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Original Research

Measuring Driving Factors and Decoupling Effect of Transportation CO_2 Emissions in Low-Carbon Regions: A Case Study from Liaoning, China

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Abstract

This paper presents the results of research aiming at uncovering provincial CO_2 emissions patterns in China, providing insights on CO_2 emissions growth in the transportation sector, and using as case to study the low-carbon pilot region of Liaoning. We performed an energy consumption analysis, a decomposition analysis, and a decoupling analysis to provide a holistic picture of transportation-related CO_2 emissions growth over the last two decades, in parallel with the four stages of the national Chinese economic and social development plan, or "Five-Year Plan" (FYP). The results indicate that the CO_2 emissions generated by the transportation sector in the Liaoning Province have been gradually increasing from the 9th FYP to the 12th FYP. Economic growth and population scale proved to be positive driving factors of CO_2 emission changes. Specifically, the economic scale played the most significant role in increasing CO_2 emissions. At the same time, energy intensity served as the principal factor in curbing CO_2 emissions, while energy structure displayed relatively weaker effects. In the period investigated, the decoupling relationships have mainly experienced a clear positive trend, from an expansive negative decoupling towards a weak decoupling. Several suggestions are provided for local authorities to achieve CO_2 emissions mitigation and sustainable development in transportation sector.

Keywords: low-carbon region, CO_2 emissions mitigation, transportation sector, LMDI method, decoupling analysis.

Introduction

Climate scientists have confirmed that the atmospheric concentrations of carbon dioxide (CO_2) have been increasing significantly over the past century, resulting in a negative influence on the global climate system [1]. Due mainly to the CO_2 emissions produced by fossil fuels consumption, climate change is considered an unprecedented global challenge [2]. The transportation sector remains the largest consumer of petroleum, and its use for freight services is increasing at a staggering rate, faster than any other applications [3]. Because of its sustained high energy consumption, the transportation industry generates approximately

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24% of total global CO_2 emissions, ranking in the second place in energy use among all industries [3]. The global CO_2 emissions from transport section will increase by 140% in 2050, compared to the level of 2000 [1]. Consequently, it is of great importance to reduce the carbon emissions from transportation industry in order to mitigate the total global carbon emissions.

Driven largely by the extensive economic growth and the huge industrial scale, freight volume turnovers in China are expected to grow on an annual basis. CO_2 emissions from fuel combustion by the transportation sector in China have recorded an increase of 762% in 2016 compared to 1990 [1]. CO_2 emissions from the transportation industry contributed to 15.9% of China's aggregate CO_2 emissions produced by fuel consumption [4]. It is projected that the energy consumption of the transportation sector in China will increase by 36% from 2015 to 2040, growing far more rapidly than in several OECD countries [3]. It can be seen that mitigation emissions in transportation has proved to be a key to achieve goals of energy conservation and carbon emissions reduction. Therefore, the research of CO_2 emissions from transportation is expected to provide implications for carbon emissions mitigation, the achievement of energy conservation and the development of green transportation.

As the world's largest CO_2 emitter, China is actively engaging in the international negotiations addressing climate issues [5]. In 2015, China ratified the Paris Agreement and made its commitment to control the average temperature increase below 2 degrees Celsius by 2100 [6-7]. To this end, the Chinese government has decided to focus on mitigating CO_2 emissions, especially from high energy-consuming industries. In parallel, in September 2019, the State Council officially promulgated the "Guidelines for the Building of a Transportation Powerful Nation", which attach a great importance to the development of a high-efficiency green traffic system, and set the specific target to become by 2035 a powerful country, with a great, low-carbon transportation [8]. Moreover, the Chinese State Council proposed the transportation sector as one of the priority sectors for energy conservation for the 13th Five-Year Plan (2016-2020). Therefore, the Chinese government is facing the unprecedented double challenge of reducing carbon emissions, while at the same time ensuring the sustainable development of the transportation industry. To address increasing carbon emissions, the Chinese government implemented low-carbon development demonstration projects and anticipated to obtain useful results from pilot regions by 2020 [9]. These pilot regions have been chosen for their emphasis on promoting energy-saving and carbon emissions mitigation, and for considering the decarbonization as one of their policy targets [10]. There is no doubt that China should promote the decarbonization of several industries, including the support to a low-carbon transportation sector. However, it is difficult to develop policy instruments for the decarbonization of the transportation industry if the current situation of CO_2 emissions patterns is not properly assessed [5]. Therefore, the assessment of the CO_2 emissions from the transportation sector in a low-carbon pilot region is likely to be essential to provide a meaningful reference to other regions in China and to policy-makers.

This paper aims at uncovering the CO_2 emissions patterns in the transportation sector, by focusing on the case study of a Chinese low-carbon province, the Liaoning Province. This is the only region designated for national low-carbon development demonstration projects in the northeastern part of China [9]. The province of Liaoning extends for 148,000 km^2, with an estimated population of 43.82 million in 2015. It is one of China's leading provinces for industrial and economic development [11]. Owing to its geographical location and industrial characteristics, in 1984, Liaoning started to build the "Shen-Da expressway", the first highway in China, to connect Shenyang and Dalian. The transportation industry in Liaoning has witnessed rapid development since 2000s. In 2003, China's first high-speed passenger train line, linking the provinces of Liaoning and Hebei, was put into operation; it is considered to be a significant symbol of high-speed railways in China. Meanwhile, as the only coastal province in the northeastern region, Liaoning has actively promoted the construction of a hub for the development of an international transportation corridor. Considered as a significant, old industrial base of China, the province of Liaoning has witnessed a spectacular economic development with the enforcement of policies to assist the old industrial base in the northeast of China, which resulted in the increase of fuel consumption from the transportation sector [12]. In 2015, the transportation freight turnover of Liaoning increased by 13.5% annually, ranking in the second place among all Chinese provinces. During this period, the associated fuel consumption grew by 9.6% per year on average, a value that was significantly 1.1% higher than the national value. With regard to the severe environmental problems and considerably rises in fuel consumption, Liaoning province is facing an unprecendented challenge on reducing environmental emissions. Considered as the only region designed for low-carbon pilot in the northeastern part of China, the authorities should pay more attention to its energy conservation and emissions reduction for Liaoning province. The Liaoning province can be served as a demonstration of sustainable development, thereby highlighting the significant importance of carbon emissions research, especially in transport sector. Due to the peculiarities of Liaoning, we chose this low-carbon pilot region to explore the driving forces of CO_2 emissions, and estimate the extent to which these are decoupled from the development of the transportation sector. Depth research of energy saving and carbon emissions in Liaoning province is an urgent requirement, to explore the path to fulfillment of carbon mitigation commitment at the national level.

