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Research on the impact of green logistics on carbon emission intensity of transportation industry

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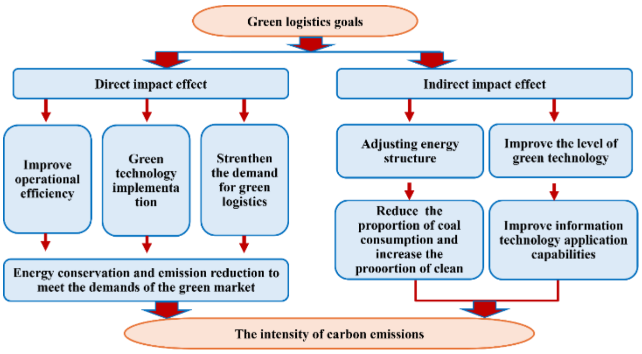
Graphical abstract



Abstract

With the serious challenge of global climate change, the Chinese government has proposed the "dual carbon" goals. In this context, the importance of green logistics as an effective way to reduce emissions in the transportation industry is becoming more and more prominent. This paper aims to explore the impact of green logistics on the carbon emission intensity of the transportation industry, in order to provide reference for relevant policy formulation and industry practice. Based on quantitative research methods, the development level of green logistics in 30 provinces in China is quantified using the entropy method, followed by an examination of the impact of green logistics on carbon emission intensity within the transportation industry through the construction of a benchmark regression model. The findings suggest that implementing green logistics can significantly reduce carbon emission intensity, with energy structure optimization being one channel for achieving this reduction. Additionally, improving information technology levels through green logistics can also help lower carbon emissions. Regional heterogeneity tests indicate that green logistics has a significant inhibitory effect on carbon intensity in western and northeast regions, while it is not as effective in central and eastern regions. Therefore, China should continue developing green logistics while considering regional differences and industry characteristics to achieve low-carbon development within the transportation industry.

Keywords: Green logistics, transportation, carbon emission, carbon intensity

1. Introduction

In response to global climate change, the Chinese government has proposed the "dual carbon" goals of achieving a "carbon peak" by 2030 and attaining "carbon neutrality" by 2060. In this context, green and low-carbon development has emerged as the sole pathway for fostering high-quality growth across various industries. According to the IEA "Emissions in 2022" report, China's total energy-related carbon emissions from 2021 to 2022 amount to approximately 12.1 billion tons. While the transportation sector is one of the major sectors of fossil energy consumption and greenhouse gas emissions, constituting around 10% of the overall carbon emissions. Confronted with pressing environmental challenges, the task of promoting carbon emission reduction in the transportation sector is not only urgent, but also of great practical significance and contemporary value. In addition to promoting environmental investments, implementing green logistics practices is a crucial step towards realizing the objective of achieving "carbon neutrality" (Zhu *et al.* 2023). Therefore, green logistics, as a sustainable logistics model, is of great significance in reducing the carbon emission intensity of the transportation industry.

The existing research primarily focuses on green logistics, carbon emission measurement in the logistics or transportation industry, and analysis of influencing factors. Regarding green logistics, the national standard "Green Logistics Indicators and Accounting Methods" provides a foundation for constructing, evaluating, and assessing enterprise green logistics. However, challenges persist in the practical implementation and exploration of green transformation within the logistics industry. The identified issues encompass an energy consumption structure that is not sustainable, an imbalanced development of green logistics regions, and inadequate planning for the allocation of transportation resources (Wang & Yan 2023). For instance, there are significant disparities in provincial-level green logistics levels across China with a spatial development pattern that is higher in the east but lower in the west. Obstacles to green logistics development mainly stem from factors such as scientific and technological investment proportionality, goods turnover rate, total import/export ratio of goods, per capita GDP, and fixed asset investment within the logistics industry (Zhang *et al*. 2023).

In terms of carbon emissions measurement, the calculation method proposed by the Intergovernmental Panel on Climate Change (IPCC) in 2006, which is based on energy consumption, is widely adopted and commonly used for carbon emissions estimation. This method relies on constructing a carbon emission inventory list that includes production behavior and release coefficients for each pollution source. By multiplying the required energy consumption with the corresponding release coefficient, the carbon emissions of each pollution source can be calculated (Zhang *et al*. 2023). Using this approach, Chen *et al*. (2023) employed direct energy consumption data from logistics industry in 11 provinces and cities along the Yangtze River Economic Belt to calculate CO_2 emissions. Jiang & Bin (2023) estimated carbon emissions of the logistics industry during 2010-2020 while Li *et al*. (2023) extended this analysis to include transportation-related emissions including private cars. This calculation method is also used in this paper.

