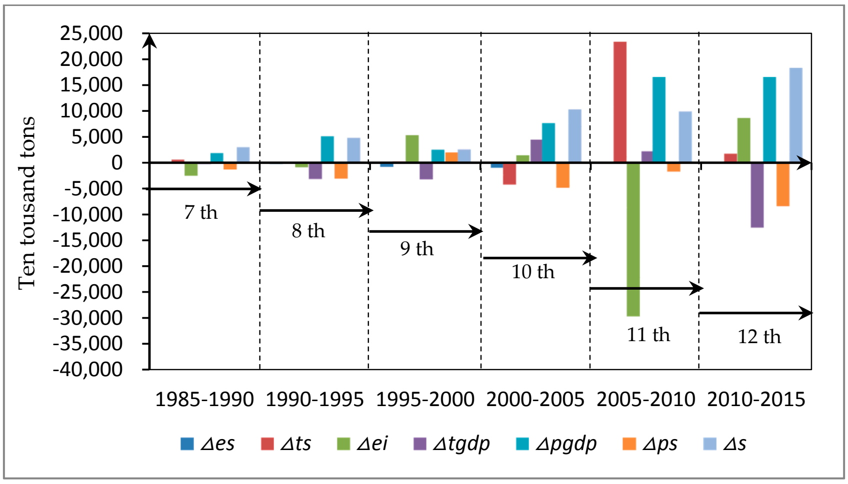

Figure 5. The decomposition results of CO_2 emission in each five-year plan Period.

1. From the seventh to the end of the 12th five-year plan period, $\Delta pgdp$ has kept increasing over the study periods. In particular, the increment of $\Delta pgdp$ in the 12th five-year period increased slowly compared to the 11th five-year period. During the 12th five-year period, China's economy entered a new normal state, which means that economic development came into an efficient, low-cost, sustainable, and steady growth stage instead of the traditional extensive growth mode. Therefore, it slowed down energy consumption. Between the 10th and 12th five-year periods, Δs had a significant contribution to the CO_2 increase. This may be attributed to the rapid progress of urbanization and expansion of urban areas in China during this period. Besides, by the 2010–2015 period (the 12th five-year plan), Δps had already contributed 48.85% of the total reduction of logistics CO_2 caused by the population density factor from 1985 to 2015, which may be attributed to measures in China such as improving the consciousness and ability of residents and employees of logistics enterprises to save energy.
2. As for Δes, it only played a curbing role during the eighth, ninth, and 10th five-year periods, which explained 1.35 million tons, 7.06 million tons, and 8.74 million tons, respectively, of the CO_2 reduction. The reason is mainly due to the decline in the proportion of coal. During this period, the electric locomotive gradually superseded the steam locomotive, which uses coal as fuel. It also can be observed that during the 12th five-year period, the contribution of Δes to CO_2 increase has also been increasing. In this period, the share of oil increased rapidly. At the same time, the proportion of clean energy use, such as compressed natural gas and electricity, was still very low. Besides, during the 11th five-year period, it should be noted that Δts contributed 234.35 million tons to the increase of CO_2, which is higher than other periods. This happened mainly due to the fast increase in the proportion of highway freight due to flexibility, which increased from 10.98% in 2005 to 30.59% in 2010. From 2005–2010, a large amount of highway infrastructure was developed in China, which in turn promoted energy consumption.

3. During 2005–2010, Δei had a significant contribution to the decline in logistics CO_2, which can explain 296.31 million tons of the decrease. It can be seen that during this period, the energy intensity of highways, railways, and waterways almost all showed a downward trend, which indicates that the measures and policies launched by the government, such as encouraging multimodal transportation and the subsidy policy for new energy vehicles, played a promoting role in CO_2 reduction. Nevertheless, it should be noted that from 2010–2015, Δei played a negative role in the reduction of CO_2. In addition, during the 12th five-year period, Δ$tgdp$ had a significant contribution to the reduction of CO_2 compared to 2000–2010. During this period, the Ministry of Transport of China focused on the implementation of the standardization of transportation equipment and the construction of a logistics information platform, which to some extent boosted the application of the internet of things, big data technology, and the improvement of the logistics service efficiency of each link.

In addition, this paper further decomposes the energy intensity (Δei) and transportation structure factor (Δts) according to freight mode, as shown in Table 6, and some findings are as follows.

Table 6. The impact of energy intensity and freight transportation structure on CO_2 emissions.