The contribution of this paper to the existing literature is two-fold. First, unlike other studies that focused on the macro level, or on the developing regions of China, we provided for the first time an insight on CO_2 emissions patterns of a low-carbon pilot region, i.e., Liaoning. More concretely, in this paper, we not only estimated the quantity of CO_2 emissions and explored the driving factors, but also paid attention to the relationship between energy, environment, and economy. In addition to the two traditional indicators of economy and population, based on the features of Liaoning, we developed a decomposition approach to include also the indicators of energy structure, energy intensity, and industrial structure, thereby facilitating the investigation of the mitigation driving forces. Moreover, we used the Tapio decoupling approach to provide an insight on the decoupling relationship among energy, environment, and economy in the transportation sector in low-carbon regions. Second, current assessments of CO_2 emissions from the transportation industry are mostly performed on a yearly basis. However, in this study, we considered the national economic plan of China and advanced a new perspective to discuss and analyze it. Specifically, our study covers the last two decades, which have been divided into four stages following the FYPs that have been implemented. Therefore, special focus will be given on the correlation among environment, energy, and economy during the four FYPs investigated.

Literature Review

Due to the growing attention received by climate change, there is an increasing amount of research focusing on the uncovering the driving forces of CO_2 emissions [13]. The structural decomposition analysis (SDA) and the Index decomposition analysis (IDA) are the most commonly adopted tools [12]. Specifically, the SDA method depends on the input-output model, which requires a high quantity of complex data [14]. Compared to SDA, IDA has been adopted by a higher number of studies [15]. There are several types of IDA, such as the Laspeyres Index and the LMDI [12]. The LMDI is normally preferred, thanks to its outstanding advantages in terms of not leaving residual terms in the results [16-17].

As a perfect technique, LMDI method has been widely used in the decomposition of CO2 emissions [18-19]. A growing number of studies utilized the LMDI approach to investigate the effects on the CO_2 emission changes in the transportation industry. Andreoni and Galmarini [20] performed an investigation of the underlying factors of CO_2 emissions changes in water and air transportation activities in European countries between 2001 and 2008. M'Raihi et al. [21] decomposed the annual CO_2 emission changes in the road transportation sector in Tunisia, to explore the contributions of the various factors, highlighting policy implications according to the findings. In recent years, several scholars have probed into the decomposition of CO_2 emissions in the Chinese transportation sector. From a national perspective, Liang et al. [22] proposed a decomposition model and analyzed the effects of six selected factors of growth of the transportation sector. Their results indicate that economic development accounted for most of the increase in CO_2 emissions, while energy efficiency was primarily responsible for suppressing CO_2 emissions. There is a limited amount of studies focusing on the decomposition of CO_2 emissions in the transportation sector at regional level. Fan and Lei [23] built an LMDI model to explore the major factors influencing CO_2 emissions changes in the transportation sector in Beijing, the capital of China. Several suggestions were advanced based on their findings. Zhu and Li [24] investigated the influencing factors of transportation CO_2 emissions in the Beijing-Tianjin-Hebei area, using the decomposition method combined with a decoupling method. They also indicated some policy implications for the development of green transportation in this area.

In parallel, the fast growth of CO_2 emissions attracted public attention on the issues of environmental and sustainable development [25]. Several indicators have been proposed to measure the process of sustainable development. Among these, the decoupling indicator can be considered as the one of the most appropriate [26-27]. Originating from the physics field of study, it was first introduced by Zhang [28] to explore the relationship between CO_2 emissions and economic activity. More into detail, the decoupling indicator evaluates the disconnecting links between economic activities and environmental pressures [29]. In 2005, Tapio [30] introduced the decoupling index to specify eight logical possibilities, divided into three categories (i.e., decoupling, coupling, and negative decoupling). The Tapio decoupling model has been adopted in several studies of various industries [31-32]. Most of the existing literature applying the decoupling model conducted a general analysis, referring to the delink states between economic growth and energy-related CO_2 emissions from a general national perspective [15, 33-34]. Zhao et al. [35] utilized the Tapio model to examine the relationship between transportation output and CO_2 emissions in the province of Guangdong, China, between 1995 and 2012. Wang et al. [36] measured transportation CO_2 emissions and economic activity in Jiangsu between 2005 and 2012. Yang and Ma [37] quantitatively investigated the decoupling relationship between economic growth and CO_2 emissions in seaborne transportation from 2000 to 2017. Finally, Wang et al. [38] used an improved Tapio model to estimate the decoupling effect at national level. The previous decoupling analyses of the transportation sector are significant references for the present study.

Most of the existing studies focus on carbon emissions from the transportation sector at the national level, rather than addressing environmental issues at the provincial level. Even in the case of limited regional-level studies, the case studies developed failed to concentrate on the sustainable development of transportation in low-carbon pilot regions. Moreover, scholars omitted to link the carbon emissions status quo to the national economy plan and policies, i.e., the FYP. This study aims to fill these gaps by uncovering the transportation CO_2 emissions patterns in the Liaoning Province. The empirical results indicated in this paper are likely to provide solid references for the authorities to establish realistic carbon mitigation regulations in the transportation industry, under the current development trends.