In addition, there are many studies on the factors influencing carbon emissions in the logistics and transportation industry. For instance, economic growth is typically accompanied by an upsurge in energy demand, and the extensive utilization of fossil fuels contributes to the escalation of carbon emissions. Liu & Li (2022) discovered that continuous economic development was the primary driver behind the persistent increase in carbon emissions from Hubei Province's transportation industry. Guo & Wang (2021) demonstrated that per capita GDP within the logistics sector has a growing influence on its carbon emissions. Apart from economic factors, energy efficiency and demographic factors also contribute to carbon emissions (Zeng 2021; Yan & Xu 2024). However, energy intensity and industrial structure impede the logistics industry's carbon emission reduction efforts (Jiang & Zhang 2023). Furthermore, certain factors associated with the logistics industry also affect its carbon emissions. Through empirical analysis, Wang & Ma (2021) confirmed that transportation structure, energy efficiency level of transportation equipment, transportation organization level, and infrastructure density primarily influence transportation-related carbon emissions. Gu (2023) found that the rate of clean energy adoption and the level of transport energy intensity had a significant effect on both the freight turnover rate and passenger turnover rate of the transport sector, while highlighting the level of urbanization as another influencing factor on its overall level of carbon emissions. Scenarios related to carbon emissions in the logistics sector differ significantly, with the accelerated electrification scenario being the most consistent with future trends in this sector (Wang & Shao 2023). Cargo transportation plays a pivotal role in the transportation industry, and enhancing the share of railway freight, the extent of railway electrification, and the adoption rate of electric vehicles are effective strategies for achieving environmentally friendly and sustainable development in China's freight transport industry (Wen & Song 2022).

In the existing academic literature, although the quantitative assessment of the level of green logistics development and its drivers have been widely explored, and the carbon emissions generated by the logistics and transportation industries and the influencing factors behind them have been analyzed in detail, however, there is relatively little literature on the specific influencing mechanisms and effects of green logistics on carbon emissions in the transportation industry. This provides rich space and value for this paper to further explore the relationship between green logistics and carbon emissions in the transportation industry. Therefore, an in-depth study of the effect of green logistics on the carbon emission intensity of the transportation industry is of theoretical and practical significance. The main contribution of this paper is to supplement the impact of green logistics on carbon emissions in the transportation industry. Existing studies have considered few influencing factors, constructed a simple empirical test model, and selected test indicators that do not reflect the actual situation, etc. The study in this paper fully considers the actual situation of the development of China's transportation industry and the measurement requirements of green logistics, scientifically measures the level of the development of green logistics This study takes into account the actual development of China's transportation industry, the requirements of green logistics measurement, and the level of green logistics development. This paper constructs a theoretical framework of the mechanism of green logistics to reduce carbon emissions in the transportation industry, and based on the panel data of 30 provinces in China from 2010 to 2021, we use a benchmark regression model to quantitatively assess the relationship between green logistics and carbon emission intensity in the transportation industry, which ensures the scientific validity and credibility of the research results. By focusing on how green logistics influences carbon emissions in transportation, this study aims to raise awareness among enterprises and governments regarding the significance of green logistics in reducing carbon emissions. It also urges them to implement effective measures to address challenges posed by global climate change. Moreover, this research provides valuable insights for making informed decisions about emission reduction while offering theoretical support and practical guidance for transitioning towards a low-carbon economy.

2. Theoretical analysis and research hypotheses

2.1. Theoretical framework construction

Green logistics refers to the process of reducing the environmental impact of logistics activities by making full use of logistics resources, adopting advanced logistics technologies, rationally planning and implementing logistics activities such as transportation, storage, loading and unloading, handling, packaging, circulation, processing, distribution, and information processing. Green logistics has a direct and indirect effect on the carbon emission intensity of the transportation industry. To analyze the effect mechanism of green logistics on the carbon emission intensity of transportation industry, the influence mechanism is shown in Figure 1.

