

Research on the Mechanism of Influence on Transportation Carbon Emission Driven by Digital Economy--An Empirical Analysis Based on Interprovincial Panel Data in China

Xinyu Zhang

Institute of Statistics and Applied Mathematics, Anhui University of Finance & Economics,
Bengbu Anhui 233030, China

Abstract

Driven by the "dual-carbon" goal, the role of the digital economy in carbon emission reduction in the transportation sector has attracted much attention. This study designs a comprehensive digital economy evaluation index system and calculates the total carbon emissions of the transportation sector based on data from 30 provinces in China between 2009 and 2020, using the internationally recognized IPCC methodology. The empirical analysis shows that there is a special "inverted U-shape" relationship between the digital economy and transportation carbon emissions. Further in-depth investigation reveals that the role of digital economy in promoting carbon emission reduction in the transportation sector is particularly prominent in the central and eastern regions. In addition, the digital economy can effectively promote carbon emission reduction in the transportation sector by optimizing the transportation structure and alleviating traffic congestion. This finding not only reveals the potential of the digital economy in carbon emission reduction, but also provides valuable insights for our future green transportation development.

Keywords

Digital economy, transportation, carbon emissions, mediation test, heterogeneity analysis.

1. Introduction

With the acceleration of global industrialization and overdependence on fossil energy, carbon dioxide emissions have far exceeded expectations, exacerbating environmental problems such as the greenhouse effect. To meet the challenge, China has proposed a "dual-carbon" goal aimed at promoting green and low-carbon governance. As a developing country, China's economy continues to grow rapidly, and the transportation system has become the second largest source of carbon emissions after the energy sector.

Currently, the development of China's digital economy has stepped into the stage of systematic strategic layout, paving a brand new road for the transportation sector to move towards the goal of carbon neutrality. This study focuses on the close connection between the digital economy and transportation carbon emissions, and is dedicated to exploring how digital technology drives the specific links of transportation carbon emissions reduction. With the deepening implementation of the "Digital China" strategy, academics are increasingly diversifying their discussions on the digital economy, not only constructing a comprehensive evaluation system covering digital infrastructure and industrial integration, but also analyzing its catalytic effect on industrial upgrading, especially on the intelligent transformation of the manufacturing industry. In recent years, the environmental benefits of the digital economy, especially the mechanism of carbon emission reduction, have become a new focus of research.

Low-carbon transition paths have received much attention in the field of transportation carbon research. Carbon emission accounting mostly follows the guidelines of the United Nations Panel on Climate Change, and key influencing factors include energy structure, transportation structure and metro network application. In recent years, the application of digital technology in energy saving and emission reduction has become increasingly significant, and the relationship between the digital economy and carbon emissions is closely linked. Studies have shown that industrial digitization can reduce carbon emissions by optimizing resource allocation and improving energy efficiency; however, fewer systematic studies have been conducted for the transportation sector, which needs to be further explored.

In the time span from 2009 to 2020, this paper relies on provincial panel data as the basis to construct a comprehensive evaluation system covering the elements of digital industrialization, and with the help of the mediating effect model, it explores in-depth the intrinsic mechanism of the digital economy's role in transportation carbon emissions, providing a solid theoretical basis for differentiated policy formulation.

2. Theoretical analysis and research hypothesis

2.1. Non-linear relationship between the digital economy and carbon emissions

Exploring the impact of the digital economy on carbon emissions in the transportation sector is a complex process. In the early stages of infrastructure development, the digital economy often goes hand in hand with the construction of large-scale facilities, a process that increases the demand for transportation and leads to a rise in carbon emissions from the sector. However, as facilities are built and digital transportation networks and architectures mature, the integration of cutting-edge technologies such as 5G communications and big data with intelligent transportation systems not only saves energy and reduces emissions, but also greatly improves the efficiency of the transportation sector's carbon footprint.

On the other hand, the vigorous promotion of the digital economy has strongly contributed to the sustained growth of the national economy. With the significant increase in the consumption level of the population, there is a growing demand for transportation services to meet daily shopping and travel needs, which undoubtedly puts more pressure on the transportation industry in terms of carbon emissions. However, the rapid development of the economy has given rise to green transportation modes such as new energy vehicles and shared bicycles, and these innovations have optimized the transportation structure. In addition, the rapid development of intelligent transportation technology has realized the sharing of information among transportation modes, which has significantly improved transportation efficiency and effectively reduced carbon emissions by controlling passenger and cargo flows. In summary, there may be a non-linear and complex relationship hidden between the digital economy and carbon emissions in the transportation industry. In view of this, this paper hereby proposes the following research hypotheses.

