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# Towards a Decoupling between Economic Expansion and Carbon Dioxide Emissions of the Transport Sector in the Yellow River Basin

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**Abstract:** Realizing the decoupling development between the economic expansion and carbon dioxide emissions of the transport sector is of great importance if the Yellow River basin is to achieve green and low-carbon development. In this paper, we adopt the Tapio decoupling index to examine the decoupling relationship within the transport sector in the Yellow River basin, and then introduce the standard deviational ellipse to dynamically analyze the spatial heterogeneity of carbon emissions and economic growth at the provincial level. Furthermore, based on the decoupling method, we expand the traditional logarithmic mean Divisia index decomposition (LMDI) model to decompose the decoupling index into eight sub-indices, and we identify the impact of each factor on the decoupling relationship. The results indicate that the carbon emissions of the transport sector in the Yellow River basin show the non-equilibrium characteristics of "upstream region < midstream region < downstream region". The decoupling state of the transport sector shows obvious spatial differences. The less-developed regions are more likely to present non-ideal decoupling states. The growth rate of carbon emissions in Sichuan, Qinghai, and Shandong provinces is relatively fast, and the azimuth of the transport sector's carbon emissions shows a clockwise trend. Moreover, the inhibitory effects of urbanization on decoupling in the Yellow River basin are much greater than the non-urbanization factors. In addition to the effect of urbanization, the transport structure has a major negative effect on decoupling development in the upstream and midstream regions, while energy intensity and energy structure are key to realizing a decoupled status in the downstream region. Finally, we propose some differentiated policy recommendations.

**Keywords:** $CO_2$ emissions of transport sector; decoupling relationship; standard deviational ellipse; influencing factor; Yellow River basin

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## 1. Introduction

The Yellow River basin plays an important role in the national economic development pattern, and it is an important representative area of climate warming [1]. In September 2019, General Secretary Xi Jinping elevated ecological protection and high-quality development in the Yellow River basin to constitute a major national development strategy. In the Yellow River basin, we should coordinate economic development and environmental protection and firmly pursue a green and low-carbon path of development. In September 2020, General Secretary Xi proposed the goal of a "double carbon" national independent contribution in China; that is, peak carbon emissions by 2030 and carbon neutrality by 2060 [2]. This is the first time that China has explicitly proposed the goal of carbon neutrality. China is a developing country, and this is a very challenging and arduous task. The Yellow River basin plays a very important role in China's carbon emission reduction strategy. In 2019, the total consumption of fossil energy and carbon emissions in the Yellow River basin accounted for 35.1% and 40.5% in China, respectively [3]. The Yellow River basin is facing the enormous pressure of coping with energy conservation and carbon emission reduction [4].

The transport sector is one of the industries with the largest energy consumption, and the fastest growth of carbon emissions [5]. In China, the transportation industry is second only to industry and construction, becoming the third largest energy consumer and an important source of $CO_2$ emissions [6]. With the rapid development of industrialization and urbanization, the transportation industry in the Yellow River Basin has developed rapidly [7]. In 2019, the added value of the transport sector in the Yellow River basin accounted for 28.78% in China, and the transport carbon emissions in the Yellow River basin accounted for 31.64%. If no measures are taken, the rapid development of urbanization will continue to promote transport demand and generate high carbon emissions in the Yellow River basin [8]. Accordingly, the carbon emissions of the transport sector in the Yellow River basin cannot be ignored, and they should be strictly and effectively controlled. On the one hand, the transport sector is a basic and strategic industry that plays a prominent leading role in the economic development of the Yellow River basin, and its development must be guaranteed moving forward [9]. On the other hand, the transportation industry has shown high energy consumption and high emissions for a long time, which works against meeting the requirements of green and low-carbon development in the Yellow River basin. Consequently, ensuring that the transport sector in the Yellow River basin continues to develop, while effectively reducing its energy consumption and carbon emissions, and gradually reducing the dependence of transportation development on carbon emissions, is a problem that urgently needs to be solved. To date, few papers have investigated the carbon dioxide emissions of the transport sector in the Yellow River basin. Therefore, it is necessary to study the decoupling of the economic expansion and carbon dioxide emissions of the transportation industry in the Yellow River basin.

Realizing the decoupling of economic growth from $CO_2$ emissions has been considered as the main means to achieve the goal of reduced emissions [10]. Many scholars have studied the relationship between carbon emissions and economic development. However, little research has investigated the decoupling of $CO_2$ emissions from economic growth in the Yellow River basin [11], and even less research has dynamically analyzed the spatial heterogeneity of the transport sector's carbon emissions and economic growth from the perspective of the provincial transport sector [12]. The province is the main body of carbon emission reduction policy implementation and emission reduction quota allocation, and each province is connected to and influences the others in geographical space [13]. Not considering spatial dependence and assuming the provinces are independent would result in calculation deviations [14]. When formulating specific carbon emission reduction policies, the regional differences and spatial dependence among provinces should be considered. Therefore, it is critical to analyze the dynamic spatio-temporal characteristics and heterogeneity of the provincial transport sector's $CO_2$ emissions and economic growth, considering spatial dependence, in the Yellow River basin.

The transport carbon emissions in the Yellow River basin are determined by many factors. The urbanization rate of the Yellow River basin increased from 32.22% in 2000 to 60.57% in 2020, and this has inevitably had an important impact on the carbon emissions of the transport sector [15]. On the one hand, urbanization has resulted in the transfer of populations from rural to urban areas, which promotes the realization of the transportation scale effect. It is beneficial to the transportation management department to optimize the layout of urban transportation infrastructure, promote the seamless connection of passenger transport and improve transportation efficiency, and then to reduce the per capita carbon emissions. As regards freight transportation, this is conducive to optimizing the layout of the logistics network and improving transportation efficiency, and then reducing the carbon emissions. By contrast, urbanization has led to the expansion of urban space and the separation of industry and city, and it increases the complexity of logistics networks and traffic congestion during commuting, eventually leading to increases in $CO_2$ emissions. The interweaving of the above positive and negative forces leads to a complex relationship between urbanization and transportation carbon emissions. However, previous analyses of influencing factors mostly focus on economic growth, population size, transportation efficiency and energy intensity [16]. Ignoring the impact of urbanization is not conducive to carbon emission reduction and the decoupling of the transport sector. Meanwhile, existing studies have mainly explored the factors influencing the carbon emissions of the transport sector, and few have examined the factors influencing the decoupling state.

To fill the gap, this study introduces the standard deviational ellipse to dynamically reveal the spatial heterogeneity of the carbon emissions and economic development of the provincial transport sector from multiple perspectives. Then, based on elastic decoupling theory, we extend the traditional LMDI decomposition model to decompose the decoupling index into eight influencing factors, and focus on investigating the impacts of the urbanization effect, structural adjustment effect and technological progress effect on the decoupling state of the transport sector in the Yellow River basin. Our paper could provide a scientific basis for formulating differentiated regional carbon emission reduction policies, which is important if the Yellow River basin is to achieve green and low-carbon development.

The rest of this paper is organized as follows. The next section presents the literature review. Section 3 describes methods and data sources. Section 4 presents the empirical results and provides a detailed discussion. Finally, we draw the main conclusions and propose some relevant policy suggestions.

## 2. Literature Review

Previous studies have typically used the decoupling model and environmental Kuznets curve (EKC) to study the relationship between development and carbon emissions. Udeagha et al. [17] used EKC theory to analyze the relationship between economic expansion and $CO_2$ in South Africa, and the results support the existence of an environmental Kuznets curve (EKC). Talbi et al. [18] adopted the EKC model to identify the relationship between $CO_2$ and the economic development of the road transport sector in Tunisia, and the results indicate that Tunisia's economic development has an inverted U-shaped relationship with carbon dioxide emissions. However, compared with the EKC method, the decoupling model is able to better reveal the decoupling relationship year by year and is simpler to measure. The concept of decoupling was first proposed by the Organization for Economic Co-operation and Development (OECD) in its research on energy policy issues [10]. On this basis, Tapio et al. [19] proposed the theoretical framework of elastic decoupling, which can further divide and define the decoupling index into eight decoupling statuses. The decoupling model is able to quantitatively measure the dependence year by year, and it has significant advantages in calculating the dependence of economic growth on carbon emissions [20]. Therefore, we used the Tapio decoupling method to explore the decoupling relationship within the transport sector in the Yellow River basin.

Wang et al. [21] explored the decoupling relationship between the development and carbon emissions of the transportation industry in the Eurasian logistics corridor. The findings show that the developed countries of the Eurasian logistics corridor are more likely to realize decoupling development. Wang et al. [22] investigated the decoupling states of the transport sector in China, showing that the decoupling status in the eastern region is more stable and ideal than that in the central and western regions. Wu et al. [23] found strong decoupling in developed countries. Compared with the United States and France, the decoupling state in Germany and the United Kingdom is more stable. As for developing countries, the decoupling status in China is more ideal than that of Brazil and India. However, most of the current research explores the decoupling state at the national or regional level [24] and focuses less on the decoupling relationship of the carbon emissions in the transport sector in the Yellow River basin.

To date, most studies have adopted the static spatial analysis method to examine the regional differences in $CO_2$ emissions and economic growth [13], assuming that individual regions are independent, and rarely considering the spatial heterogeneity and interaction effects of each region [14]. Anselin et al. [25] pointed out that the characteristics of a certain region may be affected by its adjacent regions. If one does not consider spatial dependence and assumes the regions are independent, it will result in calculation deviations [26]. The Yellow River basin stretches across China's more underdeveloped as well as its developed regions, and the economic and industrial development is thus imbalanced, with obvious spatial differences. Accordingly, it is of great necessity to analyze the dynamic spatio-temporal characteristics of the transport sector's carbon emissions and economic growth from a provincial perspective, so as to provide targeted suggestions for differentiated emission reduction policies. The standard deviational ellipse model (SDE) is an effective spatial statistical method that can dynamically analyze the spatial distribution of research objects considering the mean center, azimuth angle and spatial range. SDE was first proposed by Lefever et al. [27] to explore the spatio-temporal evolution of the population in the United States, and SDE has been widely used in sociology [28], geology [29], ecology [30] and other fields [31]. Therefore, our paper introduces the SDE model to analyze the spatio-temporal evolution of carbon emissions and economic development in the transport sector in the Yellow River basin, considering spatial dependence.

In the existing research on influencing factors, a decomposition model has been employed by some scholars to analyze the factors. There are two main categories of decomposition models: structural decomposition analysis (SDA) and index decomposition analysis (IDA) [32]. The structural decomposition model (SDA) requires input–output data when decomposing the influencing factors, which means higher data requirements than the index decomposition (IDA) model [33]. In the IDA index decomposition model, the LMDI decomposition model is easy to calculate and can fully decompose the impacts of factors influencing carbon emission changes [34]. In comparison with the Laspeyres exponential decomposition model, the LMDI model achieves complete decomposition without residual errors. Compared with the arithmetic mean Divisia index (AMDI) decomposition model, the LMDI model can deal with the zero value problem that may occur in eight cases [35]. Consequently, we adopted the LMDI decomposition model to analyze the factors influencing decoupling in the Yellow River basin.