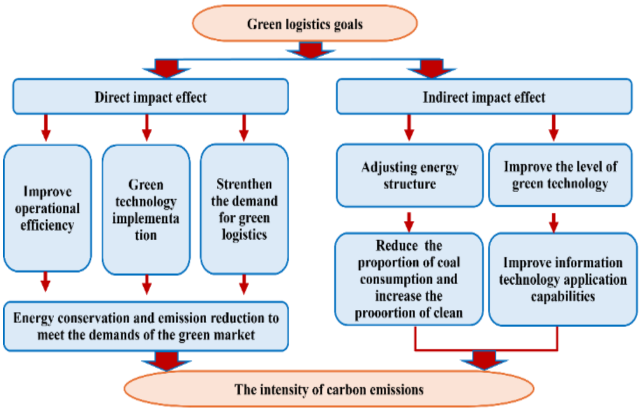


Figure 1. The mechanism of green logistics in mitigating carbon emissions within the transportation industry

2.2. The direct impact of green logistics on the carbon emission intensity of the transportation industry

2.2.1. Improving transportation efficiency

The concept of green logistics requires the integration of environmentally friendly and low-carbon principles throughout the entire process of planning, constructing, operating, and maintaining transportation infrastructure. This entails placing greater emphasis on environmental protection and energy conservation during the development of roads, railways, ports, and other transportation nodes. Through measures such as optimizing logistics network design, improving loading efficiency, and reducing empty driving rates, green logistics can improve transport effectiveness while minimizing unnecessary energy consumption and carbon emissions. Through comprehensive implementation of energy-saving initiatives across all aspects of logistics operations, green logistics mitigates the ecological impact associated with the industry (Zhu & Lai 2022).

2.2.2. Realizing the Implementation of Green Technology

Green logistics can effectively facilitate carbon emission reduction in the transportation industry through the implementation of green technologies. The innovation of green technology can reduce carbon emissions levels, Low-carbon green technologies, such as new energy vehicles, information technology, logistics equipment improvement, packaging technology, etc., effectively reduce the carbon emissions of transport vehicles. To initiate development in green logistics under the background of carbon peaking and neutrality promotion requires promoting modern technology applications in logistic packaging recycling (Zhao *et al*. 2023). With technological advancements continuing to emerge within this field, it is expected that Green Logistics will continue driving greener and more sustainable development for transportation.

2.2.3. Enhancing the industry's demand for green logistics

Green logistics also involves consumer awareness and acceptance of environmentally friendly products and services. As consumers become more aware of environmental protection, the demand for green logistics will further increase, thus promoting the low-carbon development of the entire industry. From a market demand perspective, it plays a pivotal role in reducing carbon emission intensity within the transportation sector by promoting its transition towards a low-carbon, efficient, and intelligent direction. The following hypothesis is proposed H1: Green logistics contributes to mitigating carbon intensity in the transportation industry.

2.3. The indirect impact of green logistics on the carbon emission intensity of the transportation industry

2.3.1. Adjusting the energy structure

Green logistics can significantly reduce carbon emissions in the transportation industry by optimizing the energy mix, that is, adjusting and improving energy supply and utilization methods. Green logistics promotes the adoption of low-carbon or zero-carbon alternative fuels, such as electricity, hydrogen, biofuels, etc., to replace conventional fossil fuels (e.g., diesel and gasoline). As coal consumption decreases while the consumption of other low-emission fossil fuels and renewable clean energy consumption increases, adjusting the energy structure will further facilitate carbon emission reduction (Shao 2022). Green logistics can drive a transition in the transportation industry from high-carbon to low-carbon or zero-carbon energy sources ultimately achieving sustainable development and carbon emission reduction. Based on the above findings, the following hypotheses are proposed H2: Optimization of energy structure through green logistics can effectively reduce carbon emissions in the transportation industry.

2.3.2. Improving the level of information technology

Information technology plays a pivotal role in the advancement of green logistics. By elevating the standard of information technology, it is possible to effectively mitigate carbon emission intensity within the transportation industry. For instance, through technologies like big data and cloud computing, real-time analysis of traffic conditions enables logistics companies to optimize transportation routes, thereby minimizing unnecessary driving distances and time consumption, resulting in reduced fuel usage and carbon emissions. Information technology facilitates seamless integration among multiple modes of transportation such as roadways, railways, and waterways by leveraging their respective advantages to collectively diminish overall carbon emission intensity. Informatization not only fulfills the requirements of green logistics but also serves as a pivotal force in driving the transformation of the logistics industry towards a greener and low-carbon future. Based on this analysis, hypothesis H3 is proposed: Green logistics can reduce the carbon emission intensity of the transportation industry by elevating information technology levels.