Hypothesis 1: The effect of the digital economy on carbon emissions from the transportation sector is characterized by an "inverted U-shaped" nonlinearity.

2.2. Mechanisms of the digital economy on carbon emissions in the transportation sector

Under the new situation of the deep integration of the digital economy and the transportation industry, the accelerated emergence of new forms of transportation led by intelligence has prompted the transformation of the obsolete transportation structure into a green road. Road transport has long occupied half of China's total transportation carbon emissions, and the proportion of railroads, waterways and other transportation channels in the passenger and

cargo turnover has gradually increased, so it is possible to effectively reduce the carbon emissions of road transport through the construction of a multifaceted intermodal transportation system. This paper puts forward the following hypotheses:

Proposed hypothesis 2: The digital economy can significantly reduce carbon emissions from the transport sector by optimizing the transport architecture and reducing traffic congestion.

3. Study design

3.1. Modeling

3.1.1. Benchmark regression model

In order to explore the association between the digital economy and carbon emissions in the transportation industry, the following baseline regression analysis model is constructed for validation.

$$C_{iy} = \alpha_0 + \alpha_1 D_{iy} + \alpha_2 X_{iy} + u_i + \gamma_y + \varepsilon_{iy} \quad (1)$$

$$C_{iy} = \alpha_0 + \alpha_1 D_{iy} + \alpha_2 D_{iy}^2 + \alpha_3 X_{iy} + u_i + \gamma_y + \varepsilon_{iy} \quad (2)$$

In this model, *i* and *y* represent province and year, respectively. The explanatory variable is the carbon emissions from the transportation sector in province *i* in year *y*, while the explanatory variable is the level of digital economy development in province *i* in year *y*. The explanatory variable is the level of digital economy development in province *i* in year *y*. A quadratic term for the level of digital economy development is also included, as well as the selected control variables. In addition, the fixed effects of province and year are introduced, ε represents the residuals, and β , γ , and δ are the parameters to be estimated. $C_{iy} D_{iy} D_{iy}^2 X_{iy} u_i \gamma_y \varepsilon \alpha_0 \alpha_1 \alpha_2$

3.1.2. Models of mediating effects

On top of the baseline regression model, in order to investigate how the digital economy affects carbon emissions in the transportation sector, this paper sets the transportation structure as the mediating variable and constructs the following model.

$$M_{iy} = \alpha_0 + \alpha_1 D_{iy} + \alpha_2 D_{iy}^2 + \alpha_3 X_{iy} + u_i + \gamma_y + \varepsilon_{iy} \quad (3)$$

$$C_{iy} = \alpha_0 + \alpha_1 D_{iy} + \alpha_2 D_{iy}^2 + \alpha_3 X_{iy} + \alpha_4 M_{iy} + u_i + \gamma_y + \varepsilon_{iy} \quad (4)$$

In this equation, *M* represents the mediator variable carefully selected in this paper, and the meanings of the rest of the symbols are all consistent with equation (1).

3.2. Selection of variables

3.2.1. Explanation of Explained Variables

The core variable explained in this paper is the total carbon emissions from the transportation industry, which is quantified as follows: *C* accurately represents the total amount of carbon emissions from the transportation industry; *i* distinguishes in detail the types of energy sources, which include seven categories: coal, gasoline, kerosene, diesel, fuel oil, natural gas, and electric power; *E* depicts the actual amount of energy consumed and has been converted into standard coal units; *NC* reveals the average low-level heat output of each type of energy; *EF* characterizes the carbon emissions per unit of calorific value of energy; and *CF* accurately depicts the carbon emissions per unit of heat value. has been converted to units of standard coal; *NC* reveals the average low-level heat generation of each energy category; *EF* characterizes the carbon emissions contained in the unit calorific value of energy; and *CF* accurately depicts the carbon oxidation ratio.

$$C = \sum_{i=1}^7 E_i \times NC_i \times EF_i \times CF_i \times 44/12 \tag{5}$$

3.2.2. Explanatory variables

The explanatory variable of this paper is set as digital economy (D), and its square term (D²) is added to explore the nonlinear effect on transportation carbon emissions. In addition, a set of indicators to assess the level of development of the digital economy is constructed from four different levels.

