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The Integration of Traditional Transportation Infrastructure and Informatization Development: How Does It Affect Carbon Emissions?

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Abstract: With the advent of the "Information Era", the development of an integrated infrastructure, which involves the integration of traditional transportation infrastructure and informatization development, has become a new impetus for economic growth. Meanwhile, its environmental performance remains uncovered. Using data from 30 Chinese provinces between 2013 and 2020, this study designed an index system and constructed the coupling coordination degree model to assess the development level of integrated infrastructure. The regression model was established to examine the nonlinear effect of the integrated infrastructure on carbon emissions. The influencing mechanism was also discussed through identifying the impacts of integrated infrastructure on the energy intensity, industrial structure, and technological innovation. The evaluation of the evolutionary trend showed that the level of integrated infrastructure continues to improve and displays a feature of "higher highs, lower lows", although the regional disparity was significant. The regression analysis showed that there was an inverted U–shaped relationship between integrated infrastructure and CO_2 emissions. It is also found that most provinces were below the turning point. In the mechanism analysis section, we can demonstrate that integrated infrastructure can enhance energy intensity, which might hamper reductions in emissions. However, an integrated infrastructure facilitates the development of tertiary industry, which can lead to lower carbon emissions. Based on the conclusions, some insightful policy implications are provided.

Keywords: integrated infrastructure; traditional transportation infrastructure; informatization development; carbon emissions

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1. Introduction

The last 70 years have witnessed the blistering pace of expansion of China's economy, which has been touted as the "China speed". In addition to the transformation of the economic system and opening up to the outside world, infrastructure investment has played an essential role, especially transportation infrastructure investment, which has become a pillar for economic and social development. However, in recent years, as the marginal return on traditional transportation investment has plummeted, and economic growth with a high transportation investment has aggravated environmental pollution, a solution to retaining economic growth while controlling for environmental pollution is urgently needed. Given this, China has scaled up support for several "New Infrastructure" projects to generate more economic activities and promote high–quality economic development.

According to the National Development and Reform Commission (NDRC) [1], New Infrastructure refers to digital, smart, and innovative facilities that are guided by new development concepts, driven by technological innovation, based on information networks, and oriented toward high–quality development needs. It includes three categories: information infrastructure, integrated infrastructure, and innovation infrastructure. Information infrastructure mainly refers to the infrastructure based on the new generation of information technology, while innovation infrastructure mainly refers to the infrastructure that supports scientific research, technology development, and product development. Unlike the above, integrated infrastructure is formed by the in–depth application of the Internet, big data, artificial intelligence, and other information technology to transform and upgrade traditional infrastructure. A typical example is the intelligent transportation infrastructure. In other words, integrated infrastructure is a combination of the "new" and "traditional" infrastructure. Compared with traditional transportation infrastructure, integrated infrastructure represents the digitalization, networking, and intelligent transformation of transportation, logistics, and other infrastructure [2], which encourages new industrial forms and is conducive to cost reductions and efficiency optimization.

Since 2018, the central government has attached great importance to strengthening integrated infrastructure construction. Based on the report by the Bank of China Research Institute [3], the total investment scale of the New Infrastructure was about CNY 1.2 trillion in 2020, among which investment in integrated infrastructure such as intercity high–speed railroads, urban rail transit, and new energy vehicle charging piles, accounted for nearly half of the total investment. While traditional transport infrastructure such as railways, roads, and airports connect goods and people [4], integrated infrastructure connects data and information, enabling the introduction of new types of products and services as well as new manufacturing systems and business models [2]. Over the past few years, integrated infrastructure has played a critical role in stabilizing economic growth [3]. Meanwhile, whether integrated infrastructure can mitigate environmental pollution remains unveiled.

Currently, green, low–carbon development has become a global trend. Nevertheless, China's existing energy consumption structure is still dominated by high–carbon energy. In 2020, China had the largest increase (2.1%) in energy consumption and accounted for 30.7% of the world's carbon dioxide emissions [5]. Thus, the pressure to reduce carbon emissions in the future is still enormous. To mitigate the adverse impact of carbon emissions, at the United Nations General Assembly, China committed to peaking carbon dioxide emissions by 2030 and achieving carbon neutrality by 2060. In sum, carbon reductions have been conceptualized as an important task in China's future development. Given this, in the context of deepening the construction of integrated infrastructure around the country, it is of great practical significance to explore the relationship between integrated infrastructure and carbon emissions.