3. Materials and methods

3.1. Construction of the Model

3.1.1. Benchmark regression model

Benchmark regression modeling is a statistical method used to analyze the relationship between one or more independent variables (explanatory variables) and the dependent variables (explanatory variables). By controlling the variables, the influence of other factors on the results can be reduced, and the reliability of the results can be verified through statistical tests. In this paper, the equation (1) is formulated to examine the influence of green logistics development on carbon emissions in the regional transportation industry.

$$CI_{it} = \alpha_0 + \beta GL_{it} + \gamma X_{it} + \eta_i + \varphi_t + \mu_{it} \quad (1)$$

In the regression model, *I* represents the province, *t*represents the year, The dependent variable CI denotes carbon emission intensity, while GL_{it} stands for Green Logistics. X_{it} includes control variables such as economic development (*PG*), import and export (*PI*), population density (*PD*), urbanization level (*UL*) and social consumption level (*PCC*). α_0 is the constant term of the equation, β and γ represent regression coefficients, η_i captures province fixed effects, φ_t accounts for year fixed effects, and μ_{it} reflects random disturbances

3.1.2. Mediation effect model

The mediation effect model is used to analyze the indirect relationship between variables, i.e., one variable affects the outcome variable by influencing another mediating variable, revealing the mechanism of action and indirect influence path between variables. Here, the mediator variable M is introduced in equation (1), which is used to study the influence of green logistics on the carbon emission intensity of the transportation industry through the two mediator variables of energy structure (*ES*) and information technology level (*IM*). The model is based on rigorous mathematical and statistical principles, which improves the scientific validity of the study and helps to formulate targeted policies and interventions.

$$CI_{it} = \alpha_0 + \beta GL_{it} + \rho M_{it} + \gamma X_{it} + \eta_i + \varphi_t + \mu_{it} \quad (2)$$

A mediator variable test model constructed using an intermediary variable in lieu of a dependent variable.

$$ES_{it} = \alpha_0 + \beta GL_{it} + \gamma X_{it} + \eta_i + \varphi_t + \mu_{it} \quad (3)$$

$$IM_{it} = \alpha_0 + \beta GL_{it} + \gamma X_{it} + \eta_i + \varphi_t + \mu_{it} \quad (4)$$

3.2. Variables description

3.2.1. Dependent variable: carbon intensity (CI).

The dependent variable is the carbon intensity of the transportation sector, which refers to the ratio of carbon emissions from transportation activities to the industry's GDP. Considering the industry classification provided by the China Energy Statistical Yearbook and taking into account the small proportion of energy consumption in warehousing and postal industries, we have selected energy consumption data from provincial transportation, warehousing, and postal sectors instead of transportation industry data. The energy sources considered include raw coal, crude oil, gasoline, kerosene, diesel, fuel oil, liquefied petroleum gas, and natural gas. In this paper, the calculation method provided by IPCC in “2006 IPCC Guidelines for National Greenhouse Gas Inventories” is used to calculate carbon emissions. The main calculation formula is as follows.

$$C = \sum_{i=1}^{8} C_i = \sum_{i=1}^{8} E_i \cdot F_i \quad (5)$$

In the equation, C represents the carbon emissions generated by the energy consumption of the provincial transportation industry, while C_i denotes the carbon emissions of energy. E_i signifies the energy consumption, and F_i corresponds to the CO_2 emission factor associated with energy *i*. The carbon dioxide emission coefficient per unit of energy is calculated based on numbers of factors such as average low calorific value of energy, carbon content per unit of heat, and carbon oxidation rate. These data are derived from “Guide for the Preparation of Provincial Greenhouse Gas Inventories”.

Table 1. The index system for assessing the level of green logistics development in the transportation industry

Target layer	Primary indicators	Secondary indicators	Indicator direction
Green logistics	infrastructure	Railway operating mileage	Positive
		Grade road mileage	
		Length of inland waterways	
		fixed-asset investment of logistics industry	
	Energy consumption	Total energy consumption of logistics industry	Reverse
	Environmentally sustainable	Public transport vehicles per 10,000 people	Positive
		Green area	
		The ratio of railway freight to road freight	
		Number of green patents granted	
	Scale of development	Express business volume	Positive
		Cargo turnover	
		Number of employees in the logistics industry	
		Value added of logistics industry	

3.2.2. Core explanatory variable: green logistics development level (GL)

The explanatory variable in focus is the developmental level of green logistics, for which a standardized measurement method has yet to be established within the academic community. This study builds upon relevant existing research (Huang *et al*. 2023; Chen and Zhang 2023; Wang and Guo 2024; Zhu and Lai 2022; Zhang 2023) to propose four primary indicators for green logistics: infrastructure, energy consumption, environmental friendliness, and development scale. Additionally, it considers data availability to construct an index system for assessing the level of green logistics development. Please refer to Table 1 for detailed information.