3.2.3. Mediating variables

Transportation structure (TRA) is measured in this paper as the share of highway converted turnover in total converted turnover.

Table 1: Digital economy evaluation index system

Level 1 indicators	Secondary indicators	surveying
digital economy	Internet penetration	Internet access users per 100 population
	Internet-related outputs	Total telecommunication services per capita
	Number of mobile Internet users	Cell phone subscribers per 100 population
	Digital Inclusive Finance	Digital Inclusive Finance Index

3.2.4. Control variables

In this paper, the following control variables are selected with reference to existing studies: In this paper, the following control variables were carefully selected with reference to existing studies:

First, the level of economic development (pgdp) uses gross domestic product per capita as a proxy indicator. Studies have shown that economically prosperous areas have experienced a significant increase in travel demand for tourism and shopping due to the significant increase in residents' consumption capacity, which objectively drives frequent transportation activities, thus raising the base of carbon emissions from the industry. Second, the population density (dpop) data comes from statistical yearbooks. The data shows that densely populated areas have a positively correlated upward trend in transportation energy consumption due to exponential growth in commuting flows and logistics demand. Again, industrial structure (stru) is measured by the share of tertiary industry. It is worth noting that there is a significant difference between service economy and industrial economy in terms of transportation intensity and energy type, so the transformation and upgrading of industrial structure will systematically change the generation path of transportation carbon emissions.

In the process of data collection, 30 provinces in China (excluding Tibet, Hong Kong, Macao and Taiwan) between 2009 and 2020 were selected for this paper. The key data of variables are mainly obtained from the Statistical Yearbook and China Energy Statistical Yearbook of each province. The core indicator, carbon emissions, is calculated accurately based on the provincial emission inventory data provided by CEADs China Carbon Accounting Database, which follows the IPCC subsectoral accounting methodology.

4. Analysis of empirical results

4.1. Benchmark regression

In the rigorous process of model selection, this paper adopts a fixed effect model and a random effect model and goes through the rigorous procedures of F-test, Breusch-Pagan LM test and Hausman test in order to determine the most appropriate model architecture. The test results show that the fixed effect model is the preferred model for regression analysis in this paper with its superior performance. The data in column (1) of Table 2, which can be found that the regression coefficients of the digital economy do not pass the significance test after controlling for province and time fixed effects, which indicates that a significant linear relationship has not yet been established between the digital economy and transportation carbon emissions. However, when the quadratic term of digital economy is introduced in Columns (2) to (4) of Table 2, the coefficients of the primary term of digital economy on carbon emissions from the transportation sector are significantly positive at the 5% significance level under the dual influence of province and time fixed effects, while the coefficients of its quadratic term are significantly negative at the same significance level. This result vividly reveals that the digital economy has a facilitating and then inhibiting effect on the carbon emissions of the transportation industry, i.e. there is an "inverted U-shaped" curve relationship between the two. Based on this, hypothesis 1 is verified.

4.2. Robustness analysis

4.2.1. Substitution of explanatory variables

In this paper, the comprehensive indicators of the level of development of the digital economy were re-measured using factor analysis, and the results are shown in column (1) of Table 3. After changing the calculation method, the coefficient of the primary term of the digital economy is significantly positive at the 10% significance level, and the coefficient of the secondary term is significantly negative at the 1% significance level. This result is highly consistent with the results of the benchmark regression, further validating the robustness of the model.

4.2.2. Substitution of explanatory variables

To test the robustness of the results, this paper replaces the original explanatory variables with carbon emissions per capita in the regression analysis. Column (2) of Table 3 shows that the coefficient of the primary term of the digital economy is significantly positive and the coefficient of the secondary term is significantly negative at the 5% significance level. This result reconfirms the robustness of the benchmark regression results.

4.2.3. Addressing endogeneity

The endogeneity problem is mainly caused by two-way causality, omitted variables, and measurement errors. To solve this problem, this paper uses two-stage least squares (2SLS) for regression analysis. In the first stage, the significant correlation between instrumental variables and endogenous variables is fully verified; in the second stage, the "inverted U-shape" relationship between the digital economy and carbon emissions of the transportation industry is further confirmed, and the strength of its influence is more significant than that of the baseline regression results. This finding not only strengthens the robustness of the benchmark regression results, but also provides stronger empirical support for the verification of hypothesis 1.