At present, the existing analysis of the influencing factors regarding carbon emissions mostly focuses on population changes, transportation efficiency, energy intensity and other factors, while ignoring the impact of urbanization on the transportation industry. Wang et al. [21] found that transportation intensity plays a major positive role in decoupling in developed European countries. However, for developing countries in Asia, energy intensity was the main factor inhibiting carbon emissions. Raza et al. [36] used the LMDI model to examine the factors influencing the transport sector's $CO_2$ emissions in Pakistan, which shows the economic growth effect is the significant factor promoting carbon emissions. The existing research on influencing factors in the transport sector is summarized in Table 1. China's urbanization is developing rapidly. The rapid progress of urbanization has an important effect on the transport sector's $CO_2$ from the point of view of the rapid expansion of urban space, job–housing separation, residents' income, population density and industrial agglomeration. Hence, analyzing the impacts of urbanization will help to achieve the goal of carbon emission reduction and decoupling in the transport sector. Moreover, the existing studies mainly examined the effects of various factors on $CO_2$ emissions, while fewer studies have explored the influencing factors of decoupling states in the Yellow River basin.

Through a review of previous studies, we found that the existing studies have made some achievements in coordinating the contradiction between the development of the transport sector and emission reduction, but there are some gaps in the literature: (1) As for the research object, more attention is paid to transport $CO_2$ emissions at the national or regional level, and fewer studies have focused on the Yellow River basin. (2) Most existing studies use a static analysis method to analyze the relationship of the transportation sector's $CO_2$ emissions and economic growth, rather than considering spatial dependence to dynamically analyze the spatio-temporal evolution characteristics. The Yellow River basin stretches across China's more underdeveloped to its developed regions, and the economic and industrial development is thus imbalanced. It is of great necessity to study this regional difference and analyze the dynamic spatio-temporal distribution features of the $CO_2$ emissions and economic development at a provincial level. (3) The existing analysis of influencing factors mostly focuses on economic growth, population size and energy intensity, while ignoring the impact of urbanization. This is not conducive to achieving the carbon emissions reduction target and decoupling in the transport sector. Furthermore, the current research mainly focuses on analyzing the influencing factors of carbon emissions, and there has been little exploration into the influencing factors of the decoupling state in the Yellow River basin.

**Table 1.** Summary of influencing factors explored in the existing research employing the LMDI to decompose emissions.

| References | Sectors | Influencing Factors |
|---|---|---|
| Kharbach et al., (2017) [37] | Road sector | average emission factor, vehicles ownership, population |
| Li et al., (2019) [16] | Transport sector | emissions efficiency, transport intensity, industry structure, income level, population scale |
| Liu et al., (2020) [38] | Transport sector | carbon emission factor, energy structure, energy intensity, urbanization rate, per capita service industry output |
| Raza et al., (2020) [36] | Transport sector | $CO_2$ coefficients, ratio of fossil fuel energy consumption, energy intensity, transport intensity, economic growth |
| Yu et al., (2020) [39] | Civil aviation sector | transport scale, transportation structure, energy intensity, alternative fuel effect |
| Wang et al., (2020) [21] | Transport sector | $CO_2$ intensity, energy intensity, transport intensity, economic structure, economic scale, population |
| Quan et al., (2020) [40] | Logistics industry | carbon emission coefficient, energy structure, energy intensity, economic output and population size |
| Zhang et al., (2021) [41] | Logistics industry | added value, energy consumption, personnel scale, output carbon intensity, carbon intensity of energy consumption, per capita carbon emissions, per capita added value of the logistics industry, energy intensity |
| Liu et al., (2021) [42] | Transport sector | energy structure, energy intensity, transportation structure, transportation intensity, income effect, population scale |

Therefore, as for the research object, we focus on the transport sector of the Yellow River basin. Few studies have investigated the decoupling relationship in the transport sector in the Yellow River basin. This paper focuses on the decoupling relationship of economic growth and carbon emissions in the transport sector in the Yellow River basin, and its influencing factors. This is conducive to realizing the decoupled development and carbon emission reduction goals in the Yellow River basin. This is the first contribution of our paper. Meanwhile, this paper also introduces the SDE method into the research on the carbon emissions of the transport sector in the Yellow River basin, and dynamically analyzes the spatial heterogeneity of the carbon emissions and development of the transport sector from multiple perspectives at the provincial level. Additionally, we combine the LMDI decomposition model with a decoupling method to decompose the decoupling index into eight sub-indices, and directly analyze the influencing factors of the decoupling state in the transport sector. This model allows us to focus on investigating the impact of the urbanization effect on the decoupling relationship. Our findings could help governments to formulate differentiated policy recommendations that are in line with actual local conditions in the Yellow River basin. This is another contribution of this paper.

## 3. Materials and Methods

### 3.1. Calculation of Carbon Emissions in the Transport Sector

Due to the poor availability of data on the ownership, mileage and fuel consumption per unit of various types of motor vehicles in China, the top-down carbon emission measurement method based on terminal energy consumption achieves high accuracy. Therefore, in this paper, we adopt the top-down model (see Equation (1)).

$$C = \sum_{j=1}^{m} E_j \times c_j \times 44/12 = \sum_{j=1}^{m} E_j \times ALV_j \times v_j \times r_j \times 44/12 \tag{1}$$

Here, $C$ is the $CO_2$ emissions of the transport sector; $j$ refers to the type of energy; $E_j$ is the fuel consumption of the $j$th type; $cj$ is the carbon emission coefficient of the $j$th fuel; $ALV_j$ is the average low-calorific value of the $j$th fuel; $v_j$ and $r_j$ represent carbon contents per unit calorific value and the carbon oxidation rates, respectively; and 44/12 is the chemical molecular weight conversion coefficient.

### 3.2. Decoupling Model

Based on the Tapio decoupling theory, this paper constructs the decoupling index and analyzes the characteristics of each decoupling state. The decoupling index ($T^t$) is used to analyze the decoupling relationship in carbon emissions and the added value of the transportation industry [19]. According to the value of $T^t$, $T^t$ can be divided into 8 decoupling states, and the characteristics of each decoupling state are shown in Figure 1. The decoupling index $T^t$ of the transport sector can be expressed as follows:

$$T^t = \Delta CO_2\%/\Delta IGDP\% = (\frac{C^t - C^0}{C^0})/(\frac{IGDP^t - IGDP^0}{IGDP^0}) \tag{2}$$

where $T^t$ denotes the decoupling index of the transport sector; $C$ and $IGDP$ represent the $CO_2$ emissions and the output values of the transport sector, respectively; $\Delta C\%$ and $\Delta IGDP\%$ denote the change rates of carbon emissions and output values, respectively.

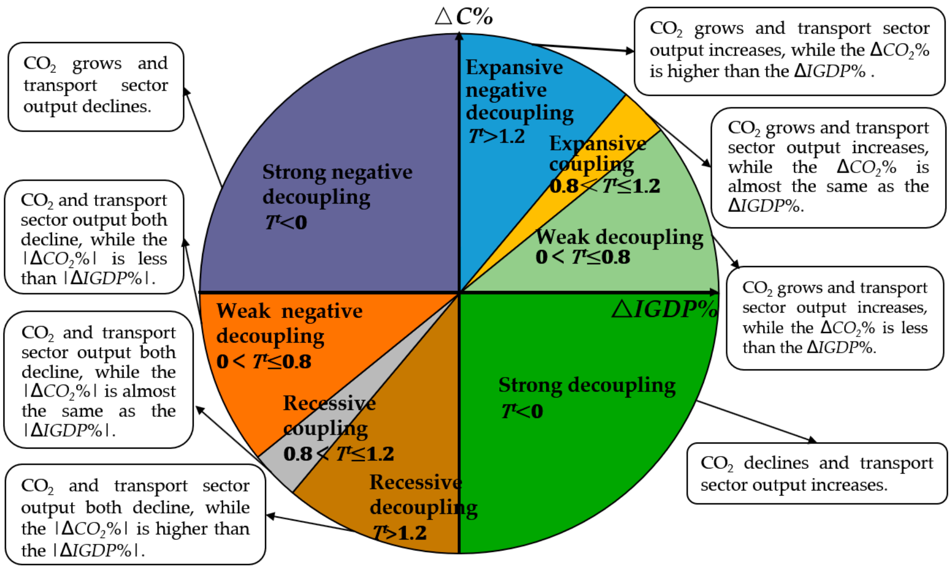

**Figure 1.** Evaluation criteria for decoupling index ($T^t$).

### *3.3. Standard Deviational Ellipse*

The standard deviational ellipse (SDE) is an effective spatial statistical method. Using the mean center, major axes, minor axes and azimuth as basic parameters, it can quantify the dynamic spatio-temporal characteristics of its objects [31]. The spatial interpretation of its basic parameters is shown in Figure 2.

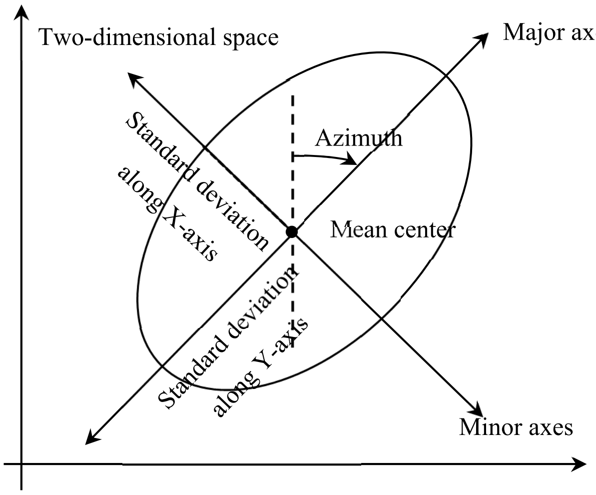

**Figure 2.** Basic parameters of the standard deviational ellipse.

The mean center of the standard deviational ellipse represents the relative position of the spatial distribution of the research object and is calculated by the weighted mean center (see Equation (3)):

$$\overline{X} = \frac{\sum_{k=1}^{9} \omega_k x_k}{\sum_{k=1}^{9} \omega_k}; \overline{Y} = \frac{\sum_{k=1}^{9} \omega_k y_k}{\sum_{k=1}^{9} \omega_k} \tag{3}$$

where $\overline{X}$ and $\overline{Y}$ refer to the coordinates of the weighted mean center of the transport sector; $k = 1, 2, 3 \ldots 9$ represent the 9 provinces in the Yellow River basin; $\omega_k$ is the weight value of the parameter; $x_k$ and $y_k$ are the longitude and latitude coordinates of the research object.

The azimuth angle of the SDE is the clockwise-measured angle between true north and the long half axis, which is used to represent the directional characteristics, as shown in Equation (4):

$$\tan\theta = \frac{\left(\sum_{k=1}^{9} \omega_k^2 \widetilde{x_k}^2 - \sum_{k=1}^{9} \omega_k^2 \widetilde{y_k}^2\right) + \sqrt{\left(\sum_{k=1}^{9} \omega_k^2 \widetilde{x_k}^2 - \sum_{k=1}^{9} \omega_k^2 \widetilde{y_k}^2\right)^2 + 4\sum_{k=1}^{9} \omega_k^2 \widetilde{x_k}^2 \widetilde{y_k}^2}}{2\sum_{k=1}^{9} \omega_k^2 \widetilde{x_k} \widetilde{y_k}} \tag{4}$$

where $\theta$ stands for the azimuth of the SDE, which is used to indicate the direction of the evolution of transport-related carbon emissions and the output value in the Yellow River basin; $\widetilde{x_k}$ and $\widetilde{y_k}$ represent the coordinates deviation from the location of each research object to the mean center.