Time Period		1985–1990	1990–1995	1995–2000	2000–2005	2005–2010	2010–2015	1985–2015
Δei	highways	−1392.16	−391.34	3033.77	−1731.34	−16,059.47	9749.99	−6790.55
	railways	−633.87	−321.01	1061.22	1222.39	−4157.78	−1885.15	−4714.21
	waterways	−408.23	−18.23	1326.12	1635.07	−8670.31	184.54	−5951.05
	aviation	−27.38	−137.36	−91.58	356.31	−743.80	615.78	−28.03
Δei_{tot}		−2461.64	−867.94	5329.53	1482.43	−29,631.36	8665.16	−17,483.84
Δts	highways	900.41	85.29	324.69	−3985.11	27,325.39	3220.60	27,871.27
	railways	−342.19	−448.67	−710.84	−1158.28	−2163.32	−1960.47	−6783.77
	waterways	61.72	197.98	347.40	1103.68	−2219.89	587.97	78.86
	aviation	55.44	191.20	324.65	−135.98	492.70	−30.33	897.68
Δts_{tot}		675.38	25.80	285.90	−4175.69	23,434.88	1817.77	22,064.04

Note: The unit of Δei and Δts is 10,000 tons.

1. When considering energy intensity, highways, railways, and waterways all have a promoting role in the reduction of logistics CO_2, which accounted for 99.84% of the CO_2 change influenced by energy intensity. Besides, the reduction effects of railways and waterways were greater than those of highways and aviation. In particular, with a series of policies launched for the construction of low-carbon integrated transportation systems, the energy utilization efficiency of highways—that is, with higher energy consumption per freight turnover—was improved for most periods. Since the share of freight turnover by highways is relatively high, a small increase in the energy intensity of highways can result in a noticeable change in the total changes of logistics CO_2.
2. As for the freight transportation structure, railways played an important role in reducing CO_2 emissions. However, highways and aviation played promoting roles during 1985–2015, which contributed 278.71 million tons and 8.98 million tons to CO_2 increases, respectively. As analyzed previously, the main reason is attributed to the freight transport modes shift from more energy-efficient modes (i.e., railways, waterways) to less energy-efficient modes (i.e., highways, aviation) due to flexibility and increasing requirements for the timeliness of transportation, particularly during 2005–2010. Notably, the transportation structure effect of waterways has played an apparent promoting role in CO_2 reduction during 2005–2010. In 2008, the global financial crisis broke out, and international trade was reduced, which resulted in ocean transportation reduction.

3.2. Decoupling Analysis Based on Decomposition Results

The decoupling relationship between CO_2 emissions in the logistics industry and logistics output during 1985–2015 is shown in Table 7 and Figure 6. The logistics industry in China has developed rapidly, $\Delta IGDP > 0$ and $\Delta CO_2 > 0$; thus, only three kinds of decoupling states occurred, as can be seen in Table 7.

Table 7. The decoupling index of the logistics industry in China.

Time Period	$\Delta CO_2\%$	$\Delta IGDP\%$	D^t	Decoupling State
1985–1986	0.073	0.139	0.525	weak decoupling
1986–1987	0.033	0.096	0.347	weak decoupling
1987–1988	0.043	0.125	0.345	weak decoupling
1988–1989	0.040	0.042	0.959	expansive coupling
1989–1990	0.004	0.083	0.043	weak decoupling
1990–1991	0.041	0.106	0.388	weak decoupling
1991–1992	0.054	0.100	0.538	weak decoupling
1992–1993	0.096	0.126	0.766	weak decoupling
1993–1994	0.010	0.085	0.119	weak decoupling
1994–1995	0.051	0.110	0.464	weak decoupling
1995–1996	0.014	0.111	0.127	weak decoupling
1996–1997	0.266	0.092	2.897	expansive negative decoupling
1997–1998	0.087	0.106	0.823	expansive coupling
1998–1999	0.116	0.122	0.949	expansive coupling
1999–2000	0.074	0.086	0.864	expansive coupling
2000–2001	0.033	0.088	0.375	weak decoupling
2001–2002	0.076	0.071	1.068	expansive coupling
2002–2003	0.142	0.061	2.319	expansive negative decoupling
2003–2004	0.172	0.145	1.186	expansive coupling
2004–2005	0.093	0.112	0.831	expansive coupling
2005–2006	0.113	0.100	1.131	expansive coupling
2006–2007	0.118	0.118	0.999	expansive coupling
2007–2008	0.101	0.073	1.373	expansive negative decoupling
2008–2009	0.036	0.042	0.861	expansive coupling
2009–2010	0.111	0.089	1.254	expansive negative decoupling
2010–2011	0.097	0.094	1.037	expansive coupling
2011–2012	0.105	0.061	1.723	expansive negative decoupling
2012–2013	0.069	0.066	1.043	expansive coupling
2013–2014	0.042	0.070	0.605	weak decoupling
2014–2015	0.053	0.041	1.294	expansive negative decoupling

During the past three decades, a weak decoupling state and expansive coupling state occurred in 12 years, respectively, and an expansive negative decoupling state appeared in the other six years, which implies that the development of the logistics industry has had a relatively strong dependence on carbon dioxide emissions. As displayed in Figure 6, the variation of decoupling index from 1985 to 2015 can be divided into three stages.