As the fixed-asset investment of the logistics industry is no longer disclosed in the yearbook after 2017, subsequent data has been estimated using the published annual growth rate. The total energy consumption of the logistics industry encompasses raw coal, petroleum, gasoline, kerosene, diesel, fuel oil, liquefied petroleum gas and natural gas converted into standard coal for transportation, storage and postal activities. Cargo turnover refers to the cumulative product of goods transported by various means of transport and their corresponding distances within a specific period. The calculation formula is as follows: cargo turnover = ∑ (cargo transport quantity * transport distance).

In this study, the entropy method is employed to determine the weight of the secondary index (Zhu and Lai 2022). The degree of dispersion of the secondary index is assessed by calculating its entropy value. A higher influence weight on comprehensive evaluation is assigned to indices with greater degrees of dispersion. Mathematically determining the weights of the indicators reduces the influence of subjective judgments and is able to reflect the variability of the indicators. By employing dimensionless processing, which takes into account variations in quantification standards among different indicators, more accurate and reliable comparisons and operations between variables can be achieved.

For positive indicators, perform the following treatments:

$$Y_{ij} = \frac{X_{ij} - \min\left(X_{ij}\right)}{\max\left(X_{ij}\right) - \min\left(X_{ij}\right)} + 0.01 \tag{6}$$

Negative indicators are treated as follows:

$$Y_{ij} = \frac{\max\left(X_{ij}\right) - X_{ij}}{\max\left(X_{ij}\right) - \min\left(X_{ij}\right)} + 0.01 \tag{7}$$

In the given formula, *i* represent the year and *j* represents the indicator. Y_{ij} denotes the actual values, while max (X_{ij}) and min (X_{ij}) represent the maximum and minimum values in each province. The normalized value is added to 0.01 to avoid the insignificance of logarithmic calculations in entropy estimation (Xu 2021).

After dimensionless processing of the data, the influence weight ω_j for index is calculated. ω_j indicates the importance of indicator j in the overall evaluation.

$$\omega_j = \frac{\left(1 - e_j\right)}{\sum_{j=1}^{m}\left(1 - E_j\right)} \tag{8}$$

$e_j = -\frac{1}{\ln n}\sum_{i=1}^{n} p_{ij}\ln\left(p_{ij}\right)$ is the entropy value of indicator *j*, $p_{ij} = \frac{Y_{ij}}{\sum_{i=1}^{n} Y_{ij}}$ is used to calculate the weight. *n* denotes the number of sample years, while *m* represents the count of indicators.

Finally, the development level of green logistics in each province has been comprehensively assessed over the years. The evaluation value is determined by summing the product of each index weight ω_j and its non-dimensional value Y_{ij}.

$$GL_i = \sum_{j=1}^{m}\omega_j Y_{ij} \tag{9}$$

3.2.3. Mediation variables

Some influencing factors, such as the policy and legal environment, are difficult to measure, and the impact of these general factors is often reflected in actual transportation activities. Therefore, only factors that are related to energy consumption are considered here. According to the above theoretical analysis, green economy mainly affects carbon emission intensity through energy structure and technological innovation. Therefore, the following intermediary variables are selected.

The first indicator is the energy structure (ES), which reflects the customary practice of selecting the percentage of coal consumption in the transportation industry to total energy consumption. The second indicator is the level of information technology (IM), which measures the ratio of post and telecommunications business to GDP.

3.2.4. Control variables

Economic development, population, and other factors are the primary determinants of carbon emissions in the transportation industry. Furthermore, it is documented that exports and imports have a negative effect on carbon emission (Rethabile *et al*. 2023). Additionally, the level of urbanization affects carbon emission intensity (Liu *et al*. 2023; Gu 2023). Considering these research findings alongside industry characteristics, this paper selects the following control variables.

The first indicator is economic development (PG), which is measured by GDP per capita.

The second indicator is import and export (PI), which represents the ratio of total imports and exports to domestic destinations compared to the total imports and exports from both domestic destinations and source places.

The third indicator is population density (PD), calculated as the ratio of regional population to provincial administrative division area.