As shown in Equations (5) and (6), $\sigma_x$ and $\sigma_y$ represent the standard deviations of the major axes and the minor axes, respectively. The longer the $\sigma_y$, the more significant the directional characteristics. The longer the $\sigma_x$, the more obvious the discrete characteristics of the research object.

$$\sigma_x = \sqrt{\frac{\sum_{k=1}^{9} \left(\omega_k \widetilde{x_k} cos\theta - \omega_k \widetilde{y_k} \sin\theta\right)^2}{\sum_{k=1}^{9} \omega_k^2}} \tag{5}$$

$$\sigma_y = \sqrt{\frac{\sum_{i=1}^{9} \left(\omega_i \widetilde{x_i} \sin\theta - \omega_i \widetilde{y_i} cos\theta\right)^2}{\sum_{i=1}^{9} \omega_i^2}} \tag{6}$$

### *3.4. LMDI Decomposition Model of Drivers of Decoupling State*

The urbanization rate of the Yellow River basin increased from 32.22% in 2000 to 60.57% in 2020. The rapid development of urbanization has an important impact on transport-related carbon emissions. Specifically, this impact is realized through the income urbanization effect, the population urbanization effect and the urban spatial expansion effect. The impact mechanism is as follows:

1. The development of urbanization is often accompanied by rapid economic growth and an increase in per capita income. This results in improvements in residents' living standards and new transport demands, thereby affecting the carbon emissions of the transport sector. At the same time, based on the extensive publicity and advocacy of low-carbon transportation and the green life concept, residents' awareness of energy conservation and emission reduction has been improved. This leads to a reduction in the growth rate of transport-related carbon emissions. In this paper, the change to carbon emissions in the transport sector, caused by economic growth and lifestyle changes in the process of urbanization, is called the income urbanization effect.
2. Urbanization leads to the transfer of population from rural areas to urban areas, as well as industrial agglomeration, which can promote the transport scale effect of the transport sector to a certain extent. For passenger transport, this helps the transport management department to optimize the layout of urban transport infrastructure and accelerate the development of public transport, improve transport efficiency and reduce per capita transport carbon emissions. As regards freight transportation, this is conducive to optimizing the logistics network's layout, giving play to the scale effect and reducing carbon emissions. Meanwhile, as large numbers of rural people pour into cities, the demand for transportation infrastructure construction increases, as well as the demand for travel and logistics, which in turn results in more energy consumption. In this paper, the change in transport-related $CO_2$ caused by the change in population density in the process of urbanization is called the population urbanization effect.
3. Urbanization has resulted in the expansion of the urban area and job–housing separation. This leads to an increase in the urban commuting distance and the demand for private cars, as well as a sharp rise in traffic congestion during the commuting period. At the same time, the spatial expansion of the urban area increases the production and marketing distance, as well as improving the complexity of the logistics network and increasing the required transportation distance, which ultimately leads to an increase in transport $CO_2$ emissions. In this paper, the change of carbon emissions caused by spatial expansion in the process of urbanization is called the spatial urbanization effect.

Consequently, this study expands the traditional Kaya equation and decomposes eight variables to analyze the influencing factors: energy structure, transport structure, energy intensity, transport efficiency, industrial proportion, the income urbanization effect, the population urbanization effect and the spatial urbanization effect. The modified LMDI decomposition model is constructed as shown in Equation (7):

$$\begin{aligned} C^t &= \sum_i \sum_j \frac{C^t_{ij}}{E^t_{ij}} \times \frac{E^t_{ij}}{E^t_i} \times \frac{T^t_i}{T^t} \times \frac{E^t_i}{T^t_i} \times \frac{T^t}{IGDP^t} \times \frac{IGDP^t}{GDP^t} \times \frac{GDP^t}{P^t_u} \times \frac{P^t_u}{Area^t} \times Area^t \\ &= \sum_i \sum_j \mathrm{c}f^t_{ij} \times es^t_{ij} \times ts^t_i \times ei^t_i \times tg^t \times gs^t \times pgdp^t \times ps^t \times s^t \end{aligned} \tag{7}$$

where $C^t$ denotes the carbon emissions of the transport sector in the $t$th year; $i$ = 1, 2, 3 and 4 refer to the four modes of transportation (highway, railway, water transport and aviation); $j$ represents the type of energy; $E$ denotes energy consumption; $T$ is transportation turnover; $IGDP$ is the output of the transport sector; $GDP$ is the gross domestic product; $P_u$ stands for the population of the city; and $Area$ indicates the area of the urban built-up region.

$es_{ij}^t = E_{ij}^t / E_i^t$ is the proportion represented by the *j*th energy type in the total energy consumption of the *i*th transportation mode in the target year *t*, which indicates the impact of energy structure on carbon emissions; $ts_i^t = T_i^t / T^t$ is the transportation structure effect; $ei_i^t = E_i^t / T_i^t$ is the energy intensity effect; $tg^t = T^t / GDP^t$ is the transportation turnover per unit of *GDP*, which denotes the impact of transportation efficiency on carbon emissions; $gs^t = IGDP^t / GDP^t$ is the share of the added value of the transport sector in the *GDP*; $pgdp^t = GDP^t / p_u^t$ is the per capita *GDP*; $ps^t = P_u^t / Area^t$ is the population per unit of urban built-up area; $s^t = Area^t$ represents the impact of spatial expansion on carbon emissions; $cf_{ij}^t$ represents the carbon emission coefficient of the *i*th energy type. $cf_{ij}^t$ is a constant value, so the contribution of this indicator to the change in transport carbon emissions is 0.

Then, on the basis of the LMDI additive decomposition model [43], this can be divided into eight influencing effects, and the formula is expressed as follows:

$$\Delta C = C^t - C^0 = \Delta es + \Delta ts + \Delta ei + \Delta tg + \Delta gs + \Delta pgdp + \Delta ps + \Delta s \tag{8}$$

The respective effects are written as

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

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

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

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

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

$$\Delta pgdp = \sum_{ij} w(C_{ij}^t, C_{ij}^0) \ln(\frac{pgdp^t}{pgdp^0}) \tag{14}$$

$$\Delta ps = \sum_{ij} w(C_{ij}^t, C_{ij}^0) \ln(\frac{ps^t}{ps^0}) \tag{15}$$

$$\Delta s = \sum_{ij} w(C_{ij}^t, C_{ij}^0) \ln(\frac{s^t}{s^0}) \tag{16}$$

Equation (17) shows the calculation method of the weight of each influencing factor.

$$w(C_{ij}^t, C_{ij}^0) = \frac{C_{ij}^t - C_{ij}^0}{\ln C_{ij}^t - \ln C_{ij}^0} \tag{17}$$

To further identify the factors influencing the decoupling relationship, we combine Equation (2) and Equation (8) and decompose the decoupling index $T^t$ into eight effects, as shown in Equation (18):

$$\begin{aligned} T^t &= \left(\frac{C^t-C^0}{C^0}\right)/\left(\frac{IGDP^t-IGDP^0}{IGDP^0}\right) = \frac{C^t-C^0}{IGDP^t-IGDP^0} \times \frac{IGDP^0}{C^0} \\ &= \frac{\Delta C^t}{\Delta IGDP^t} \times \frac{IGDP^0}{C^0} = \frac{\Delta es+\Delta ts+\Delta ei+\Delta tg+\Delta gs+\Delta pgdp+\Delta ps+\Delta s}{\Delta IGDP^t} \times \frac{IGDP^0}{C^0} \\ &= \left(\frac{\Delta es}{\Delta IGDP^t} + \frac{\Delta ts}{\Delta IGDP^t} + \frac{\Delta ei}{\Delta IGDP^t} + \frac{\Delta tg}{\Delta IGDP^t} + \frac{\Delta gs}{\Delta IGDP^t} + \frac{\Delta pgdp}{\Delta IGDP^t} + \frac{\Delta ps}{\Delta IGDP^t} + \frac{\Delta s}{\Delta IGDP^t}\right) \times \frac{IGDP^0}{C^0} \\ &= T^t_{es} + T^t_{ts} + T^t_{ei} + T^t_{tg} + T^t_{gs} + T^t_{pgdp} + T^t_{ps} + T^t_{s} \end{aligned} \tag{18}$$

where $T^t_{es}$ represents the energy structure's effect on the decoupling state of the transport sector; $T^t_{ts}$ indicates the impacts of the mode shift in the transport sector on the decoupling state; $T^t_{es}$ and $T^t_{ts}$ are both used to measure the impact of structural adjustments on the decoupling relationship; $T^t_{gs}$ refers to the effect of industrial proportion on the decoupling state; $T^t_{ei}$ and $T^t_{tg}$ stand for the energy intensity effect and transport efficiency effect, respectively, and both of them represent the influence of technological progress on the decoupling relationship of the transport sector; $T^t_{pgdp}$, $T^t_{ps}$ and $T^t_{s}$ denote the income urbanization effect, the population urbanization effect and the spatial urbanization effect, which are adopted to examine the impact of urbanization development on decoupling development.

As the transport sector in the Yellow River basin has developed rapidly, $\Delta IGDP\% > 0$, four decoupling states may be identified (as illustrated in Figure 1). A negative value of the influencing factor implies a net reduction in $T^t$, which indicates that the influencing factor plays a promoting role in the decoupling relationship. A positive influencing factor reflects an increase in $T^t$, indicating that the influencing factor has an inhibitory effect on the decoupling. The smaller the value of $T^t$, the greater the probability of strong decoupling.

## *3.5. Research Area and Data Sources*

### 3.5.1. Research Area

The Yellow River basin covers Qinghai, Ningxia, Gansu, Sichuan, Inner Mongolia, Shaanxi, Shanxi, Henan and Shandong, and across the East, Middle and West of nine provinces of China (its specific location is shown in Figure 3—the orange area is the Yellow River basin). The basin stretches across the more underdeveloped as well as developed areas of China. It is the main region of the supply of agricultural products, energy, chemicals and other materials. As a consistent, strategic and leading industry, the transport sector plays an important role in the economic development of the Yellow River basin. However, the transport sector has been in a state of high energy consumption, emissions and pollution for a long time, meaning it deviates far from the requirements related to protecting the ecological environment of the Yellow River basin. Therefore, it is urgent and necessary to study the decoupling relationship in the transport sector in the Yellow River basin.

### 3.5.2. Data Sources

In this paper, we use data from the transport sector in nine provinces from 2000 to 2019 to analyze the decoupling relationship between carbon emissions and the development of the transport sector in the Yellow River basin. The selection of carbon emission coefficients is important to the accuracy of the carbon emission calculation [44]. In order to better represent China's actual situation, we selected emission coefficients from the Guidelines to Provincial Lists of Greenhouse Gas Inventory and Energy Statistical Yearbook, which have Chinese characteristics, instead of IPCC data. The specific variables are shown in Appendix A, Tables A1 and A2.

**Figure 3.** Location of Yellow River basin in China.

The data regarding GDP, the output of the transport sector and urban population are derived from the Provincial Statistical Yearbook (2001–2020), and the output is measured by the added value in the transport sector. The GDP and added value are converted to constant prices for the year 2000. The data on transportation turnover are taken from the Provincial Statistical Yearbook (2001–2020) and the China Transport Statistical Yearbook. The transportation turnover can be measured by freight turnover (unit: ton-kilometer) and passenger turnover volume (unit: person-kilometer). To unify the unit used to calculate the total converted turnover, passenger turnover is converted to freight turnover through conversion coefficients (see Table A3). The conversion coefficient and calculation method are derived from studies by Li et al. [16] and Liu et al. [45]. The data on the urban built-up area are from the China Urban Construction Statistical Yearbook (2001–2019).