1. Before 1997, the relationship between the logistics output and CO_2 emissions remained in a weak decoupling state except for 1989; in particular, in 1990, 1994, and 1996, the development of the logistics industry became less dependent on CO_2 emissions.
2. The second stage is from 1998 to 2003, in addition to 2001 and 2003; expansive coupling appeared in the rest of the years. It can be observed that the relationship between logistics development and CO_2 emissions changed from a weak decoupling state that had dominated in the first stage to an expansive coupling state that dominated in the second stage, which implies that the development of the logistics industry had become more dependent on energy consumption.
3. The third stage is from 2004 to 2015. Seven years showed an expansive coupling state, and four years showed an expansive negative decoupling state. It can be seen that there was an increase in the number of years within the expansive negative decoupling state in the third stage,

which indicates that the growth rate of CO_2 is higher than the logistics outputs in recent years. Therefore, in order to achieve the emission reduction target of reducing CO_2 emission intensity by 60–65% by 2030 compared to 2005, it is urgent for China to take measures to reduce CO_2 emissions and improve the efficiency of energy utilization in the logistics sector.

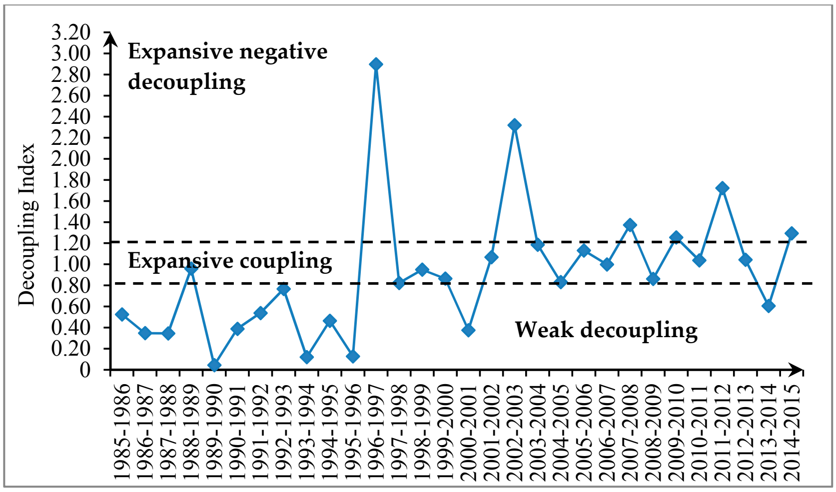

Figure 6. The decoupling state of the logistics industry for the 1985–2015 period.

This paper further decomposes the total decoupling index into seven sub-decoupling indices to analyze what factors have influenced the total decoupling state. The decomposition results for the 1985–2015 period are listed in Table 8, and several results are explained as follows.

Table 8. The decomposition of the total decoupling index for the 1985–2015 period.

Time Period	D_{es}	D_{ts}	D_{ei}	D_{tgdp}	D_{pgdp}	D_{ps}	D_s
1985–1990	0.009	0.131	−0.479	−0.036	0.376	−0.246	0.597
1990–1995	−0.020	0.004	−0.126	−0.448	0.752	−0.442	0.709
1995–2000	−0.082	0.033	0.622	−0.370	0.300	0.238	0.308
2000–2005	−0.067	−0.321	0.114	0.348	0.591	−0.367	0.797
2005–2010	0.001	1.282	−1.621	0.122	0.909	−0.092	0.545
2010–2015	0.006	0.083	0.395	−0.569	0.757	−0.380	0.837