Material and Methods

CO_2 Emissions Estimation Approach

According to the IPCC guidelines, there are two possible approaches to measure the CO_2 emissions of the transportation sector [39]. The bottom-up method is more widely used to deal with the practical situations of transportation activities. However, the data collection system is considerably complex and entails great uncertainty. Hence, it is more accurate to estimate CO_2 emissions by using a top-down approach, considering different fuels for energy consumption [24]. In this paper, we adopted a top-down fuel-based approach to calculate the CO_2 emissions of the transportation sector. The calculation formula, adopted in several studies [40-42], is the following:

$$C = \sum_i E_i \times EF_i \tag{1}$$

...where C represents the CO_2 emissions produced by transportation activities in year t; E_i refers to the consumption of fuel i; and EF_i stands for the CO_2 emission factor of fuel i.

We considered the fuel consumption of four principal transport modes, i.e., road, railway, shipping, and aviation. According to statistical data, there are six major energy sources involved in end-use energy-related CO_2 emissions, namely raw coal, gasoline, kerosene, diesel, fuel oil, and natural gas. Table 1 illustrates the CO_2 emission factors used in this study. Railways depend on electricity, which may indirectly produce CO_2 emissions [40]. Therefore, we considered only the direct CO_2 emissions produced in the transportation industry, while indirect CO_2 emissions (such as CO_2 emissions produced by electricity) have not been taken into consideration.

CO_2 Emission Changes Decomposition Approach

We decomposed CO_2 emission changes in the transportation sector in Liaoning by adopting the LMDI model, as follows:

$$\begin{aligned} C &= \sum_i C_i = \sum \frac{C_i}{E_i} \times \frac{E_i}{E} \times \frac{E}{GDP_{tr}} \times \frac{GDP_{tr}}{GDP} \times \frac{GDP}{P} \times P \\ &= \sum_i EF_i \times ES_i \times EI \times IS \times G \times P \end{aligned} \tag{2}$$

...where C denotes the aggregate CO_2 emissions from transportation in Liaoning; C_i refers the CO_2 emissions produced by energy sources i; E_i denotes the end-use consumption from energy sources i; E is the total energy consumption from the transportation sector; GDP_{tr} denotes the output values of the transportation industry in Liaoning; GDP represents the gross domestic product of Liaoning; P stands for the population scale of Liaoning; EF_i denotes the emission factor of energy sources i; ES_i refers to the energy structure of the transportation sector; EI denotes the energy intensity, which stands for energy efficiency; IS represents the industrial structure, referring to the share of GDP of the transportation industry; and G is the per capita GDP of Liaoning.

Due to the limited temporal range of our study, we assumed that the emission factors of different types of fuel remained stable during the two decades. Thus, the emission factor effect can be considered as equal to zero. Based on Eq. (2), the variations in CO_2 emissions

Table 1. CO_2 emission factors of different types of fuels.

Fuel type	Potential carbon content (kg C/GJ)	Oxidation rate (%)	LCV (KJ/Kg or KJ/m^3)	EF (tCO_2/ton or t $CO_2/10^3$ m^3)
Raw Coal	26.37	98	20,908	1.981
Gasoline	18.9	98	43,070	2.925
Kerosene	19.6	98	43,070	3.033
Diesel	20.2	98	42,652	3.096
Fuel oil	21.1	98	41,816	3.17
Natural gas	15.3	98	38,931	2.162

Data: Guo et al. [30].

in the Liaoning transportation industry, from the base year 0 to the final year T, can be expressed as follows:

$$\Delta C^T = C^T - C^0 = \Delta C^T_{es} + \Delta C^T_{ei} + \Delta C^T_{is} + \Delta C^T_{act} + \Delta C^T_{pop} \tag{3}$$

$$\Delta C^T_{es} = \sum_i \frac{C_i^T - C_i^0}{\ln\left(C_i^T\right) - \ln\left(C_i^0\right)} \ln\left(\frac{ES_i^T}{ES_i^0}\right) \tag{4}$$

$$\Delta C^T_{ei} = \sum_i \frac{C_i^T - C_i^0}{\ln\left(C_i^T\right) - \ln\left(C_i^0\right)} \ln\left(\frac{EI_i^T}{EI_i^0}\right) \tag{5}$$

$$\Delta C^T_{is} = \sum_i \frac{C_i^T - C_i^0}{\ln\left(C_i^T\right) - \ln\left(C_i^0\right)} \ln\left(\frac{IS_i^T}{IS_i^0}\right) \tag{6}$$

$$\Delta C^T_{act} = \sum_i \frac{C_i^T - C_i^0}{\ln\left(C_i^T\right) - \ln\left(C_i^0\right)} \ln\left(\frac{G^T}{G^0}\right) \tag{7}$$

$$\Delta C^T_{pop} = \sum_i \frac{C_i^T - C_i^0}{\ln\left(C_i^T\right) - \ln\left(C_i^0\right)} \ln\left(\frac{P_i^T}{P_i^0}\right) \tag{8}$$

...where ΔC^T denotes the CO_2 emission changes between base-year emissions (C^0) and final year emissions (C^T) and ΔC^T_{es}, ΔC^T_{ei}, ΔC^T_{is}, ΔC^T_{act}, and ΔC^T_{pop} denote the effects of energy consumption structure, energy intensity, industrial structure, economic growth, and population scale, respectively, on carbon emissions.

To overcome the zero-values issue implied in the LMDI model, Ang [43] proposed to use an extremely small value, such as 10-20, to substitute zeros. This type of strategy has shown to be robust, and allows to achieve satisfying results even in high extreme cases [44].

The Tapio Decoupling Model

According to the refinement described in the Literature review section, the Tapio decoupling index has been regarded as an appropriate indicator of environmental sustainability. Thus, we adopted the Tapio's criterion, consisting of the ratio of percentage change of CO_2 emissions to the economic indicators, from the baseline year 0 to the final year T [25]. The Tapio decoupling index can be expressed as follows:

$$D_T = \frac{\%VC_T}{\%VGDP_T} \tag{9}$$

...where D_T represents the decoupling index from the baseline year 0 to the final year T; and $\%VC_T$ and $\%VGDP_T$ represent the percentage change of CO_2 emissions and Liaoning's provincial *GDP* from year 0 to year *T*, respectively. These two percentage change values can be calculated as follows:

$$\%VC_T = \frac{C_T - C_0}{C_0} \times 100\% \tag{10}$$

$$\%VGDP_T = \frac{GDP_T - GDP_0}{GDP_0} \times 100\% \tag{11}$$

Decoupling states are classified into eight logical possibilities according to the decoupling index [30], as shown in Fig. 1. To not overinterpret slight changes as significant, a±20%variation of elasticity around the value of 1.0 was still considered as coupling.