## 4. Results and Discussion

Using Equation (1), transport carbon emissions in the Yellow River basin are calculated. In order to better analyze the results, according to economic development level and geographical location, the nine provinces studied can be divided into three regions (as listed in Table 2).

**Table 2.** Categorization of researched regions (data from Yellow River Yearbook).

| Region | Province |
|---|---|
| Upstream region | Qinghai, Ningxia, Gansu, Sichuan |
| Midstream region | Inner Mongolia, Shaanxi, Shanxi |
| Downstream region | Henan, Shandong |

### *4.1. Spatio-Temporal Differences of Transport Sector's Carbon Emissions*

#### 4.1.1. Spatio-Temporal Differences Analysis at Regional Level

As shown in Figure 4, the transport carbon emissions in four regions increased in 2000–2019. In particular, from 2004 to 2012, transport carbon emissions increased rapidly. This is in agreement with the results of Li et al. [16]. In 2004–2012, the Yellow River basin experienced a critical period of rapid development in terms of urbanization (from 37.22% in 2004 to 48.25% in 2012) and the transport sector, which increased the investment in transportation infrastructure construction and has led to an increase in carbon emissions. The transport sector's $CO_2$ emissions in four regions appeared to decline in 2012–2013. The main reason may be that the investment in transportation infrastructure construction decreased in 2012. Since 2014, the carbon emissions of the transport sector have shown a gentle upward trend.

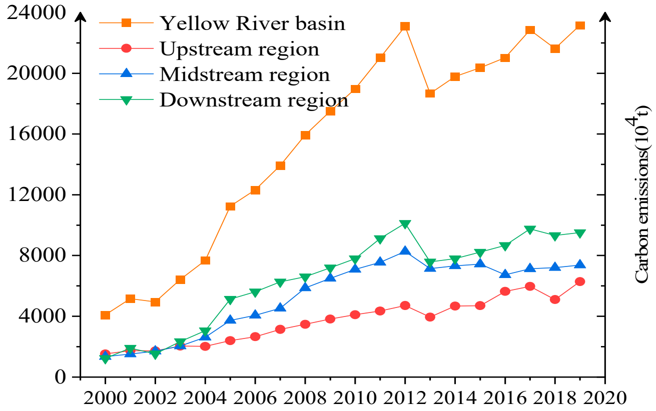

**Figure 4.** The transport sector's carbon emissions in the Yellow River basin.

In 2004, transport carbon emissions from the upstream, midstream and downstream regions were at similar levels. However, as transportation in the downstream and midstream regions developed quickly, carbon emissions in these regions increased rapidly. Furthermore, transport-related carbon emissions in the downstream region were higher than those in the midstream region from 2004 to 2019. In addition, from 2000 to 2019, the average growth rate of carbon emissions from the transport sector in the Yellow River basin was 10.37%, and the average growth rate of transport carbon emissions in the downstream region was 13.54%—much higher than those of the midstream (10.09%) and upstream regions (8.33%).

### 4.1.2. Spatio-Temporal Differences Analysis at Provincial Level

In order to clarify the spatial-temporal patterns of transport-related $CO_2$ emissions, this study visualizes the provincial transport sector's carbon emissions in 2000, 2004, 2008, 2012, 2016 and 2019 using the ArcGIS software platform. The natural break point method was used to divide the provinces into three types: the low-carbon emissions zone, medium-carbon emissions zone and high-carbon emissions zone (See Figure 5). As shown in Figures 5 and A1, the transport carbon emissions present an imbalanced characteristic of "upstream region < midstream region < downstream region", and the carbon emissions of Henan Province and Shandong Province in the downstream region are higher than those in other provinces. In 2019, the transport carbon emissions in the Henan and Shandong provinces in the downstream region accounted for 41.06% of the total carbon emissions of the nine provinces, while the transport sector's carbon emissions in the upstream region only accounted for 27.11% in the Yellow River basin.

The transport sector's $CO_2$ emissions in the upstream provinces are lower than those in the midstream and downstream provinces. However, the carbon emissions of the transport sector in Sichuan Province are relatively high—the average energy-related carbon emissions here from 2000 to 2019 rank third among the provinces in the Yellow River basin, after Shandong Province and Henan. This is because Sichuan is a province with a large population and economy, and it has a complete industrial system as well as prominent logistics, tourism and retail trade. This is consistent with the results of Jiang et al. [46], who pointed out that with the continuous promotion of national strategies such as The Development of the Western Region, the transport sector of Sichuan Province has been developing rapidly, while the pressure related to transport carbon emissions has also increased.

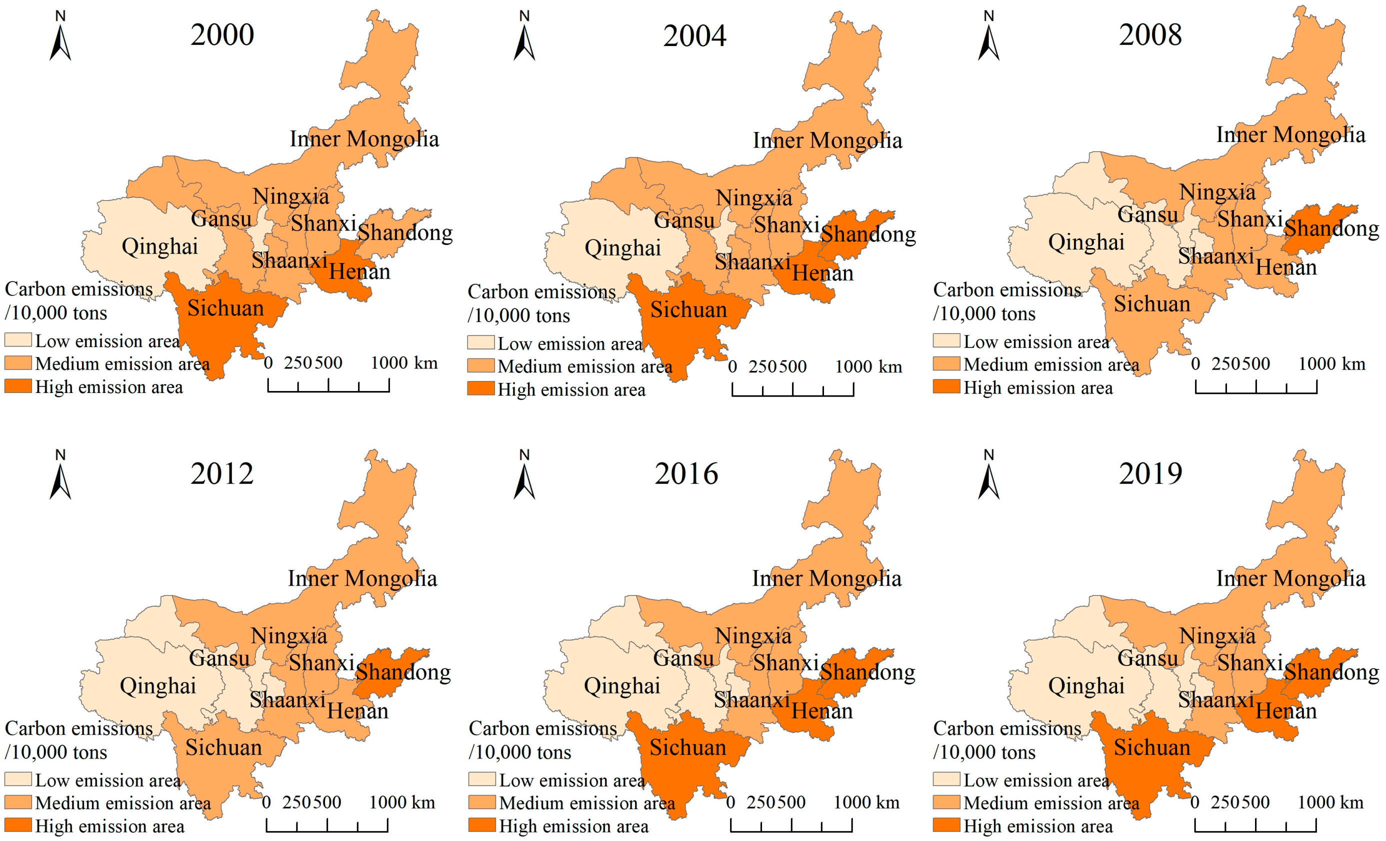

**Figure 5.** Spatio-temporal patterns of the transport sector's carbon emissions in the Yellow River basin.

## *4.2. Decoupling Relationship of the Carbon Emissions and Economic Growth*

### 4.2.1. Analysis of the Carbon Emissions and Economic Growth in Transport Sector

The added values and carbon emissions of the transport sector in 2000, 2004, 2008, 2012, 2016 and 2019 are shown in Figure 6. The transport sector's carbon emissions in most provinces show an increasing trend with the economic growth of the transport sector, and the level of economic activity in the transport sector is positively correlated with carbon emissions. This is in agreement with the conclusion of Du et al. [12]. As detailed in Figure 6, the provincial data in the Yellow River basin exhibit differences, which is consistent with the results of Wang et al. [47]. Consequently, when designing the low-carbon path, we should seriously consider the spatial heterogeneity of carbon emissions and the economy in different regions of the Yellow River basin, and formulate policy recommendations that are in line with actual local conditions.

Shandong and Henan provinces have the highest carbon emissions, and the carbon emissions of Shandong and Henan rank first and second, respectively. The economies of these two regions are relatively developed, and their transport sectors develop rapidly. This leads to more traffic demand and, in turn, to greater transport carbon emissions. The results show that the level of economic development is highly related to regional transport carbon emissions, and this finding corroborates the conclusion of Zhang et al. [48]. It shows that the downstream region of the Yellow River basin is key to controlling carbon emissions in the transport sector and formulating energy-saving and emission reduction strategies. Furthermore, while promoting transport development in the downstream region, more attention should be paid to energy conservation and emissions reduction.

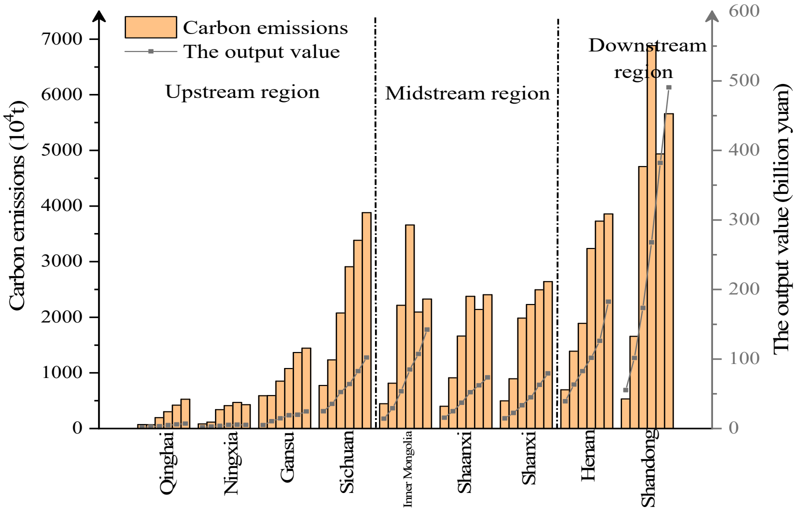

**Figure 6.** The carbon emissions and output value of the transport sector in the Yellow River basin.

Among all provinces, the growth rate of transport carbon emissions in Shaanxi Province is low. After being assigned into the first batch of low-carbon pilot provinces, Shaanxi Province has actively formulated implementation plans to comprehensively promote low-carbon transformation, and improved its energy-saving and emission reduction capacity in key fields such as the industry, construction and transport sectors. During “the 13th Five Year Plan”, Shaanxi Province has made remarkable achievements in low-carbon transformation, resulting in a decrease in the growth rate of carbon emissions. For Sichuan Province, not only are the transport carbon emissions high, but the growth rate of carbon emissions is also fast. There is an urgent need to realize the decoupled development of the transport sector in Sichuan.