The fourth indicator measures urbanization level (UL) by calculating the number of urban populations divided by regional total population for each province.

Fifth, social consumption level (PCC), which is the total retail sales of consumer goods per capita, is the ratio of the total retail sales of consumer goods to the regional population.

3.3. Data sources

The study covers 30 provinces in China from 2010 to 2021, and the data are mainly derived from the China Energy Statistical Yearbook, the Tertiary Industry Statistical Yearbook, the China Logistics Yearbook, the China Urban Construction Statistical Yearbook, the National Bureau of Statistics and the statistical yearbooks of various provinces, municipalities and autonomous regions. In addition, linear interpolation is used to handle missing data. For reasons such as comparability and consistency of data, the data for individual indicators are appropriately revised based on the underlying data.

4. Results & discussion

4.1. Descriptive statistics of underlying data

In order to study the impact of green logistics on the carbon emission intensity of 30 provinces in China (excluding Tibet Autonomous Region, *Taiwan Province, Hong Kong Special Administrative Region and Macao Special Administrative Region),* 360 sample data from 2010 to 2021 were selected, covering major variables such as carbon intensity (CI) and green logistics (GL). The descriptive statistics are as follows.

Table 2. Descriptive statistics of major variables

variable	N	mean	SD	min	max	p50
CI	360	1.970	1.010	0.280	7.340	1.840
GL	360	0.450	0.170	0.140	0.880	0.430
PG	360	0.540	0.290	0.130	1.880	0.470
PI	360	0.500	0.150	0.180	0.830	0.470
PD	360	0.470	0.700	0.0100	3.930	0.290
PCC	360	0.210	0.120	0.0400	0.730	0.190
UL	360	0.590	0.120	0.340	0.900	0.570

Table 3. Baseline regression results

VARIABLES	CI	CI	CI	CI	CI	CI
GL	-2.088***	-2.085***	-2.205***	-2.038***	-1.923***	-2.258***
	(-4.62)	(-4.68)	(-5.08)	(-4.75)	(-4.20)	(-4.73)
PG		-1.361***	-1.137***	-0.112	0.239	1.526*
		(-3.17)	(-2.70)	(-0.22)	(0.34)	(1.72)
PI			-2.680***	-2.348***	-2.391***	-1.825***
			(-4.34)	(-3.83)	(-3.87)	(-2.77)
PD				-6.060***	-5.833***	-3.830**
				(-3.58)	(-3.38)	(-2.00)
PCC					-0.852	-2.346*
					(-0.72)	(-1.75)
UL						6.871**
						(2.34)
Constant	2.039***	2.466***	3.833***	6.007***	5.893***	0.985
	(14.18)	(12.61)	(10.41)	(8.49)	(8.12)	(0.44)
Observations	360	360	360	360	360	360
R-squared	0.346	0.367	0.402	0.425	0.426	0.436
Number of ids	30	30	30	30	30	30

*Note: To pass the 1% confidence test, ** to pass the 5% confidence test, * to pass the 10% confidence test, and the results of the T test are in parentheses.*

4.2. Baseline regression

The impact of green logistics on carbon emissions in the transportation industry is examined using a fixed-effect model, and the relationship between variables in time series data is analyzed. Control variables including economic development (PG), import and export (PI), population density (PD), urbanization level (UL), and social consumption level (PCC) are included. Table 3 presents the baseline regression results for the association between green logistics and carbon intensity in the transportation sector. Columns (1) show the regression results without control variables, while columns (2) to (6) exhibit the regression results with each control variable added sequentially (Table 3).

Based on the regression results, it is evident that green logistics significantly impact the carbon emissions of the transportation industry, irrespective of the inclusion of control variables. The coefficients associated with green logistics exhibit negative values at a 5% confidence level, providing evidence for the reduction in carbon emission intensity through green logistics and confirming hypothesis H1. A higher level of green logistics development corresponds to a lower carbon intensity within the transportation industry. This can be attributed to both the implementation of eco-friendly transportation infrastructure and technologies, as well as increased demand for green logistics which effectively promotes low-carbon development in this sector. Considering control variables, import and export (PI) in columns (3)-(6) demonstrate significant negative correlation at a 1% confidence level, indicating an inverse relationship between imports and carbon emission intensity within a context of sustainable development. Previous studies have also highlighted how import trade has contributed significantly to China's efforts in reducing carbon emissions (Liu *et al*. 2023). The population density (PD) and urbanization level (UL) among the control variables were significant at 5% confidence, indicating that there was a significant negative correlation between population density and carbon intensity of the transportation sector. The coefficient of urbanization level is significantly positive at the level of 5%, indicating that urbanization will aggravate carbon emission intensity, and the higher the urbanization level, the higher the carbon emission intensity of the transportation industry. The coefficient of the social consumption level (PCC) is positive, indicating that the total retail sales of consumer goods per capita will significantly increase the carbon emission intensity, mainly because the growth of the scale of social consumer goods will increase the business demand for transportation services, so "carbon reduction" also needs to pay attention to carbon emissions in the consumption sector.