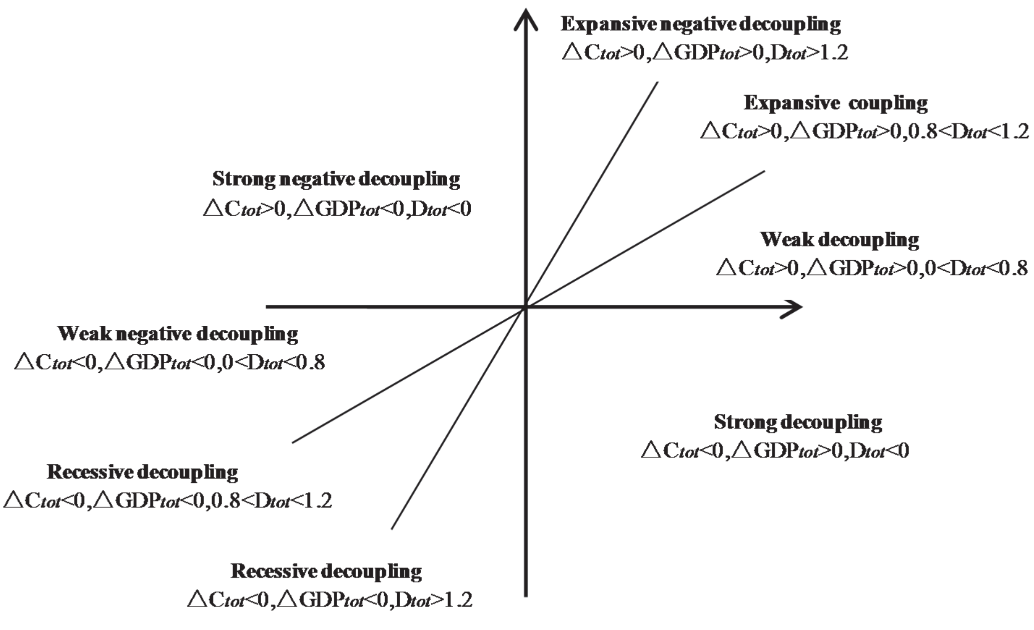

Fig. 1. The eight decoupling states of the Tapio decoupling model.

Data Sources

In this paper, we considered six energy types, namely raw coal, kerosene, gasoline, fuel oil, diesel, and natural gas. When calculating total energy consumption, we quoted the end-use consumption unit in standard coal equivalent. We obtained the standard coal coefficients of various fossil fuels from the China Energy Statistical Yearbooks. The GDP of Liaoning, the GDP of transportation industry and population data have been obtained from various issues of the Liaoning statistical yearbook 1996-2015 [45]. Population is measured in million persons. As for economic indicators, the GDP of Liaoning is quoted in billion Yuan and converted into constant 2005 prices to eliminate the deflation effect.

The temporal range of our investigation stretches along two decades from 1996 to 2015, in line with the national FYP periods, namely 1996-2000 (9th FYP), 2001-2005 (10th FYP), 2006-2010 (11th FYP), and 2011-2015 (12th FYP).

Results and Discussion

Analysis of the Status Quo

Fig. 2 shows the trends of aggregate transportation CO_2 emissions and related annual growth. CO_2 emissions from the transportation sector in Liaoning have experienced a considerable increase (see Fig. 3), from 4.54 million tons (Mt) in 1996 to 36.15 Mt in 2015, with an annual average growth of 11.53%. During the first decade (1996-2005), CO_2 emissions in the transportation sector have risen fivefold, with three sharp increases in the periods 1996-1997, 1999-2001, and 2004-2005. After 2005, CO_2 emissions had a steady yearly growth with small occasional fluctuations. This may be attributed to

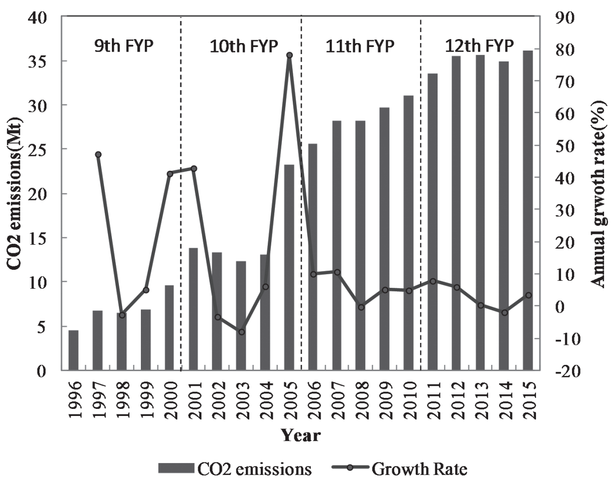

Fig. 2. CO_2 emissions and annual growth rate from the transportation sector in Liaoning.