On the contrary, the total carbon emissions of the transport sectors in Qinghai, Ningxia and Gansu are relatively low. During 2000–2019, the average carbon emissions in Qinghai, Ningxia and Gansu were 2.441 million tons, 3.281 million tons and 9.912 million tons, respectively, which are low in the context of the nine provinces in the Yellow River basin. This is mainly because the natural conditions of these provinces are relatively poor, the transport development level is relatively low, and their scientific and technological innovation abilities, economic structure adjustments and urbanization processes are lacking [14]. Meanwhile, compared with the growth rate of their output value, the growth rate of their carbon emissions is fast.

### 4.2.2. Decoupling Analysis of the Transport Sector

The decoupling index of the transport sector in the Yellow River basin during 2000–2019 is shown in Table 3 and Figure 7. Since the transport sector has developed rapidly in the Yellow River basin, $\Delta IGDP\% > 0$, there are only four decoupling states: expansive negative decoupling, expansive coupling, weak decoupling and strong decoupling (see Table 3).

During 2000–2019, a weak decoupling state and strong decoupling state could be seen over 4 and 3 years, respectively. However, expansive negative decoupling and expansive coupling occurred in 6 years and 7 years, respectively. In recent years, the weak decoupling state has developed. However, fewer years have shown a strong decoupling state. As can be seen in Figure 7, the change in the decoupling index from 2000 to 2019 can be divided into three stages.

**Table 3.** The decoupling index of the transport sector in the Yellow River basin.

| Time | $\Delta C\%$ | $\Delta IGDP\%$ | $T^t$ | Decoupling States |
|---|---|---|---|---|
| 2000 | 0.230 | 0.135 | 1.703 | END |
| 2001 | 0.260 | 0.117 | 2.212 | END |
| 2002 | −0.041 | 0.119 | −0.345 | SD |
| 2003 | 0.297 | 0.123 | 2.404 | END |
| 2004 | 0.198 | 0.206 | 0.959 | EC |
| 2005 | 0.465 | 0.122 | 3.802 | END |
| 2006 | 0.094 | 0.116 | 0.807 | EC |
| 2007 | 0.131 | 0.132 | 0.988 | EC |
| 2008 | 0.145 | 0.094 | 1.530 | END |
| 2009 | 0.097 | 0.073 | 1.321 | END |
| 2010 | 0.085 | 0.100 | 0.852 | EC |
| 2011 | 0.108 | 0.101 | 1.067 | EC |
| 2012 | 0.098 | 0.089 | 1.103 | EC |
| 2013 | −0.192 | 0.073 | −2.621 | SD |
| 2014 | 0.060 | 0.079 | 0.755 | WD |
| 2015 | 0.029 | 0.067 | 0.438 | WD |
| 2016 | 0.033 | 0.073 | 0.453 | WD |
| 2017 | 0.086 | 0.094 | 0.916 | EC |
| 2018 | −0.054 | 0.082 | −0.660 | SD |
| 2019 | 0.072 | 0.095 | 0.755 | WD |

Note—END: expansive negative decoupling; EC: expansive coupling; WD: weak decoupling; SD: strong decoupling.

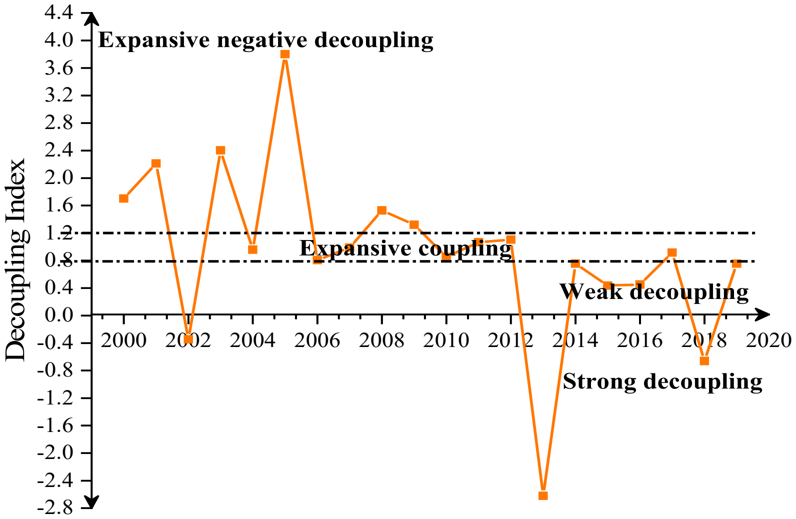

**Figure 7.** The decoupling state of the transport sector from 2000 to 2019 in the Yellow River basin.

1. The first stage is from 2000 to 2005, wherein the decoupling index showed an expansive negative decoupling status, except for 2002 and 2004. This stage is dominated by expansive negative decoupling, which suggests that the development of the transport sector is highly dependent on carbon emissions.
2. The second stage is from 2006 to 2012, during which the Yellow River basin showed expansive coupling, implying that the development of the transport sector here became less dependent on carbon emissions compared to the first stage.
3. The third stage is from 2013 to 2019, excluding 2017, during which the transport sector presented weak decoupling or strong decoupling. The decoupling state from 2000 to 2019 showed a change trend of "expansive negative decoupling, expansive coupling and then weak decoupling" in the first, second and third stages, respectively. However, there were still fewer years showing strong decoupling. Therefore, much

effort is still needed to achieve decoupling development. This is consistent with the findings of Liu et al. [38].

In order to intuitively reflect the spatio-temporal distribution pattern of the decoupling relationship, we used ArcGIS to visualize the spatio-temporal decoupling status in nine provinces of the Yellow River basin in 2000, 2004, 2008, 2012, 2016 and 2019. According to Figure 8 and Table A4, in the upstream region of the Yellow River basin, the decoupling relationship in the transport sector′s carbon emissions for Qinghai, Ningxia, Gansu and Sichuan from 2000 to 2016 was not ideal, showing an alternating state of expansive negative decoupling and expansive coupling. This is in agreement with the conclusions of Wang et al. [22] and Zhang et al. [49], who illustrated that less-developed regions have great potential to reduce $CO_2$ emissions. In 2019, the decoupling relationship of Qinghai, Ningxia and Gansu provinces improved, showing a weak decoupling relationship, while Sichuan Province still showed an expansive negative decoupling relationship.

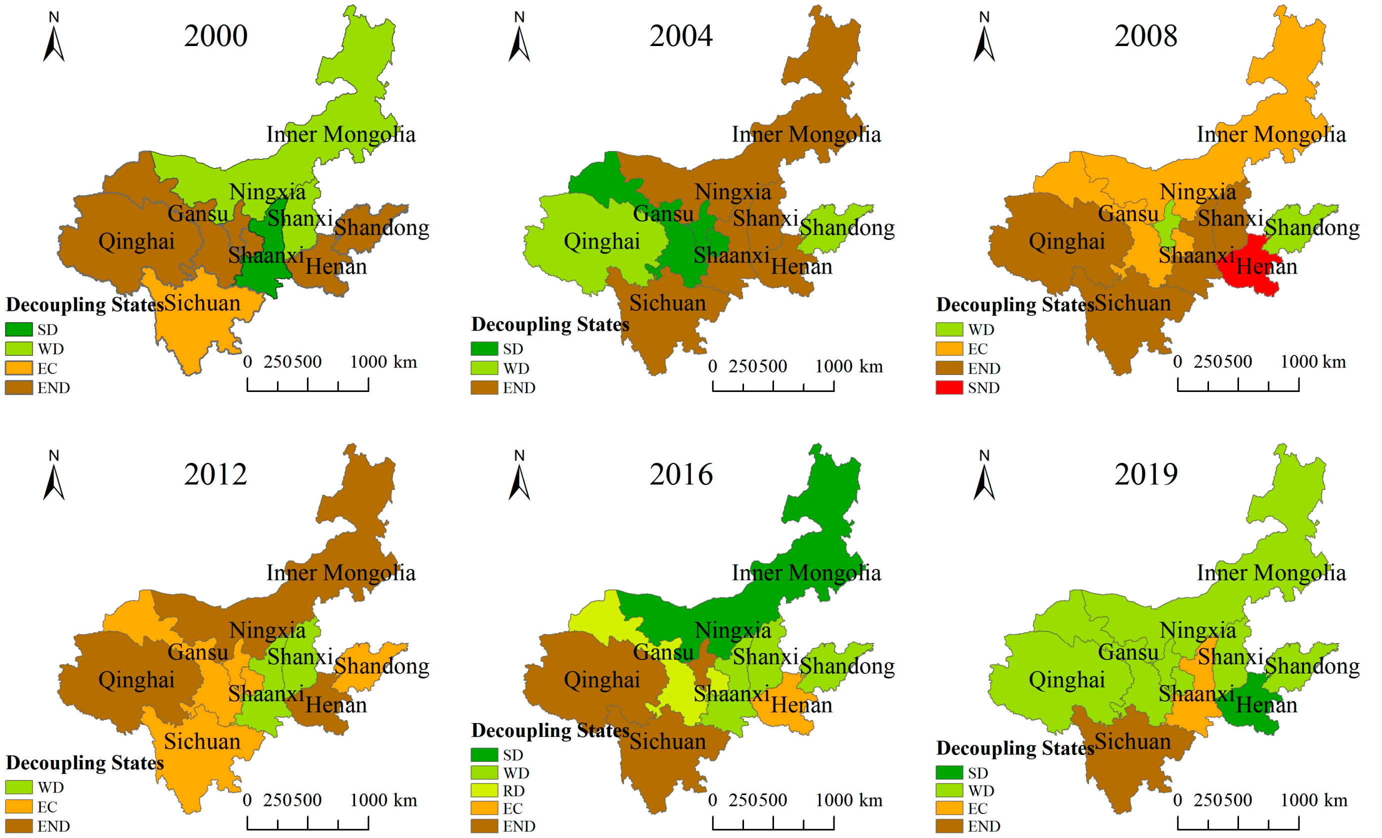

**Figure 8.** Spatio-temporal patterns of decoupling states at the provincial level (SND: strong negative decoupling; END: expansive negative decoupling; EC: expansive coupling; RD: recessive decoupling; WD: weak decoupling; SD: strong decoupling).

As for the midstream region, the overall decoupling status is comparatively ideal. In 2000, the carbon emissions decoupling status of the transport sector in Inner Mongolia, Shanxi and Shaanxi was very good, showing strong decoupling or weak decoupling. However, the decoupling status fluctuated in 2004 and 2008, showing expansive negative decoupling or expansive coupling. Since 2012, the decoupling state has improved. In 2019, the decoupling states in most provinces of the midstream region showed weak decoupling.