To date, the relevant studies have mainly focused on the impact of traditional transportation infrastructure on carbon emissions [4,6–8], or the impact of information technology on carbon emissions [9–12]. Meanwhile, few studies have examined the relationship between integrated infrastructure and carbon emissions directly. As pointed out by some studies, the application of information technology to the traditional industry can optimize the facility operations through data analysis and mining [13], improve the efficiency of facility operation and service [14], and thereby contribute to energy–saving. In addition, integrated infrastructure reflects a new form of business mode that can digitally empower other areas of the economy [15], thus leading to green and sustainable development. At the same time, with the advancement in integrated infrastructure, the problem of high energy consumption is gradually being exposed [16,17]. In particular, since the construction of integrated infrastructure still relies on energy–intensive industries such as power, metal smelting, petroleum coking, chemicals, and coal mining, and its upstream is closely related to energy–intensive industries [18], the emission reduction potential of integrated infrastructure is still influenced by the "high carbon lock–in" effect of its upstream industries.

The marginal contributions of this study contain three aspects. First, the existing literature has mainly focused on traditional transportation infrastructure, while insufficient attention has been paid to integrated infrastructure. Research on the measurement and evolutionary trends of integrated infrastructure construction is scarce, and the carbon reduction effects of integrated infrastructure have received little attention among economists. This study designed an index system to assess the integrated infrastructure. By measuring the degree of coupling coordination between the traditional transportation infrastructure subsystem and the informatization development subsystem, the level of development of integrated infrastructure during the sample period can be obtained. The spatial–temporal trend of integrated infrastructure is also analyzed to enhance our understanding of the evolutionary characteristics of integrated infrastructure. Second, the previous research has mainly focused on the impact of traditional transportation infrastructure on carbon emissions, while little attention has been paid to the impact of integrated infrastructure on carbon emissions. Using the panel data of 30 provinces in China from 2013 to 2020, we examined the relationship between integrated infrastructure and carbon emissions and identified the nonlinear effect of integrated infrastructure. The empirical results have a certain enlightening significance regarding how to use integrated infrastructure to reduce pollution emissions. Third, the existing studies offer little evidence of the mechanism between integrated infrastructure and carbon emissions. This study clarifies the difference between the traditional transportation infrastructure and integrated infrastructure and discusses the theoretical mechanism through which integrated infrastructure affects carbon emissions, which facilitates a comprehensive and rigorous understanding of the role that integrated infrastructure plays in emission reductions and helps to achieve better policy outcomes.

The remainder of this paper is organized as follows. Section 2 presents the literature review and theoretical mechanism. Section 3 specifies the methodology and model specification, variables selection, and data source. Section 4 analyzes the evolutionary characteristics of integrated infrastructure. Section 5 provides the regression results regarding the impact of integrated infrastructure on carbon emissions. A discussion of the empirical results is given in Section 6. Section 7 summarizes our conclusions and proposes relevant policy implications.

2. Literature Review

As the problem of environmental pollution becomes increasingly serious, scholars have been paying close attention to research on carbon emissions [19–21]. However, since the concepts of New Infrastructure and integrated infrastructure were proposed in 2020, few studies have considered the impact of integrated infrastructure on carbon emissions. Given this, based on the definition of integrated infrastructure, this study tries to review the research on the impact of traditional transportation infrastructure on carbon emissions, and the impact of informatization development on carbon emissions.

2.1. Traditional Transportation Infrastructure and Carbon Emissions

Many of the existing studies have focused on the impact of traditional transportation infrastructure on carbon emissions and their influencing mechanism, which mainly includes technological innovation, economic growth, energy intensity, industrial agglomeration, etc. However, there is no single consensus on the direction of this relationship. Some research claims that transportation infrastructure leads to higher carbon emissions. For example, using panel data for 283 cities between 2003 and 2013, Xie et al. [22] found that transportation infrastructure increases carbon emissions through economic growth and technological innovation. Similarly, Chen et al. [23] provided evidence that transport infrastructure could induce carbon emissions via congestion. Saidi and Hammami [6] reported a similar finding, looking at freight transport infrastructure. Based on a cross–country perspective, the work by Churchill et al. [24] for OECD nations suggests that a 1% increase in transport infrastructure is associated with an increase in CO_2 emissions of about 0.4%. Similar findings were also obtained by Neves et al. [25] and Nasreen et al. [7].