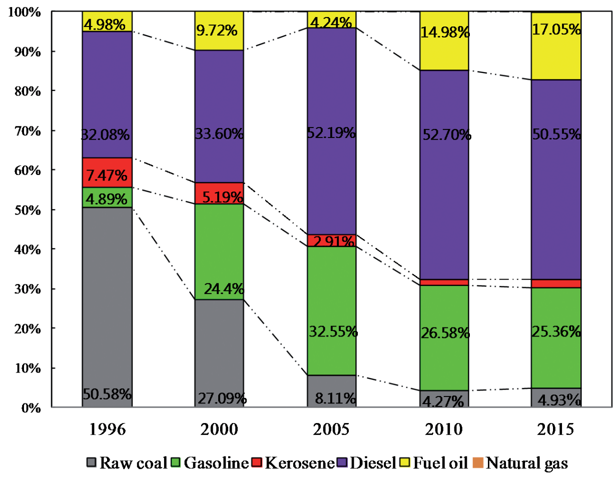

Fig. 3. Shares of CO_2 emissions of different types of fuels.

the economic transition triggered by the authorities. The Chinese government has paid increasing attention to high-quality economic development, and devoted itself to change the paradigm of economic growth from extensive to intensive during the 11th FYP. By the end of the 11th FYP, China basically accomplished the middle stage of industrialization, stepping into the late stage of industrialization with the 12th FYP and accelerating the construction of a socialist harmonious society, based on resource conservation and environmental protection [46].

Fig. 3 illustrates the contribution to CO_2 emissions made by different types of fuels between 1996 and 2015. In general, the energy structure in the transportation sector has experienced significant changes over the last two decades. It is evident that, before 2000, more than half of total CO_2 emissions from the transportation sector were mostly produced by raw coal, while after 2000, oil-based energy sources generated the majority of CO_2 emissions. The share of CO_2 emissions generated by raw coal decreased significantly, from 50.6% in 1995 to 4.9% in 2015. This may be attributed to the rapid development of high-way railways over the last decades, which may have propelled the consumption of electricity rather than raw coal. Among the different types of oil-based energy sources, diesel and gasoline produced the highest quantity of CO_2 emissions in 2015, accounting for 50.6% and 25.3% of total CO_2 emissions, respectively. This indicates that highway transportation had a predominant role in the past decades. In parallel, the proportion of CO_2 emissions from fuel oil has witnessed a clear increase, from 4.87% in 1996 to 17.05% in 2015 (see Fig. 3). Since fuel oil is used for water transportation, this increase testifies the dramatic expansion of the demand for water transportation during the period investigated. Compared to the other types of fuel, the share of kerosene had an opposite tendency, whereby its proportion of CO_2 emissions dropped to 2.02% in 2015 from 7.47% in 1996. This can be explained by the fact that aviation transportation in the province of Liaoning did not develop as much as other transport modes.

Considered as a type of clean energy, natural gas began contributing to CO_2 emissions from 2008, with an increasing trend in the following years. The use of natural gas increased to 30.3 thousand tons in 2015, i.e., 150 times more than in 2008. This may be due to the implementation of policies promoting clean transportation. Thus, natural gas consumption, and associated CO_2 emissions, for both road and water transportation have experienced a considerable expansion. However, compared to the other traditional energy sources, the amount of CO_2 emissions from natural gas still occupies an extremely small and not significant proportion of 0.2% in 2015, as illustrated in Fig. 3.

Decomposition Analysis of CO_2 Emissions from the Transportation Sector

The decomposition results of CO_2 emission yearly changes are shown in Fig. 4. Economic activities and population scale contributed to CO_2 emissions growth, while energy intensity, energy structure, and industrial structure appeared to act as inhibitors. More into detail, economic development proved to be the most significant contributor to the increment in CO_2 emissions. The decomposition results of the LMDI study on the transportation sector every five years, corresponding to the different FYP periods, are illustrated in Fig. 5. The effects of all influencing factors are analyzed in the following paragraphs.

Energy Structure

As shown in Fig. 4, energy structure had a negative impact on transportation CO_2 emissions in Liaoning. This impact, however, showed fluctuations over the whole period investigated. The accumulated inhibitory effect of energy structure was likely to be limited, contributing to approximately -3% of total changes in CO_2 emissions. The effect of energy structure found in

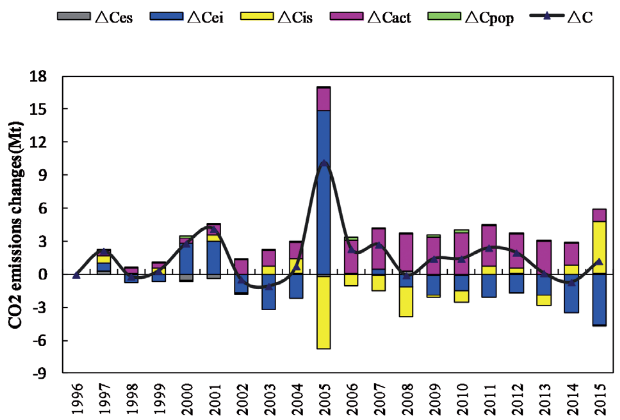

Fig. 4. Decomposition results of CO_2 emissions yearly changes.

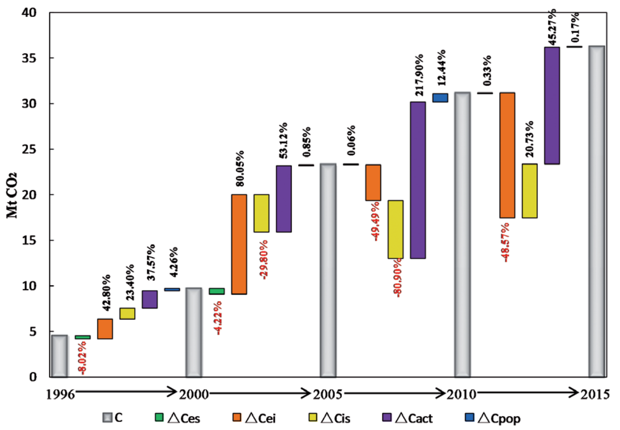

Fig. 5. Decomposition results of carbon emission driving factors during the five FYP stages between 1996 and 2015.

this study is similar to the majority of previous studies on transportation CO_2 emissions at the regional level in China [24, 36]. Though the suppression effect was not as significant as the other driving forces, the adjustment of energy structure cannot be ignored in relation to the control of the increase of CO_2 emissions.