As regards the downstream region, in 2000, 2004 and 2008, the decoupling state of carbon emissions in Henan Province was not ideal, showing an alternating state of expansive negative decoupling and strong negative decoupling. From 2012 to 2019, the carbon emissions decoupling state in Henan Province improved, gradually changing from expansive negative decoupling and expansive coupling to strong decoupling. The decoupling status in Shandong Province is relatively ideal. Excluding 2000 and 2012, Shandong Province has been in a weak decoupling state, but its total transport carbon emissions remain high. In 2019, the transport carbon emissions in the two provinces of the downstream region accounted for 41.06% of the total carbon emissions of the whole Yellow River basin, meaning it remains the key area for emissions reduction in the Yellow River basin.

### 4.2.3. Spatio-Temporal Dynamic Analysis of the Carbon Emissions and the Economy in Transport Sector

The dynamic spatio-temporal characteristics—as well as the imbalance of carbon emissions and development—of the transport sector should also be evaluated, so as to formulate differentiated emission reduction strategies. As there is significant spatial dependence between regions, not considering spatial dependence will result in calculation deviations [26]. This study adopts the standard deviational ellipse analysis method to analyze the spatio-temporal dynamic variation trends of the transport sector's $CO_2$ emissions and the output in the Yellow River basin from multiple perspectives. Using Equations (3)–(6), the mean center, standard deviations and azimuth can be measured (see Figure 9 and Table 4).

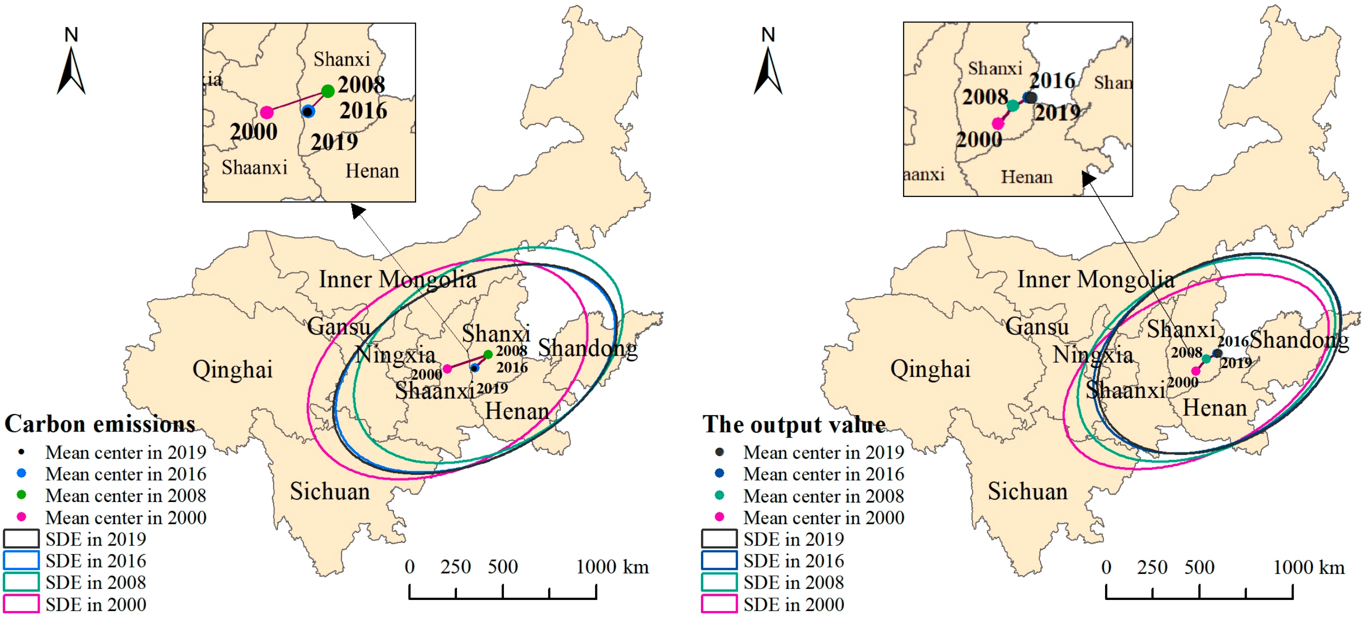

**Figure 9.** The spatio-temporal dynamic characteristics of the carbon emissions and output of the transport sector.

**Table 4.** Standard deviational ellipse parameters of $CO_2$ and output value of transport sector in the Yellow River basin.

| Year | Object | Coord | Coord | *X*-axis Standard Deviation (km) | *Y*-axis Standard Deviation (km) | Azimuth (Degree) | Mean Center City |
|---|---|---|---|---|---|---|---|
| 2000 | $CO_2$ | 109.08° E | 36.08° N | 518.50 | 799.63 | 62.62° | Yan'an, Shaanxi Province |
| 2008 | | 111.62° E | 36.64° N | 497.96 | 777.57 | 60.57° | Linfen, Shanxi Province |
| 2016 | | 110.77° E | 36.03° N | 479.82 | 800.29 | 63.82° | Linfen, Shanxi Province |
| 2019 | | 110.74° E | 36.02° N | 479.58 | 814.35 | 63.67° | Linfen, Shanxi Province |
| 2000 | output value | 112.14° E | 35.77° N | 432.51 | 767.84 | 62.59° | Jincheng, Shanxi Province |
| 2008 | | 112.81° E | 36.32° N | 472.83 | 742.03 | 61.47° | Changzhi, Shanxi Province |
| 2016 | | 113.52° E | 36.55° N | 471.53 | 710.48 | 61.66° | Changzhi, Shanxi Province |
| 2019 | | 113.62° E | 36.55° N | 475.67 | 696.27 | 60.76° | Handan, Hebei Province |

1. The spatial coverage of the transport sector's carbon emissions and the output is mainly in the midstream and downstream regions. The mean center of transport carbon emissions is concentrated in the downstream region, mainly in Shaanxi and

Shanxi. The mean center of transport output is also concentrated in the downstream region, but it is more eastward than the mean center of transport carbon emissions, mainly concentrated in Shanxi Province. Moreover, the mean center of the transport output shows a trend of shifting further eastward from 2000 to 2019. The main reason is that the transport output in the downstream provinces is relatively high. Specifically, in 2019, the output in Shandong and Henan accounted for 60.80% of the total transport output of the Yellow River basin. The transport output in Shandong Province alone accounted for 44.32%, and its growth rate was high, which indicates that the transport sector of downstream provinces is well developed, but carbon emissions are high. This finding is in agreement with that of Du et al. [14], who indicated these regions must take more responsibility for reducing carbon emissions.

2. As for the standard deviation of SDE, the $Y$-axis standard deviation of transport carbon emissions and the output presents a "northeast–southwest" distribution characteristic. Moreover, the $Y$-axis standard deviation of the carbon emissions becomes longer, and the $X$-axis standard deviation becomes shorter. Specifically, the $Y$-axis increased from 799.63 km in 2000 to 814.35 km in 2019, while the $X$-axis decreased from 518.50 km in 2000 to 479.58 km in 2019. The results show that the directional characteristic of transport carbon emissions is more obvious, and Shandong, Henan, Shanxi and Shaanxi form a cluster of high-value areas of transport carbon emissions. This finding is consistent with that of Gong et al. [4]. In contrast, the $Y$-axis standard deviation of the transport output has become shorter and the $X$-axis longer in the study period. In detail, the $Y$-axis standard deviation of the transport output decreased from 767.84 km in 2000 to 696.27 km in 2019, while the $X$-axis increased from 432.51 km in 2000 to 475.67 km in 2019. This indicates that the discrete characteristics of the transport output have become more obvious. The main reason for this phenomenon is the rapid growth in added value of the transport sector in Shandong, Inner Mongolia and Gansu.
3. As for the direction of SDE, the azimuth $\theta$ of the transport carbon emissions generally shows a clockwise trend, and the azimuth increased from 62.62° in 2000 to 63.67° in 2019. This could be attributed to the rapid growth of the transport carbon emissions in Sichuan, Shandong and Qinghai Provinces. On the contrary, the azimuth of the transport output value in the Yellow River basin shows a counterclockwise trend. Specifically, the azimuth decreased from 62.59° in 2000 to 60.76° in 2019, which indicates that the "northeast–southwest" spatial distribution pattern of the transport output has become more obvious.

### *4.3. Decomposition Analysis of the Decoupling Relationship*

In Figure 10, the factors influencing the decoupling relationship of the transport sector in the Yellow River basin are decomposed. We further decomposed and analyzed the influencing factors of the decoupling relationship from the perspectives of the upstream, midstream and downstream regions and provinces, respectively, as shown in Figures 11 and 12.