Table 2: Benchmark regression results

variant	(1)	(2)	(3)	(4)
D	0.071 0.031 (0.042) 0.253 **	0.026	0.249 **	0.271**

	(0.102)	0.275**			
	(0.124)				
	(0.118)		(0.042)	(0.102)	(0.124)
D^2			-0.042	-0.090 ***	-0.089**
			(0.021)	(0.029)	(0.035)
pgdp	0.323**	0.460***	0.231***	0.460***	0.484***
	(--)	0.484*** (--)	0.484*** (--)	0.484*** (--)	
	(0.149)		(0.083)	(0.119)	(0.135)
dpop			-0.760	0.290	0.069
			(0.916)	(0.834)	(0.124)
					(0.903)
stru			0.042	0.040	0.049
			(0.043)	(0.041)	(0.036)
					(0.041)
_cons			0.024	0.043*	0.382*
			(0.139)	(0.021)	(0.224)
					(0.169)
Province fixed			containment	containment	uncontrolled
					containment
fixed time			containment	uncontrolled	containment
					containment
control variable			containment	containment	containment
					containment
N			360	360	360
R^2			0.328	0.276	0.353

Note: Values in parentheses represent standard deviations; ***, **, and * imply statistical significance at the 1%, 5%, and 10% significance levels, respectively.

Table 3: Robustness test

variant	(1)	(2)
D	0.439*	0.598*
	(0.219)	(0.251)
D^2	-0.143**	-0.451**
	(0.053)	(0.189)
pgdp	0.527**	0.368**
	(0.146)	(0.134)
dpop	0.218	-2.013*
	(0.965)	(1.019)
stru	0.059	0.136*
	(0.043)	(0.068)
_cons	0.746**	0.093
	(0.310)	(0.185)
R^2	0.386	0.319

4.3. Mechanism of action tests

The results in column (1) of table 4 show that the coefficient of the primary term of the digital economy is significantly negative at the 10 per cent level of significance, while the coefficient of the secondary term is significantly positive at the 1 per cent level of significance, which indicates that there is a significant "U-shape" relationship between the digital economy and the transportation structure. This phenomenon can be attributed to the early stage of the

development of the digital economy, road transportation still dominates in the field of transportation, resulting in an imbalance in the transportation structure. With the further development of the digital economy, the transportation network has been gradually improved, and the coverage of the railroad, water transport and aviation networks has increased significantly, thus promoting the optimization of the transportation structure.

Column (2) of table 4 shows the results of the regression with the inclusion of the transport structure variable. The relationship between the digital economy and carbon emissions from transportation remains "inverted U-shaped", and the coefficient changes. The coefficient of transportation structure is significantly negative at the 1% significance level, indicating that optimizing transportation structure helps reduce carbon emissions. Currently, road trucks account for more than half of the transportation and mainly rely on fossil energy as fuel, which is an important reason for the high carbon emissions from transportation. This result further highlights the urgency of transforming the transportation structure to achieve the carbon reduction target. Based on this, hypothesis 2 is validated.

Table 4: Mechanism test regression results

variant	(1)	(2)
	tran	C
D	-0.247*	0.223**
	(0.141)	(0.103)
D^2	0.104 ***	-0.063***
	(0.034)	(0.019)
tran		-0.185***
		(0.0441)
_cons	0.478	-0.439
	(0.819)	(0.601)
R^2	0.245	0.389

4.4. Heterogeneity analysis

Benchmark regression analysis reveals that the rapid development of the digital economy can effectively promote the reduction of carbon emissions in the transportation industry. In order to study whether this carbon reduction effect is different in different regions, this paper divides the 30 provinces (autonomous regions and municipalities) into three regions based on geographic location, namely central, western and eastern regions, and systematically examines the interaction between the level of development of the digital economy and carbon emissions from the transportation sector in each region. It is found that in the central and eastern regions, the inhibiting effect of digital economy on transportation carbon emissions is more significant, while it is relatively weak in the western region. This difference may stem from the higher level of digital economy development in the central and eastern regions and the deeper integration of digitalization with the transportation industry. In addition, these regions have significant advantages in financial resources, science and technology innovation, attracting a large number of high-tech and high-end talents, thus accelerating the process of industrial upgrading and energy structure optimization.