Specifically, as shown in Fig. 5, energy structure played a curbing role during the periods 1996-2000 (corresponding to the 9th FYP) and 2000-2005 (corresponding to the 10th FYP). This can be mainly attributed to the decline of the proportion of raw coal to total fuel consumption. During these periods, traditional steam locomotives fueled by raw coal were gradually replaced by high-speed electric locomotives [47]. The decline in raw coal consumption contributed to the variation of the energy structure. After 2010, Liaoning implemented a series of policies focusing on the optimization of the energy structure in the transportation sector. To reduce dependence on oil consumption, clean and green energy sources, such as natural gas and electricity, have been recommended in road transportation, especially for city buses. However, the objective of energy structure optimization entails a long-term transformation. Therefore, energy structure optimization plays an indispensable role in decreasing CO_2 emissions from the transportation sector.

Energy Intensity

Energy intensity is an index of energy efficiency; it is measured by fuel consumption per unit of GDP [48]. The decomposition results show that energy intensity (-4.58 Mt) had a clear inhibiting role on the increment of CO_2 emissions from the transportation sector, with a cumulative contribution of -14.5%. Our results are in line with other earlier studies [1, 4]. Energy intensity contributed to the increase of CO_2 emissions during both the 9th and the 10th FYP, whereas it played an inhibiting role in the next two stages (see Fig. 5).

As shown in Fig. 6, energy intensity had several fluctuations between 1996 and 2005, which may be

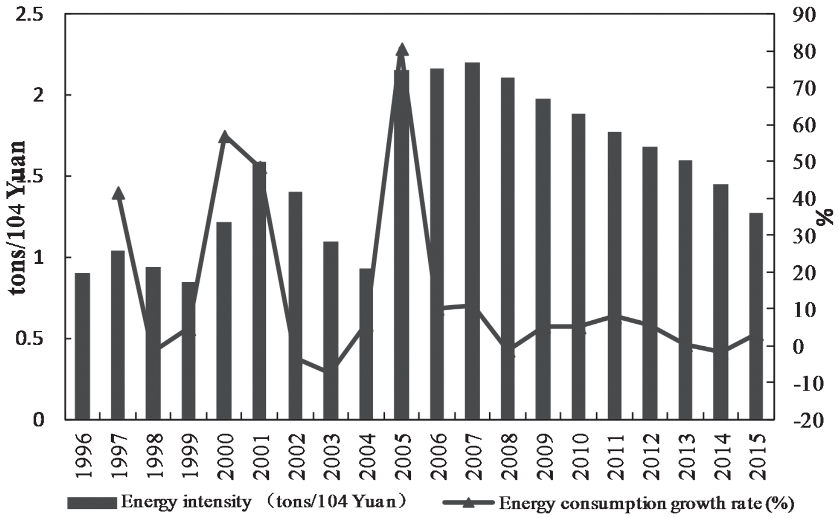

Fig. 6. Variation in energy intensity and energy consumption growth rates.

attributed to the expansion of the use of private cars and the rapid development of water transportation demand. In this period, the boom of transportation industry focused on demand expansion rather than on energy efficiency. After 2007, energy intensity in the transportation sector in Liaoning declined steadily on an annual basis, from 2.2 tons standard coal equivalent per 10^4 Yuan, to 1.27 tons standard coal equivalent per 10^4 Yuan in 2015. Theoretically, a decrease in energy intensity implies an improvement in the energy efficiency of the transportation sector. This may be due to the adoption of advanced energy efficiency transportation tools during the 11th FYP (2006-2010). For example, the capital of Liaoning province, Shenyang, has purchased a large number of newly-built, high-efficiency buses to replace the old gasoline ones [49]. In general, the reduction in CO_2 emissions due to the decline in energy intensity was larger than its positive effects on the CO_2 emission increase, resulting in a significant mitigation of emissions from the transportation sector from 1996 to 2015.

Industrial Structure

Generally, industrial structure inhibited the increment of CO_2 emissions, with continuous fluctuations during the last two decades. The adjustment of the industrial structure likely involved various factors, resulting in difficulties in optimizing the structure of the

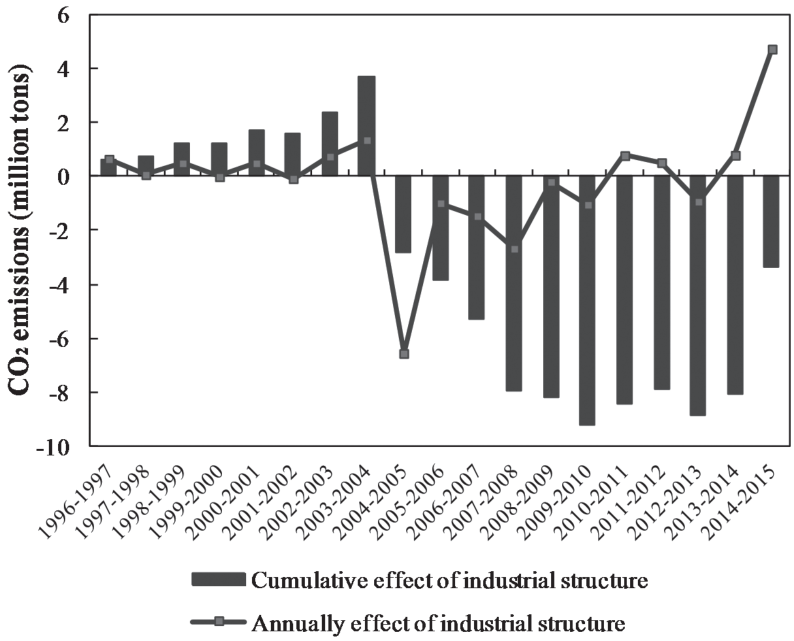

Fig. 7. Annual and cumulative effect of industrial structure on CO_2 emissions.

transportation sector [41]. Fig. 7 illustrates the annual contribution and the cumulative effects of industrial structure on carbon emissions between 1996 and 2015. The effects of industrial structure were different across the various stages investigated. The proportion of the transportation sector to all industries was almost unchanged over the 9th FYP, and subsequently showed a slight increase trend at the beginning of the 10th FYP. In 2005, Liaoning put great emphasis on the adjustment of the industrial structure; thus, the optimization of the structure of the transportation sector had a positive influence on CO_2 emission reduction. During the 12th FYP, the effect of industrial structure followed an increasing trend with frequent volatility, indicating a bottleneck in structure restructuring in Liaoning. All things considered, the suppressing effect of the industrial structure overwhelmed its stimulating effect, contributing to a total of -3.33 Mt of CO_2 emissions over the period investigated.