1. First, the economic growth effect on the decoupling progress (D_{pgdp}) and the urban built-up area expansion effect on the decoupling progress (D_s) are both greater than zero, and they both contributed to the main inhibiting effect on the decoupling relationship. It is suggested that in order to achieve the decoupling between logistics development and CO_2 emissions, China has to reasonably plan its urban spatial structure. The spatial separation of residences and workplaces and the increase of transportation distance have played an important role in the increase of logistics CO_2 emissions. Therefore, it is urgent for China to rationally plan and develop the new industrial city, constructing a new city with highly concentrated industries and perfect urban function. Second, the value of the energy intensity decoupling effect (D_{ei}), transportation intensity decoupling effect (D_{tgdp}), and population density decoupling effect (D_{ps}) are almost negative, except for a few years, which indicate that D_{ei}, D_{tgdp}, and D_{ps} played a promoting role in the decoupling relationship, except for several years. It should be noted that D_{tgdp} played an inhibiting effect on the decoupling progress in the 2000–2005 and 2005–2010 periods, which may be attributed to the low transportation efficiency caused by traffic congestion and the lack of a logistics information platform construction. Finally, D_{ts} played a small inhibiting role in the decoupling relationship, and D_{es} played a promoting role in the decoupling relationship except for the 1985–1990, 2005–2010, and 2010–2015 periods.

2. A more obvious expansive negative decoupling occurred in 1997, as displayed in Table 7, which can be explained by the energy intensity effect on decoupling relationships. In the 1995–2000 period, the energy intensity effect played a dominant role in the CO_2 increase. At the same time, it curbed the occurrence of the decoupling relationship. Moreover, obvious expansive negative decoupling also occurred in 2003, 2007, and 2012, and the total decoupling indices were 2.319, 1.373, and 1.723, respectively. In 2003 and 2012, the occurrences of expansive negative decoupling were both attributed to economic growth effects and urban built-up area expansion effects. However, in 2007, the freight structure decoupling index (D_{ts}) was a dominating factor for inhibiting the decoupling relationship, which implies that it is important for the government to take measures to achieve traffic avoidance and promote efficiently and profitably freight-shifting from road to other more environmentally-friendly and sustainable modes.

4. Conclusions and Policy Implications

4.1. Conclusions

This paper built an extended LMDI model to decompose the CO_2 emission changes of the logistics industry from 1985 to 2015 (from the early stage of the reform and opening up to the end of the 12th five-year plan) through examining the effects of technological progress, structural adjustment, and urbanization. Simultaneously, we further decomposed the effects of energy intensity and freight transportation structures from the aspect of each freight mode. Then, we introduced a decoupling model that combined the decomposition results to analyze whether the development of the logistics was becoming less dependent on CO_2 emissions, and determine the main factors that influenced the decoupling state. The contributions of this paper are not only research objectives: we also constructed research models. In addition, the findings of this paper have significant policy implications for energy saving and emission reduction in the logistics industry. The main conclusions are as follows.

1. CO_2 emissions in the logistics industry increased by 737.55 million tons (8.4 times) during 1985–2015, with an annual rate of 7.86%. Specifically, the urbanization effect proved to be the decisive factor for the increase in CO_2 emissions, while the technological progress effect played a significant inhibiting role in CO_2 change. In particular, the economic growth and the urban built-up area expansion played a significant role in the increase of logistics CO_2, and contributed a total of 999 million tons to CO_2 change. Freight transportation structure was the second largest cause for the increase of logistics CO_2, which happened mainly due to the freight transportation shift in China. However, energy intensity and transportation intensity, which indicated the impact of the technical application on logistics CO_2 change, appeared to be the dominating factors for the decline in CO_2 and contributed 23.71% and 16.49%, respectively, to CO_2 change. Therefore, the government is advised to make the best use of the two factors to reduce logistics CO_2.
2. According to the analysis by time periods, the contribution of urban built-up area expansion to CO_2 increase has shown a rising trend during the 10th, 11th, and 12th five-year periods; this is mainly due to the rapid progress of urbanization and the increase of transportation distance. Energy intensity had an evident promoting effect on the CO_2 increase during the 12th five-year period compared to the 10th and 11th five-year periods, which may be attributed to the energy efficiency decline of the highways between 2010 and 2015. At the same time, energy structure and freight transportation structure played significant promoting roles during the 2005–2015 and 2005–2010 periods, respectively, which was mainly due to the sharp increase in oil consumption and increase in the share of highways and aviation freight transportation in logistics. In particular, the energy structure had great reduction potentials. The emission reduction potential of new energy and clean energy also cannot be ignored. Besides, during the 12th five-year period, transportation intensity contributed 102.70% to the total CO_2 decline caused by transportation intensity from 1985–2015, which is closely related to the application of logistics technologies in recent years.