5. Conclusion

Based on the inter-provincial panel data from 2009 to 2020, this study systematically examines the impact mechanism of digital economy on carbon emissions in the transportation industry

using a two-way fixed-effects model. The empirical results show that there is a significant "inverted U-shaped" nonlinear relationship between the digital economy and transportation carbon emissions, which indicates that its development has a facilitating effect on carbon emission reduction at a specific stage. The regional heterogeneity analysis further reveals that the emission reduction effect of digital economy in the central and eastern regions is significantly better than that in the western region. The mediating mechanism test shows that the optimization of transportation structure and congestion relief are important paths for carbon emission reduction driven by the digital economy. These findings provide a theoretical basis for differentiated policy design, and also point out the direction for deepening the integration of digital technology and the transportation industry. Based on the findings, this paper puts forward the following policy recommendations.

Based on the above findings, the paper makes the following policy recommendations:

(1) Deepening the integration of the digital economy with the transportation industry and upgrading the digitalization level in the field of transportation are important tasks for current development. By building an intelligent traffic management system, improving the big data decision-making platform, and upgrading the intelligent supervision system, we will realize the digital control of the whole transportation process. We will focus on promoting the application of 5G, IoT and other technologies in logistics scheduling, travel services and other scenarios, accelerating the formation of a "digital+ transportation" ecosystem, and promoting the transformation of the industry into an intelligent and low-carbon one.

(2) Optimizing transportation modes is the key to reducing carbon emissions. Currently, road transportation is the main source of carbon emissions. In order to build a green transportation system, the Government should promote multimodal transportation, advocate rail and waterway transportation and reduce reliance on road transportation. It should simultaneously promote the substitution of new energy trucks, electric ships and other clean transport capacity, and establish a carbon footprint monitoring platform to achieve systematic optimization of transport modes.

(3) The Government should formulate appropriate development strategies based on the characteristics and advantages of different regions to achieve the overall carbon reduction target. The central and eastern regions should explore the construction of intelligent transportation demonstration zones based on the first-mover advantage of the digital economy; the western regions need to strengthen digital infrastructure investment and support transportation digital transformation through special funds. At the same time, a cross-regional technology collaboration mechanism should be established to promote the piloting of innovative modes such as autonomous driving and shared mobility, so as to narrow the regional development gap through the technology diffusion effect.

Acknowledgements

This work is supported by Anhui University of Finance & Economics 2024 Undergraduate Research innovation fund project fund, Project number: XSKY24226.

References

- [1] HUANG Qunhui, YU Yongze, ZHANG Songlin. Internet development and manufacturing productivity enhancement: internal mechanism and Chinese experience[J]. *China Industrial Economy*, 2019,(08):5-23.
- [2] LU Huapu, FENG Haixia. Analysis and reflection on achieving carbon neutrality in transportation[J]. *Journal of Sustainable Development Economics*, 2022,(Z1):63-67.

- [3] Chen Xiaodong, Yang Xiaoxia. The impact of digital economy development on industrial structure upgrading - A study based on gray correlation entropy and dissipative structure theory[J]. Reform, 2021,(03):26-39.
- [4] Liu M, Zhang X, Zhang M, et al. Influencing factors of carbon emissions in transportation industry based on CD function and LMDI decomposition model. China as an example[J]. Environmental Impact Assessment Review, 2021, 90(1):106623.
- [5] WANG Shan, YU Donghua. Study on the carbon reduction effect and role path of digital economy--an empirical investigation based on the carbon emission efficiency of China's manufacturing industry[J]. Science Research, 2024, 42(02):310-321.
- [6] Jiao Ping, Zhang Shuai. Impact of digitization on carbon emission intensity of transportation--an empirical investigation based on inter-provincial panel data[J]. East China Economic Management, 2023, 37(01):15-23.
- [7] Zhang Xueliang. Does China's transportation infrastructure promote regional economic growth--Another discussion on the spatial spillover effect of transportation infrastructure[J]. China Social Science, 2012,(03):60-77+206.
- [8] TIAN Peining, MAO Baohua, TONG Ruiying, et al. Analysis of carbon emission level and intensity in China's transportation industry and different modes of transportation[J]. Progress in Climate Change Research, 2023, 19(03):347-356.