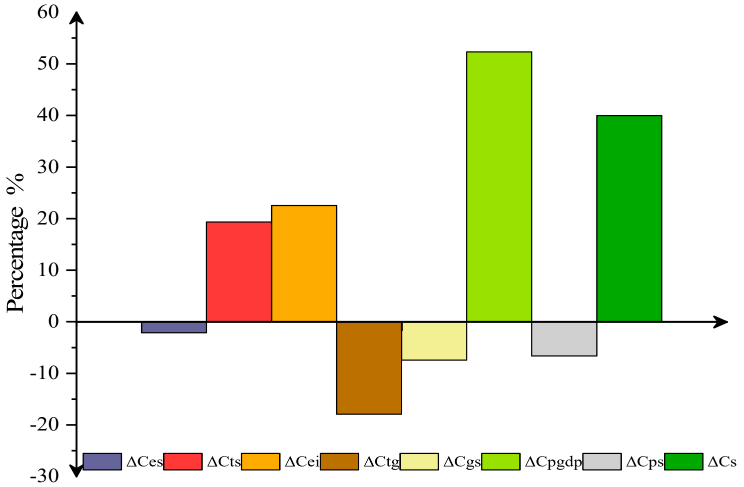

**Figure 10.** Contribution of influencing factors to the decoupling of the transport sector in the Yellow River basin.

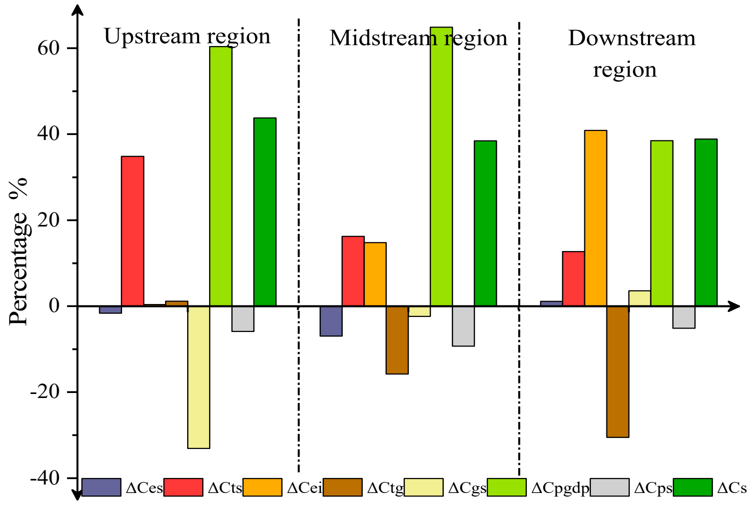

**Figure 11.** Decomposition results of the decoupling state of the transport sector at the regional level.

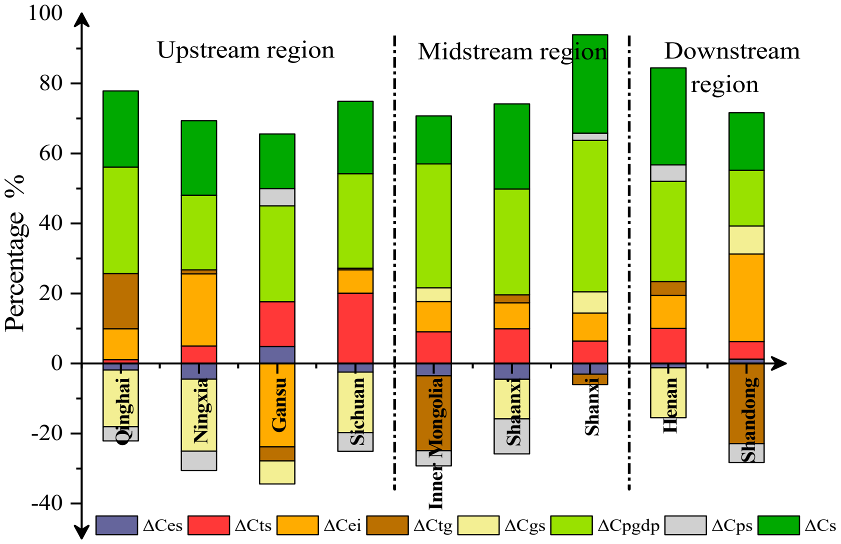

**Figure 12.** Decomposition results of the decoupling state of the transport sector at the provincial level.

As can be seen from Figure 10, the inhibitory effect of urbanization on the decoupling of the transport sector in the Yellow River basin is far greater than other factors, which is in agreement with the conclusion of Liu et al. [38]. The income urbanization effect ($\Delta C_{pgdp}$), spatial urbanization effect ($\Delta C_s$), energy intensity ($\Delta C_{ei}$) and transport structure ($\Delta C_{ts}$) are the main factors inhibiting the development of transport sector decoupling. In particular, the income urbanization effect ($\Delta C_{pgdp}$) plays the dominant negative role in the decoupling relationship (52.31%), which indicates that, with the improvement of residents' living standards, the transportation demand and energy consumption have increased significantly, resulting in the continuous growth of the transport sector's carbon emissions. This is in agreement with the results of Raza et al. [36]. The spatial urbanization effect ($\Delta C_s$) significantly inhibits the decoupling of transport carbon emissions (39.97%), which is second only to the income urbanization effect. The reason is that the spatial urbanization effect has led to the "job–housing separation" phenomenon and the continuous growth of residents' demand for mobility. Meanwhile, it has caused an increase in the transportation distance between places of production and consumption, an increase in logistics network complexity and transportation distance, and finally, inhibited the decoupling relationship.

The effect of energy intensity ($\Delta C_{ei}$) ranks third (22.53%) in terms of prohibiting the decoupling state, indicating that the energy use efficiency and key technology level of low-carbon transport equipment in the Yellow River basin still need to be improved. Furthermore, the transport structure effect ($\Delta C_{ts}$) is also a restraining factor (19.34%), which is in agreement with the results of Zhang et al. [49]. This demonstrates that the provinces in the Yellow River basin still need to optimize their transportation structures, and promote the green and low-carbon transformation of transportation in the main coal-producing areas, such as Shanxi, Shaanxi and Inner Mongolia.

The transport efficiency effect ($\Delta C_{tg}$), industrial structure effect ($\Delta C_{gs}$), population urbanization effect ($\Delta C_{ps}$) and energy structure effect ($\Delta C_{es}$) are the main factors promoting the decoupling state. Among them, the transport efficiency effect ($\Delta C_{tg}$) has a major effect on promoting the decoupling of transport carbon emissions (−17.93%), showing that the transportation turnover required for value added per unit decreases, and the transportation efficiency improves. The industrial structure effect ($\Delta C_{gs}$) ranks second in promoting the decoupling relationship (−7.45%), which may be related to the characteristics of the transport sector. The transport sector is an important, basic, leading and service-oriented industry within the national economy, and it serves other industries. Moreover, transportation is an energy-intensive industry, and the decline in its share of GDP has promoted decoupling development.

The population urbanization effect ($\Delta C_{ps}$) plays a minor role (−6.64%) in promoting decoupling. This indicates that, on the one hand, the urban area expansion rate is greater than the population growth rate. Meanwhile, urbanization development leads to population concentrations and industrial agglomeration in the urban area. To a certain extent, it promotes the realization of the transport scale effect in the transport sector. On the other hand, the population urbanization effect leads to the agglomeration of the logistics industry, promotes the development of freight transportation and logistics enterprises, improves the integration of transportation equipment, and finally, reduces the carbon emissions of the transport sector. The energy structure effect ($\Delta C_{es}$) has a very slightly positive effect (−2.12%) in terms of promoting decoupling development, which is consistent with the findings of Zhu et al. [50]. This indicates that optimizing the energy structure has great potential in terms of realizing decoupling in the Yellow River basin in the future.

As detailed in Figure 11, the inhibitory effects of spatial urbanization ($\Delta C_s$) and income urbanization ($\Delta C_{pgdp}$) on the decoupling relationship in the upstream and midstream regions (especially in Qinghai, Sichuan, Shaanxi and Shanxi Provinces) are much higher than in the downstream region (as shown in Figure 12). The reason is that the economic development of these regions is relatively lacking. With The Development of the Western Region and the Rise of Central China strategies, and the continuous advancement of the urbanization process, the urban space in these regions has expanded significantly. In the meantime, the increase in residents' income levels has triggered a large number of transport demands, which has a negative effect on the decoupling of the transport sector.

With regard to the upstream region of the Yellow River basin, in addition to the income urbanization effect ($\Delta C_{pgdp}$) and the spatial urbanization effect ($\Delta C_s$), the transport structure effect ($\Delta C_{ts}$) plays a strong negative role in the decoupling of the transport sector. Especially for Gansu and Sichuan Provinces, the inhibitory effect of this factor on the decoupling state is significantly higher than other factors. It shows that adjusting transport structure is important to the formulation of carbon emission reduction policies in the transport sector in the upstream region. Meanwhile, energy intensity ($\Delta C_{ei}$) plays a significant negative role in the decoupling relationship in Ningxia, Qinghai and Sichuan. In addition, the transport efficiency effect ($\Delta C_{tg}$) has a negative influence on decoupling, especially in Qinghai.

As for the midstream region of the Yellow River basin, except for $\Delta C_{pgdp}$ and $\Delta C_s$, the transport structure effect ($\Delta C_{ts}$) and energy intensity effect ($\Delta C_{ei}$) are significantly more inhibitory for the decoupling relationship than other factors. This implies that optimizing the transportation structure and improving energy efficiency are important ways to achieve decoupling in the midstream region. Especially for Inner Mongolia and Shaanxi, we should further optimize the transportation structure and promote the development of intermodal transport. Meanwhile, for Inner Mongolia and Shanxi, it is necessary to further promote the innovation of green transportation technology, promote low-carbon transport equipment, establish standard vehicle carbon emission systems and improve the energy efficiency.

In terms of the downstream region, in addition to $\Delta C_{pgdp}$ and $\Delta C_s$, energy intensity ($\Delta C_{ei}$) plays a significantly negative role in decoupling. This indicates that improving energy use efficiency is an important way to achieve the decoupling of the transport sector in the downstream region. Especially for Shandong Province, it is of great priority to further improve the standard and specification systems of green transportation and promote equipment upgrades, so as to strictly control the energy consumption and emission limits and improve energy efficiency. The transport structure effect ($\Delta C_{ts}$) has a negative influence on decoupling, especially in Henan. At the same time, energy structure ($\Delta C_{es}$) also has a negative influence on the decoupling of the downstream region, indicating that the promotion and application of new energy and clean energy is an important direction for formulating emission reduction policies in the future.

## 5. Conclusions and Policy Implication

The aim of our paper was to analyze the decoupling relationship between the development and $CO_2$ emissions of the transport sector in the Yellow River basin, and to provide a scientific basis for the formulation of differentiated carbon emission reduction policies. In this paper, the Tapio decoupling method was employed to examine the decoupling relationship of the transport sector in the Yellow River basin, and the SDE model was introduced to dynamically analyze the spatio-temporal characteristics of provincial carbon emissions and the added value from multiple perspectives. In addition, we combined the LMDI decomposition model with the decoupling method, and decomposed the decoupling index into eight effects to directly investigate the factors influencing the decoupling relationship. The main conclusions are as follows.

### 5.1. Main Conclusions

From this research, we found that the transport sector's carbon emissions in the Yellow River basin have obvious spatial heterogeneity, showing a non-equilibrium characteristic of "upstream region < midstream region < downstream region". The results show that the level of economic development is highly related to regional transport carbon emissions. The transport carbon emissions of Henan and Shandong are significantly higher than those of other provinces. The transport sectors in these two provinces are well developed, but the carbon emissions are very high, which indicates they should take more responsibility for reducing carbon emissions. In contrast, the upstream region has the lowest total carbon emissions.

From 2000 to 2019, the decoupling relationship in the Yellow River basin improved, showing a trend of "expansive negative decoupling, expansive coupling, weak decoupling". The decoupling state in the upstream area is not ideal, which suggests that the less-developed regions have great potential to reduce $CO_2$ emissions. In Sichuan Province, not only are the transport carbon emissions high, but the growth rate of carbon emission is also fast. This is a key area to realizing decoupling development. Moreover, the mean centers of the carbon emissions and the output value in the transport sector are concentrated in the downstream region, and the mean center of the transport output is more eastward than that of carbon emissions. The $Y$-axis of SDE shows that the carbon emissions and the output of the transport sector present a "northeast–southwest" spatial distribution characteristic. The growth rate of carbon emissions in Sichuan, Qinghai and Shandong is relatively fast, and the azimuth of the transport carbon emissions shows a clockwise trend.

The inhibitory effects of urbanization on decoupling in the Yellow River basin are much stronger than those of the non-urbanization factors. The income urbanization effect ($\Delta C_{pgdp}$), spatial urbanization effect ($\Delta C_s$), energy intensity ($\Delta C_{ei}$) and transport structure ($\Delta C_{ts}$) are the main factors restraining the occurrence of decoupling. Meanwhile, energy structure ($\Delta C_{es}$) shows great potential in terms of $CO_2$ emissions reduction in the transport sector in the future. In addition to $\Delta C_{pgdp}$ and $\Delta C_s$, transport structure ($\Delta C_{ts}$) has a major negative effect on realizing decoupling development in the upstream region, while transport structure ($\Delta C_{ts}$) and energy intensity ($\Delta C_{ei}$) have significant inhibitory effects on the realization of decoupling in the midstream region. Moreover, energy intensity ($\Delta C_{ei}$) and energy structure ($\Delta C_{es}$) are key to realizing decoupling status in the downstream region.

### 5.2. Policy Implications

This paper proposes some policy implications that can be used to help the Yellow River basin effectively realize decoupling development and formulate differentiated carbon emission abatement policies.