Meanwhile, other studies have found that transportation infrastructure is associated with lower carbon emissions. For instance, Han et al. [26] examined the relationship between infrastructure stock and CO_2 emissions and found that a 1% increase in the material stocks of infrastructure would lead to a 0.11% decrease in CO_2 emissions at the country level. The study by Lin and Chen [4] demonstrated that the construction of land transport infrastructure significantly enhanced the carbon dioxide emissions performance of China's manufacturing industry through various influencing mechanisms such as by forming a scale effect and achieving electric energy substitution. Moreover, Zhang [27] pointed out that highway infrastructure can trigger an agglomeration effect in cities and regions, and thereby support emission reductions. Based on the 2011–2020 provincial data in China, Liu et al. [28] indicated that technological progress, accompanied by transportation developments, could reduce carbon emissions. In addition, some of the research also documents that the improvement in transportation infrastructure can reduce carbon emissions by enhancing energy efficiency [8,29,30]. Tan et al. [30] demonstrated that an increase in road density can reduce energy intensity in the long–term, especially in Western China.

Additionally, a few studies have also found evidence of a nonlinear relationship. Xu et al. [31] found an inverted U–shaped relationship between highway infrastructure and CO_2 emissions. This finding is consistent with the study of Chen et al. [32], which focused on land freight structure.

2.2. Informatization Development and Carbon Emissions

In terms of the relationship between informatization development and carbon emissions, most studies have confirmed the emissions–mitigating effect of informatization development. Based on urban data from 2015 to 2018, Qiao et al. [33] discovered that information infrastructure can significantly reduce air pollution. Similarly, using China's A–share listed companies from 2015 to 2019 as the sample, Qiao et al. [2] found that the application of "New Infrastructure" technology is helpful to incorporate pollution control and green transformation. In addition, some research has tested the impact of network infrastructure on pollution emissions based on a quasi–natural experiment regarding the broadband policy [10,11,34] and demonstrate that green innovation, industrial structure upgrading, and resource allocation efficiency are effective channels for information infrastructure to improve the performance in greenhouse gas emissions. For example, using the panel data for 281 prefecture–level cities in China from 2003 to 2018, Dong et al. [11] treated the Broadband China policy as a quasi–natural experiment, and found that information infrastructure significantly improves urban GHG emission performance.

However, a group of studies has also claimed that informatization development can exacerbate pollution emissions. Jiang and Liu [35] discovered that information technology facilitates the development of emerging economies, which might lead to larger carbon emissions. A similar conclusion was obtained by Cheng et al. [17], who showed that information technology significantly aggravated environmental pollution, and that the rebound effect of information technology on environmental pollution played a leading role.

There is also a third view: that the relationship between informatization development and carbon emissions is complex. The study by Higón et al. [9] suggests that the relationship between information and communication technologies (ICTs) and CO_2 emissions is an inverted U–shaped relationship. Similarly, Li [13] documented that, although digital transformation fosters economic performance at an accelerating rate, it depicts an inverse U–shaped relationship with environmental performance. By employing the Panel Quantile Granger Causality (PQGC) methods, Bildirici et al. [12] found evidence of bidirectional causality between ICT investment and carbon emissions.

Some of the literature has also examined the impact of Industry 4.0 technologies (I40Ts) on carbon emissions [36–38]. For example, Lopes de Sousa Jabbour et al. [38] discovered that I40Ts not only increase the production efficiency, but are also beneficial to minimizing waste and emissions. Meanwhile, Beier et al. [39] were concerned about the energy consumption of I40Ts.

Above all, the existing research has mainly focused on either traditional transportation infrastructure or informatization development, while few studies have combined the perspectives of traditional transportation infrastructure and informatization development. In the context of a new wave of the information revolution, this study draws attention to integrated infrastructure, the integration of traditional transportation infrastructure and informatization development, and designed an index system and constructed the coupling coordination model to explore its evolutionary characteristics. In addition, despite the substantial progress in identifying the relationship between traditional transportation infrastructure and carbon emissions, limited evidence is provided to examine the impact of integrated infrastructure on carbon emissions. Although the study of Qiao et al. [2] analyzed the effect of "new infrastructure" on the sustainable development of enterprises, it focused on the impact of the new infrastructure at the firm level, and little evidence was given at the regional level. Using China's provincial–level panel data from 2013 to 2020, this study disentangles the nonlinear relationship between integrated infrastructure and carbon emissions. Third, the existing literature mainly studies how traditional transportation infrastructure affects carbon emissions, and lacks an in–depth analysis of the mechanism between integrated infrastructure and carbon emissions. This study proposes a scientific framework for analyzing the mechanism through which integrated infrastructure affects carbon emissions.