Economic Growth

The GDP per capita is considered a crucial measure of both economic activity and living standard [50]. As shown in Fig. 4 and Fig. 5, economic activity was the most significant positive influencing factor driving the increment of CO_2 emissions, confirming the results of several previous studies [21, 23-24]. In the period 1996-2015, the economic output contributed to an aggregate increase of 39.06 Mt CO_2 emissions, accounting for a cumulative effect of 123.5% of total change.

The GDP per capita of Liaoning increased from 8,413 Yuan in 1996 to 51,432 Yuan in 2015, with an annual growth rate of 10%. Theoretically, transportation demand ties tightly to economic growth. As economic levels enhance, people are expected to pursue a high life quality, which includes the use of a convenient transportation system [20]. Therefore, the request of an efficient transportation system impels the growth of the demand for transportation. In practice, between the 9th and the 12th FYP, the number of vehicles in Liaoning increased by 14.2% annually, far exceeding economic growth. Such expansion in transportation demand entails a substantial increase of fuel consumption and associated CO_2 emissions. In addition, another significant factor behind the fast growth of transportation demand was the recent boom of the tourism industry, which is heavily reliant on different transportation means such as vehicles, high speed railways, aviation, and shipping.

The results presented in this paper show that over the past two decades, the increase in carbon emissions was aggressively determined by the economic output. In the next five years, the growth rate of Liaoning economy is projected to be not lower than the average national growth, i.e., 6.5% annually. To this purpose, it is desirable that economic activities continue to stimulate transportation demand and associated CO_2 emissions. Under such circumstances, without new mitigation policies, the CO_2 emissions from the transportation industry in Liaoning are expected to increase steadily in the long period.

Population Scale

In relation to population scale, the decomposition results indicate that it was a positive driving force, which is in line with the findings of previous studies [24]. Compared to the effect of economic growth, the cumulative effect of population scale is not as significant, contributing only for 4.3% of aggregate CO_2 emission changes. It is very likely that population growth propels the acceleration of the urbanization process, which inevitably contributes to fuel consumption demand, and to related environmental issues in the transportation sector [51]. It is likely that population increase will boost the demand for mobility and thus contribute to the generation of more pollutants [52]. After the 1980s, population size has increased by only 8%, due to the rigorous enforcement of family planning policies by the authorities of Liaoning. Nevertheless, its contribution to CO_2 emission increase in the transportation industry between 1996 and 2015 was steady and positive. Analysis of the decoupling between CO_2 emissions and economic growth in the transportation sector**.**

The decoupling relation between CO_2 emissions and the GDP of Liaoning during the period 1996-2015 is illustrated in Table 2 and Fig. 8. As shown in Table 2, the decoupling index was equal to 1.24 during the whole study period, indicating a status of expansive negative decoupling (END). Fig. 8 illustrates the variation of the decoupling states during the various FYPs. With regard to the different periods, Liaoning's transportation sector underwent two main states, i.e., END in the periods 1996-2000 and 2000-2005, and weak decoupling (WD) in 2005-2010 and 2010-2015. Despite the fact that only two states appeared, the decoupling index showed a constant decrease trend during the different periods, from 2.93 in 1996-2000 to 0.36 in 2010-2015.

The 9th FYP period was characterized by an END with a relatively high indicator (2.93), indicating that the increase of CO_2 emissions was clearly higher than that of economic development. During this period, China was facing the consequences of the Asian financial crisis

Table 2. Decoupling index of the transportation sector in Liaoning.

Year	$\%VC$	$\%VGDP$	D	Decoupling state
1996-2000	1.13	0.38	2.93	END
2000-2005	1.40	0.70	2.00	END
2005-2010	1.34	0.92	0.37	WD
2010-2015	1.16	0.46	0.36	WD
1996-2015	6.96	5.60	1.24	END

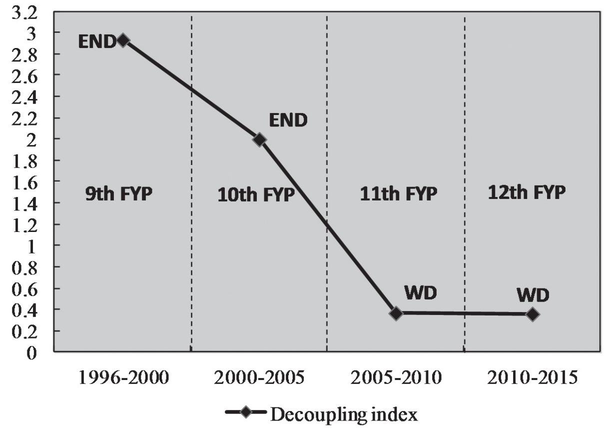

Fig. 8. Decoupling status and trends in the period 1995-2015.

in 1997, and the devastation caused by catastrophic flooding all over the country in 1998. Hence, it was desirable for the local government to promote economic development, to recover from the consequences of these events. In parallel, China was preparing to enter the WTO. Under these circumstances, the national policies overemphasized macro-level prosperity, rather than being concerned over environmental issues. Hence, the CO_2 emissions from the transportation sector in Liaoning recorded an average annual growth rate of 20.8%, which was far higher than that of the economic development (8.5%), thus contributing to the appearance of an END state.

During the 10th FYP period, the national economy gradually recovered from the previous depression, while China successfully entered the WTO. As a result, the economy of Liaoning developed at a staggering rate, with an average GDP growth of 11.2%. Such a sustained economic prosperity promoted energy consumption from the transportation industry, thereby increasing CO_2 emissions at annual average rate of 19.2%. The decoupling index of this second period showed an apparent decrease trend compared with the 9th FYP period, from 2.93 to 1.99. However, due to the relatively high decoupling index value, there was still an END between economic growth and CO_2 emissions in the transportation industry.