Table 4. Results of mediation effect test

VARIABLES	CI	ES	CI	IM	CI
GL	-2.258***	-0.002*	-2.230***	0.009*	-2.290***
	(-4.73)	(1.84)	(-4.68)	(1.88)	(-4.83)
ES			13.960*		
			(-1.92)		
IM					-3.484**
					(2.31)
Constant	0.985	0.003	1.021	0.217***	0.230
	(0.44)	(0.20)	(0.46)	(2.63)	(0.10)
Observations	360	360	360	360	360
R-squared	0.436	0.074	0.440	0.884	0.446
Number of ids	30	30	30	30	30

Table 5. Robustness test results

VARIABLES	Substitution Variable (UD)	Tail reduction 5% (CI)
GL	-0.349***	-1.440***
	(-3.62)	(-3.56)
Constant	0.709***	1.987***
	(3.46)	(3.27)
Observations	360	360
R-squared	0.644	0.466
Number of ids	30	30

4.3. Mediation effect

The development of green logistics can optimize the energy structure and promote the advancement and application of information technology. To examine the indirect impact of mediating variables on carbon emission intensity in the transportation industry, it is essential to assess the effects of explanatory and control variables on these mediating factors. This assessment primarily involves analyzing how independent variables, mediator variables, and control variables influence dependent variables, as well as how independent variables affect mediator variables. By considering the design of mediating variable and employing equations (2) to (4) to determine intermediate variable models, we can comprehend the influence of mediating factors by evaluating both their magnitude and direction (Table 4).

The results in column (2) demonstrate a significant negative impact of green logistics development on the energy structure, which is statistically significant at a confidence level of 10%. This indicates that as the level of green logistics development increases, there is a decrease in the proportion of coal energy consumption within the transportation industry. Consequently, there is also a reduction in demand and consumption of fossil energy, leading to an optimized energy structure. Column (3) reveals that improving the energy structure can significantly reduce carbon intensity within the transportation industry. Therefore, optimizing the energy structure serves as one pathway for green logistics to achieve carbon intensity reduction within this sector. These findings validate hypothesis H2. Columns (4) and (5) present evidence supporting a positive effect of green logistics on information technology levels within the transportation industry. Furthermore, enhancing information technology levels significantly reduces carbon emission intensity within this sector. Thus, these results confirm hypothesis H3: by improving information technology levels, green logistics can effectively reduce carbon emission intensity within the transportation industry.

4.4. Discussion of robustness and heterogeneity

4.4.1. Discussion of robustness test

The reliability of the benchmark regression results was assessed by replacing the explanatory variables and shrinking the tail. The first is to replace the explanatory variable, carbon intensity is selected as the explanatory variable in the benchmark regression, and the per capita carbon emission (UD) is selected to replace the carbon intensity as the explanatory variable to test the robustness of the benchmark regression results (Xie, 2022), and the per capita carbon emission is expressed by the ratio of the carbon emissions of each province to the population of each province over the years. Second, to avoid the influence of the sample extremes on the regression results, all samples were tailed by 5%. Column (1) is the result of substitution variables, and the results of tail reduction are shown in column (2), from which it can be found that the impact coefficient of green economy is significantly negative at the 1% level, which is consistent with the benchmark regression results (Table 5).