First, our study shows that the inhibitory effects of urbanization on decoupling in the Yellow River basin are much stronger than non-urbanization factors. Authorities in the Yellow River basin should reduce the impacts of urbanization on the decoupling relationship. In the process of promoting urbanization, it is necessary to reasonably plan the urban spatial structure, so as to strengthen the overall integration and unity of urban planning, ensure comprehensive urban transportation planning and carry out special planning for public transport in the Yellow River basin. The inhibitory effects of spatial urbanization ($\Delta C_s$) and income urbanization ($\Delta C_{pgdp}$) on the decoupling relationship in the upstream and midstream regions are much greater than in the downstream region. Therefore, the upstream and midstream regions (especially Qinghai, Sichuan, Shaanxi and Shanxi) should build a public transport system composed of "rail transit + bus + slow traffic system" according to the local conditions, and improve facilities and services to actively develop green and low-carbon mobility.

Second, the upstream regions are more likely to present a non-ideal decoupling state. Adjusting the transport structure is an important direction in the formulation of carbon emissions reduction policies for the transport sector. Especially for Gansu and Sichuan, the inhibitory effect of transport structure ($\Delta C_{ts}$) on decoupling is significantly higher than those of other factors. These provinces should further promote the development of intermodal transport and shift roadways to more environmentally friendly modes, such as waterways and railways, so as to alleviate carbon emissions. Energy intensity ($\Delta C_{ei}$) plays a strong negative role in the decoupling relationship in Ningxia, Qinghai and Sichuan. Consequently, these provinces should further improve the energy efficiency of their transport equipment and promote equipment upgrades. Moreover, in Qinghai, the transport efficiency effect ($\Delta C_{tg}$) has a major negative influence on decoupling. Qinghai should accelerate the development of intelligent transport and promote efficient modes of organization (such as piggyback transportation, urban green freight distribution and container modular automobile transportation), in order to promote the effective connection of various transportation modes and improve the efficiency of transport organization.

Third, in the midstream region, the transport structure effect ($\Delta C_{ts}$) and energy intensity effect ($\Delta C_{ei}$) have significantly higher inhibitory impacts on the decoupling relationship than other factors. Therefore, optimizing the transport structure and improving energy efficiency are important ways to achieve decoupling. As regards Inner Mongolia and Shaanxi, in order to further optimize the transportation structure, they should promote the construction of comprehensive transportation hubs and the development of intermodal transport, such as road–rail intermodal transport and air–ground intermodal transport. Furthermore, the midstream region should improve its comprehensive transportation energy efficiency, promote the application of low-carbon technology, raise the standards for vehicle energy consumption limits and accelerate the withdrawal of traditional fuel vehicles.

Finally, for the downstream region, the transport sectors in these two provinces are well developed, but the carbon emissions are very high; thus, they should take more responsibility for reducing carbon emissions. Further improving energy use efficiency and optimizing the energy structure are key to realizing decoupling. Energy intensity ($\Delta C_{ei}$) has a dominant negative effect on decoupling in the downstream region, especially in Shandong. These provinces should improve their low-carbon transportation standards and specification systems, and promote equipment upgrades and energy-saving driving to further improve energy efficiency. In addition, the inhibitory effect of energy structure ($\Delta C_{es}$) on the decoupling of the downstream region is greater than that in other regions. Hence, the downstream region should promote the use of clean energy (such as hydrogen energy and liquefied natural gas) and renewable fuels (such as ethanol and biodiesel based on crops), promote transportation electrification and increase the proportion of renewable energy used in power generation.

This paper also has limitations. We did not explore the decoupling relationship from the perspective of transport sub-sectors such as roads, railways and waterways, meaning that we cannot propose differentiated emission reduction suggestions from the perspectives of each transportation mode. In the future, we will carry out further research from the perspectives of different transport modes.

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## Appendix A

**Table A1.** The values of the major fossil fuel variables.

| Variables | Coal | Coke | Crude Oil | Gasoline | Kerosene | Diesel Fuel | Fuel Oil | Liquefied Petroleum Gas | Natural Gas |
|---|---|---|---|---|---|---|---|---|---|
| $ALVj$ (TJ/$10^4$ t) | 209.08 | 284.35 | 418.16 | 430.70 | 430.70 | 426.52 | 418.16 | 501.79 | 3893.10 |
| $Vj$ (t/TJ) | 26.37 | 29.50 | 20.10 | 18.90 | 19.50 | 20.20 | 21.10 | 17.2 | 15.30 |
| $rj$ | 0.94 | 0.93 | 0.98 | 0.98 | 0.98 | 0.98 | 0.98 | 0.98 | 0.99 |

Note: the $ALVj$ unit of natural gas is TJ/$10^8$ m$^3$. $ALVj$ is provided by the Energy Statistical Yearbook. $V_j$ and $r_j$ are sourced from the Guidelines to Provincial Lists of Greenhouse Gas Inventory.

**Table A2.** The carbon emission coefficients of main energy.

| Energy | Coal | Coke | Crude Oil | Gasoline | Kerosene | Diesel Oil | Fuel Oil | Liquefied Petroleum Gas | Natural Gas |
|---|---|---|---|---|---|---|---|---|---|
| Unit coefficient | (kg·kg$^{-1}$)<br>1.9003 | (kg·kg$^{-1}$)<br>2.8604 | (kg·kg$^{-1}$)<br>3.0202 | (kg·kg$^{-1}$)<br>2.9251 | (kg·kg$^{-1}$)<br>3.0179 | (kg·kg$^{-1}$)<br>3.0959 | (kg·kg$^{-1}$)<br>3.1705 | (kg·kg$^{-1}$)<br>3.1013 | (kg·m$^{-3}$)<br>2.1622 |

Note: The carbon emissions coefficient is obtained by multiplying $ALVj$ by $Vj$ by $rj$ by 44/12.

**Table A3.** The coefficients of converting passenger turnover to freight turnover.

| Transport Sub-Sectors | Railway | Road | Waterway | Aviation |
|---|---|---|---|---|
| Coefficient | 1 | 1/10 | 1/3 | 1:13.7 |

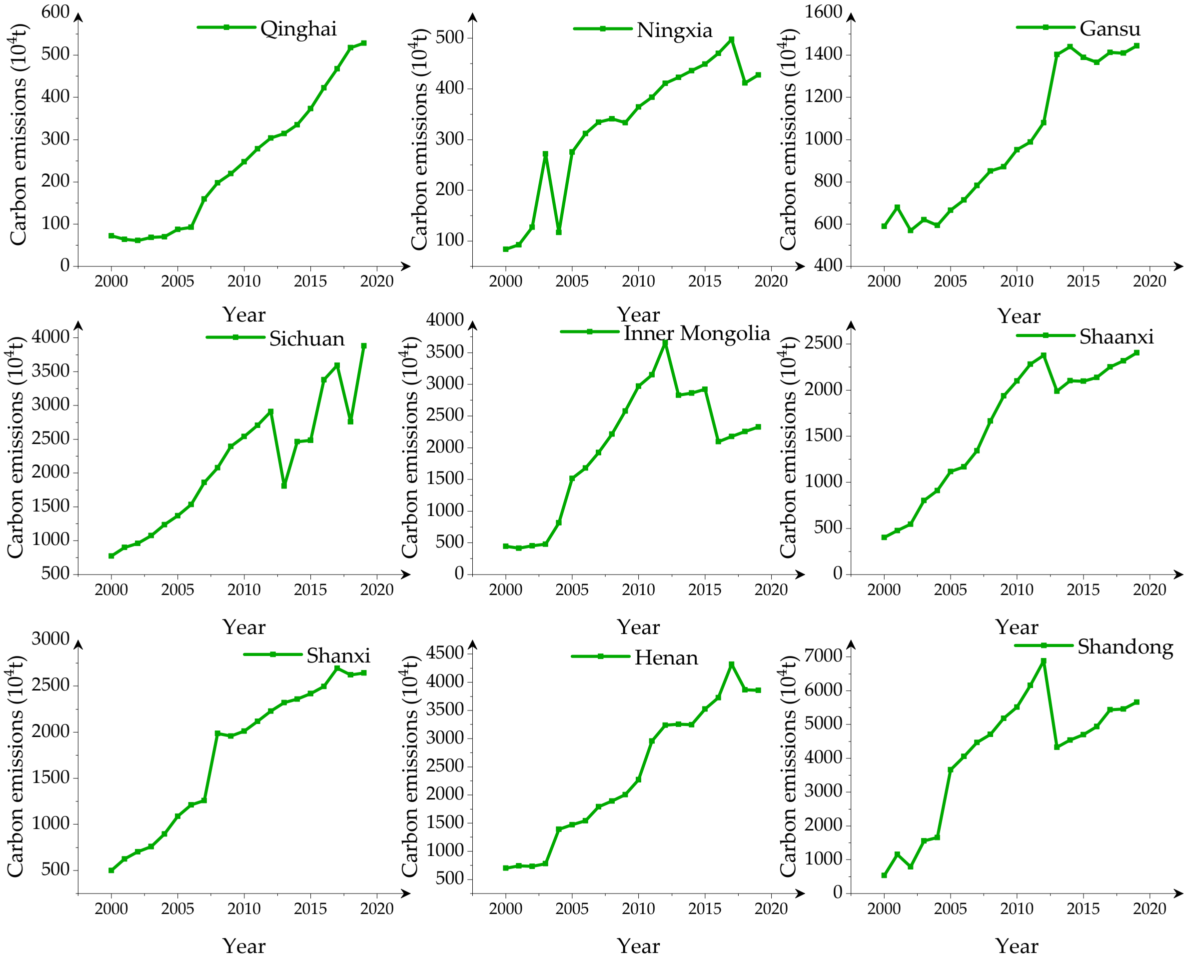

**Figure A1.** The transport carbon emissions trend in nine provinces of the Yellow River basin.

**Table A4.** The decoupling states of the transport sector at the provincial level.

| **Region** | **2000** | | **2004** | | **2008** | | **2012** | | **2016** | | **2019** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $T^t$ | **State** | $T^t$ | **State** | $T^t$ | **State** | $T^t$ | **State** | $T^t$ | **State** | $T^t$ | **State** |
| Qinghai | 5.490 | END | 0.451 | WD | 6.238 | END | 1.658 | END | 2.962 | END | 0.313 | WD |
| Ningxia | 1.869 | END | −8.148 | SD | 0.191 | WD | 0.835 | EC | 3.602 | END | 0.734 | WD |
| Gansu | 3.184 | END | −0.188 | SD | 1.097 | EC | 0.884 | EC | 2.530 | RD | 0.313 | WD |
| Sichuan | 0.907 | EC | 1.613 | END | 1.666 | END | 0.993 | EC | 5.898 | END | 5.810 | END |
| Inner Mongolia | 0.357 | WD | 3.184 | END | 0.861 | EC | 1.445 | END | −4.365 | SD | 0.736 | WD |
| Shaanxi | −0.220 | SD | 1.303 | END | 2.569 | END | 0.524 | WD | 0.290 | WD | 0.815 | EC |
| Shanxi | 0.695 | WD | 1.568 | END | 4.868 | END | 0.637 | WD | 0.468 | WD | 0.108 | WD |
| Henan | 1.229 | END | 4.321 | END | −2.743 | SND | 1.555 | END | 1.183 | EC | −0.012 | SD |
| Shandong | 6.775 | END | 0.197 | WD | 0.389 | WD | 1.183 | EC | 0.541 | WD | 0.421 | WD |

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