During the 11th FYP period, the authorities attached great importance to environmental sustainability [53]. Several national policies were implemented to strengthen and encourage energy conservation. For instance, the national medium- and long-term science and technology development program (2006-2020) was proposed in 2006, aiming at promoting energy saving and resources conservation in the transportation sector [36]. This type of strategy played a significant role in mitigating transportation CO_2 emissions. In this period, the economy of Liaoning recorded a continuous high-speed growth at an annual rate of 14%, which surpassed that of CO_2 emissions. As a result, a WD state occurred for the first time in two decades.

The 12th FYP period was characterized by a WD with an index of 0.36, which was almost identical to that of the 11th FYP period. The results indicate that the national instruments implemented to foster energy efficiency have indeed achieved remarkable results at a starting phase. Nevertheless, these positive effects were confronted with a bottleneck with the passing of time. In fact, during this period, the economic development of Liaoning passed from a phase of high-speed growth (during the 11th FYP) to a phase of stable medium-speed growth. Consequently, the relationship between economic growth and carbon emissions remained in a WD state during the fourth period.

According to the results of the decoupling analysis, the national and provincial policies implemented to promote energy efficiency and CO_2 emission reduction had a somehow positive influence on the development of a low-carbon transportation system. Nevertheless, according to our results, the decoupling index in the period of the 12th FYP was nearly constant. This indicates that there is still a long way to achieve a strong decoupling of CO_2 emissions from economic development in Liaoning's transportation sector.

Conclusions

Major Conclusions

In this paper, we estimated the amount of CO_2 emissions and analyzed their features in the transportation sector of a low-carbon region of China, i.e., the province of Liaoning. We explored the driving factors of carbon emissions growth and the correlation between environment and economy, in the period between the 9th and the 12th FYP. By employing the LMDI method, we performed a decomposition analysis to examine the driving factors governing CO_2 emissions changes in the transportation industry. We also concentrated on the relationships among energy, environment, and economy, by adopting the Tapio decoupling model to examine sustainable transportation development in this low-carbon pilot region. The major conclusions of this study are as follows:

– The aggregate CO_2 emissions from the transportation sector in Liaoning have witnessed a rapid increase during the last two decades, from 4.54 Mt in 1996 to 36.15 Mt in 2015, with an annual average growth of 11.53%. The contribution of different types of fossil fuels on carbon emissions varied over the period investigated. At the end of the 12th FYP, diesel and gasoline were responsible for producing the majority of aggregate CO_2 emissions, with a respective proportion of 50.6% and 25.3%.

– Economic growth proved to be the key factor promoting CO_2 emissions over the whole period investigated. Energy intensity appeared to be the dominant negative factor, followed by the effect of industrial structure. The other two factors

considered, i.e., population scale and energy structure, had a marginal influence on CO_2 emission variations.
- During the period 1996-2015, the decoupling index for CO_2 emissions in the transportation sector followed a gradual downward trend. In other words, the decoupling state gradually shifted from a phase of expansive negative decoupling (correspondent to the 9^{th} and the 10^{th} FYP) to a phase of weak decoupling (corresponding to the 11^{th} and the 12^{th} FYP). Hence, there is still substantial room in the Liaoning Province for economic activities to decouple from transportation carbon emissions.

Policy Implications

Considering the current characteristics of CO_2 emissions, it is likely that the Liaoning provincial government will face significant challenges to control fuel consumption and mitigate the environmental issues generated by the transportation sector. Based on the findings of our research, we propose several concrete policy actions:
- Optimize the energy structure in the transportation sector. Our results showed that energy structure was an inhibiting factor of CO_2 emissions. It is expected that the energy structure should be adjusted to accelerate the utilization of renewable and cleaner energy, such as biogas and natural gas. The widespread diffusion of new-energy vehicles powered by natural gas or electricity should be promoted. In addition, regarding the diversity of different emissions factors, the proportion of high-emission fossil fuels, such as fuel oil and diesel, to total energy consumption should be reduced [54].
- Improve energy efficiency. In relation to the significant offset effect of energy intensity, authorities should place more emphasis on the improvement of energy efficiency for CO_2 emissions mitigation in the transportation industry. Technological progress is considered as the most effective approach to boost the improvement of energy efficiency [52]. Thus, corresponding policies focusing on the promotion of low-carbon technologies should be introduced, such as financial incentives for technology innovations. In parallel, newly-built, high energy efficiency vehicles are expected to produce less CO_2 emissions than inefficient ones [55]. Therefore, the provincial government of Liaoning is encouraged to progressively phase out low energy efficiency vehicles and replace them with green vehicles.
- Employ market-based approaches. Economic growth was the primary stimulator of the increment of CO_2 emissions during the study period. The economy of Liaoning is projected to maintain a steady increase trend in the future, resulting in a continuous growth of CO_2 emissions. Under these circumstances, market-based instruments should be introduced, such as carbon tax and carbon emissions trading schemes. These types of measures can not only push CO_2 emissions producers to more actively explore mitigation strategies, but also provide economic incentives for the local government [55].
- Develop the construction of transportation infrastructures. According to our results, transportation-related CO_2 emissions appeared to have a weak decoupling with economic growth after 2010. To completely break the link between economy and environmental issues, waterways facilities should be promoted, since they are the most efficient transportation mode [56]. The authorities should also focus on the development of high-speed electric railways [54]. As a public transportation mode, the expansion of high-speed railways will indeed relieve the depression of road freight transportation. In addition, it is indispensable to facilitate the utilization of green vehicles, accelerating the construction of transportation infrastructures such as corresponding gas stations. In fact, with the building of a large network of gas stations, it will be easier to recharge green vehicles in the filling stations, and to maintain a good performance.

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Conflict of Interest

The authors declare no conflict of interest.

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