4.4.2. Discussion of heterogeneity test results

The unique geographical environment and development potential of each region are shaped by the combined influence of several factors, including differences in natural conditions, economic conditions, transportation development, market characteristics, and other aspects. Considering this, an analysis is conducted on the varying impact of green logistics on the carbon intensity of the transportation industry in four regions: eastern, central, western, and northeastern. The regression results are as follows:

From the table below, it can be found that the regression coefficients of green logistics in the western and northeast regions exhibit a significant negative association at the 1% level. Conversely, no significant relationship is observed between green logistics and carbon intensity in the eastern and central regions. This implies that while there is a noticeable inhibitory effect of green logistics on carbon emissions within the transportation industry in the western and northeast regions, this effect lacks significance in the eastern and central regions. Per capita GDP (PG) has passed a significance test with a confidence level of 1%, yielding a coefficient of 1.919, indicating its substantial positive impact on carbon emissions from transportation activities. The levels of urbanization and social consumption significantly influence industry-specific carbon intensity within the central region. Furthermore, imports and exports exert significant effects on carbon intensity specifically within the western and northeastern regions, distinguishing them from their counterparts in both central and eastern areas (Table 6).

Table 6. Heterogeneity test results

VARIABLES	Eastern	Central	Western	Northeastern
	CI	CI	CI	CI
GL	-0.808	-1.616	-2.857***	-4.801***
	(-1.62)	(-1.07)	(-3.39)	(-4.58)
PG	1.919***	2.577	-0.671	1.443
	(2.71)	(0.97)	(-0.48)	(0.44)
PI	-0.396	-1.603	-2.646***	5.598***
	(-0.33)	(-1.00)	(-3.39)	(4.48)
PD	-0.033	-5.571	17.928	52.318
	(-0.02)	(-0.39)	(1.34)	(1.50)
PCC	-1.883	-8.346***	-3.116	-41.127***
	(-1.53)	(-2.69)	(-1.45)	(-4.89)
UL	1.907	27.130***	5.185	4.135
	(1.01)	(3.35)	(1.28)	(0.44)
Constant	0.412	-7.909	-0.558	-7.100
	(0.18)	(-1.20)	(-0.23)	(-0.78)
Observations	132	72	132	36
R-squared	0.283	0.741	0.628	0.961
Number of ids	10	6	11	3

5. Conclusions and recommendations

Based on the panel data of thirty provinces in China from 2011 to 2021, this study examines the impact of green logistics on carbon emission intensity within the transportation industry. The main conclusions are as follows: (1) Green logistics plays a crucial role in reducing carbon emission intensity within the transportation sector. (2) A higher level of green logistics development leads to decreased demand and consumption of fossil energy, resulting in a significant reduction in carbon intensity through improvements in energy structure.

Additionally, there is a significantly positive relationship between green logistics and information technology levels, enhancing information technology levels contributes to lower carbon emissions within the industry. (3) Geographically, the influence of green logistics on carbon emissions varies across regions. While it has an evident effect on carbon intensity within the transportation industry in western and northeastern regions, such impact is not observed in eastern and central regions. Combining theoretical analysis and empirical results, this paper puts forward the following recommendations for the carbon emission reduction challenges in China's transportation industry.

(1) Continue to promote the development of green logistics. According to the test results of the benchmark regression, the relationship between green logistics and carbon emission intensity in the transportation industry is inverse correlation, and strengthening the application of green logistics in the transportation industry can effectively realize carbon emission reduction. It is recommended that corresponding incentive policies be formulated by the government and industry associations to encourage enterprises in adopting more efficient logistics management practices and technical measures. For instance, economic incentives should be provided for the utilization of new energy transportation methods, thereby promoting the green transformation and development of logistics enterprises.

(2) Make full use of the indirect inhibiting effect of mediating variables on the intensity of transportation carbon emissions. According to the results of the intermediary test, the energy structure and the application of information technology have an indirect inhibitory effect on carbon emissions. Therefore, it is necessary to further adjust the energy structure and improve the application level of information technology in the industry, which are the keyways to realize the reduction of carbon emissions in the transportation industry.

(3) Regional differences and industry characteristics should be fully considered when formulating relevant policies and measures. According to the results of the regional heterogeneity test, the development of green logistics in the western and northeastern regions can significantly reduce the carbon emission intensity of the transportation industry, so it is necessary to adjust the green logistics policies and carbon emission reduction targets according to regional differences and implement differentiated incentives. The comparative advantages of each region are fully utilized, and interregional cooperation is encouraged to achieve overall low-carbon development.

6. Research limitations

Although this paper examines the relationship between green logistics and carbon emissions in the transportation industry, there are still some limitations. Measuring the level of green logistics development is constrained by data availability and volume limitations. For instance, indicators such as enterprises' green development management and the number of new energy vehicles also contribute to assessing green logistics. however, publicly available data currently lacks support for analysis. In addition, there may be certain constraints in selecting control variables that do not fully encompass all factors influencing carbon emissions in the transportation industry.

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