3. From the perspective of transport modes, in terms of the energy intensity, the reduction effects of the railways and waterways were greater than those of highways and aviation. Due to the rising proportion of highways, the CO_2 emission reduction effect of energy intensity was more sensitive to the improvement of the energy utilization efficiency of highways. Besides, aviation only had a small inhibiting effect on the CO_2 increase. When considering the freight transportation structure, due to the transport mode shift from more energy-efficient modes (i.e., railways, waterways) to less energy-efficient modes (i.e., highways, aviation), highways and aviation played dominating promoting roles in CO_2 increases. Moreover, the reduction effect of railways and waterways could not be neglected.
4. Weak decoupling and expansive coupling states occurred in two-thirds of the research period, and there was an increase in the number of the expansive negative decoupling state in the 11th and 12th five-year periods, which implies that the development of the logistics industry has become more dependent on CO_2 emissions. Besides, the energy intensity decoupling effect, transportation intensity decoupling effect, and population density decoupling effect were major promoting factors in the decoupling relationship. Simultaneously, it should be noted that the energy structure decoupling effect played a small promoting role in the decoupling state, and the optimization of the energy structure had great potential for reducing emissions.

4.2. Policy Implications

In order to achieve CO_2 emission reduction targets by 2030 in China and ensure that the development of China's logistics industry becomes less dependent on energy consumption, this paper identified the main influencing factors of logistics CO_2 emissions and analyzed the decoupling state between logistics development and CO_2 emissions. By the conclusions drawn above, the following policy implications ought to be considered.

1. Transform and upgrade the traditional logistics industry. The government is expected to upgrade the logistics industry further from a traditional transportation and warehousing industry to a modern logistics industry that can provide services for the complete supply chain by information technologies and a higher standardization of logistics facilities and equipment. Specifically, some policies (e.g., subsidy) can be adopted to improve service efficiency and the informatization levels of the third party logistics, manufacturing logistics, and commerce trade logistics, which can enhance the energy use efficiency, transportation efficiency, and supply chain management capabilities.
2. Accelerate the research and development of key technologies. On the one hand, the government is encouraged to promote the application of energy-saving and sustainable transport equipment (e.g., fuel-saving automatic clutch, new energy vehicles, and the distributed power supply system of trains) to control CO_2 emissions and improve energy efficiency. On the other hand, it is advised to increase funding for developing information technologies (e.g., construction of an information platform, cloud computing, intelligent labels, and path optimization technology) to reduce circuitous transportation effectively and improve logistics efficiency, especially regarding highways and aviation. In particular, it is also urged to develop and adopt big data technology to match vehicles and cargos for reducing empty-run rates. Besides, the government should vigorously promote the modernization and standardization of logistics equipment to promote the connection of various transport modes.
3. Optimize the energy structure and freight transportation structure. Energy structure played a significant promoting role during 2005–2015, which is mainly due to the sharp increase in oil consumption. Therefore, the government should encourage logistics enterprises to increase the use of new and clean energy such as natural gas, solar energy, and wind power through subsidies and carbon-trading policies. Moreover, the government is advised to learn from the Marco Polo program run by the European Commission. It is urged to shift freight to greener modes such as

railways and waterways to mitigate environmental pollution as well as traffic congestion through financial support. Simultaneously, it is urged to encourage the development of intermodal transport and common delivery to ease energy consumption. The Chinese government should strengthen the overloading management to prompt freight shift from road to railways and waterways for economic scale effects.

4. Reduce the impact of urbanization on logistics CO_2 emissions. The urban built-up area expansion factor produced the spatial separation of the residence and workplaces and the increase of transportation distance, which caused circuitous transportation problems and more fuel consumption. Therefore, the Chinese government has to plan an urban spatial structure reasonably. For example, the government can further plan and develop a new ecological industry city, with a high agglomeration of industries and urban living facilities to ease the traffic congestion caused by commuter traffic. Second, the government should scientifically plan the logistics infrastructure network and strengthen the construction of integrated freight transport hubs to reduce circuitous transportation and achieve efficient connections between different transport modes. Third, it is expected to optimize the structure for the supply chain to reduce unnecessary transportation distances. Fourth, the government should conduct further training to improve the energy-saving abilities of logistics enterprises and publicize the notion of green logistics in the 13th five-year plan period. Meanwhile, economic growth proved to have the most significant role in promoting CO_2 emission increases. Thus, the government ought to combine economic policies with energy-conservation and emission-reduction policies (such accelerating the marketization of energy price) to achieve a low-carbon economy in China.

Author Contributions: Shiqing Zhang and Jianwei Wang conceived, designed and wrote the paper; Wenlong Zheng helped to build the extended LMDI approach and construct the decoupling model.

Acknowledgments: The paper is supported by "the National Natural Science Foundation of China" (No. 51278057) and "the Fok Ying-Tong Education Foundation" (No. 151075).

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

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