3. Materials and Methods

3.1. Theoretical Mechanism

According to agglomeration economics, the development of transportation infrastructure can enhance urban accessibility [40,41] and stimulate innovation through a well–developed innovation network, which promotes the flow of technology and knowledge within the regional innovation system and facilitates innovation diffusion and spillover [28]. In addition, improvements in transportation infrastructure can optimize the allocation of resources by reducing the transaction costs [42], improving the management efficiency [43], and accelerating industrial integration [30], thereby increasing the efficiency of resource utilization.

According to the ecological modernization theory, the inherent conflict between industrial and ecological civilizations can be resolved under the same development route [44]. This argument suggests that the construction of integrated infrastructure can achieve both industrial and ecological outcomes, which provides a theoretical basis for examining the role of the integrated infrastructure in mitigating pollution emissions. How does an integrated infrastructure affect carbon emissions? Unlike traditional transportation infrastructure such as railroads and highways, integrated infrastructure performs a digital and intelligent transformation of traditional transportation facilities, which can have a substantial impact on energy use, industrial structure, and technological innovation, and therefore, carbon emissions. Therefore, in this study, the mechanism through which integrated infrastructure affects carbon emissions is identified from the perspectives of energy intensity, industrial structure, and technological innovation.

(1) Energy intensity

With the application of 5G networks, data centers, and other information technology to traditional transportation infrastructure, a large amount of information and data will be generated [14]. These can be regarded as important production factors to replace energy. Compared with energy, data are cleaner and more environmentally friendly. Therefore, replacing the energy factor with the data factor can reduce energy consumption in the production, flow, and consumption process [45], thus leading to lower pollution. Additionally, the introduction of data to the traditional production process can digitally integrate traditional input factors such as labor and capital [46], thus improving the factor allocation efficiency and alleviating pollution emissions.

Meanwhile, it is notable that the development of integrated infrastructure requires the construction and operation of several 5G base stations and data centers, which will inevitably increase the demand for electricity supply. Since thermal power stations take up about 4/5 of China's electricity supply [17], the development of integrated infrastructure will induce a large amount of fossil energy consumption [18], thereby accelerating pollution emissions. In addition, the investments in integrated infrastructure can also result in higher energy consumption while expanding the market size and stimulating economic growth [16]. Since it is difficult for companies to upgrade the production technology and equipment in the short–term, the energy saved from the substitution of energy factors is easily offset by the energy demand caused by the increase in the scale of output, thus triggering the "energy rebound" effect and generating higher emissions [47,48].

(2) Industrial structure

The integrated infrastructure itself represents a new type of industry that utilizes data in traditional transportation infrastructure, which is based on information technology and the data's network character. This will not only enhance the marginal benefits of the traditional transportation infrastructure but also help broaden the production and operation scope of traditional transportation industries [49] such as green transportation and shared transportation, which strongly promote the greener and cleaner transformation and development of the transportation industry.

In addition, from the supply side, the development of integrated infrastructure relies on a series of information technologies such as 5G, artificial intelligence, and big data, which depend on large amounts of capital investment and platform services [50]. This suggests that improvements in the integrated infrastructure will increase the dependence on productive services such as finance and business services [51], thus strongly boosting the demand for modern services such as R&D and innovation, modern logistics, information networks, and financial and business services [52]. As the industrial structure adjusts to the service industry, pollution emissions will tend to decrease [53].

(3) Technological innovation

According to the theory of externalities, the integrated infrastructure has strong externalities and network effects, which can reduce information transmission barriers, speed up the dissemination of digital knowledge and technology, and optimize interpersonal collaborations [54]. This will help to foster a series of green technologies with the externality of technology [55], thereby reducing pollution emissions. In addition, according to the theory of network effect, the openness and connectedness characteristics of integrated infrastructure can further expand the scope of the regional economic hinterland, allowing for it to absorb human resources within a broader geographical space, which effectively boosts the accumulation of human capital [56] and facilitates pollution mitigation.

However, some studies have claimed that the information transformation of traditional transportation industries might generate more uncertainty [57], which will inhibit the employees' innovation capabilities [58] by inducing technology stress, addiction, and misuse [59]. Specifically, the application of integrated infrastructure will greatly increase the difficulty and complexity of governance, thus preventing some companies from effectively using it for R&D activities. Moreover, the use of information technology may also have negative consequences for individuals and their skills, which could inhibit future creative and innovative endeavors [60]. Furthermore, excess investment in integrated infrastructure can be futile and even redundant, leading to sunk costs without any potential contribution to green innovation [61]. This will reduce the resource utilization efficiency and generate more wasteful outputs.

The impact mechanism is displayed in Figure 1.

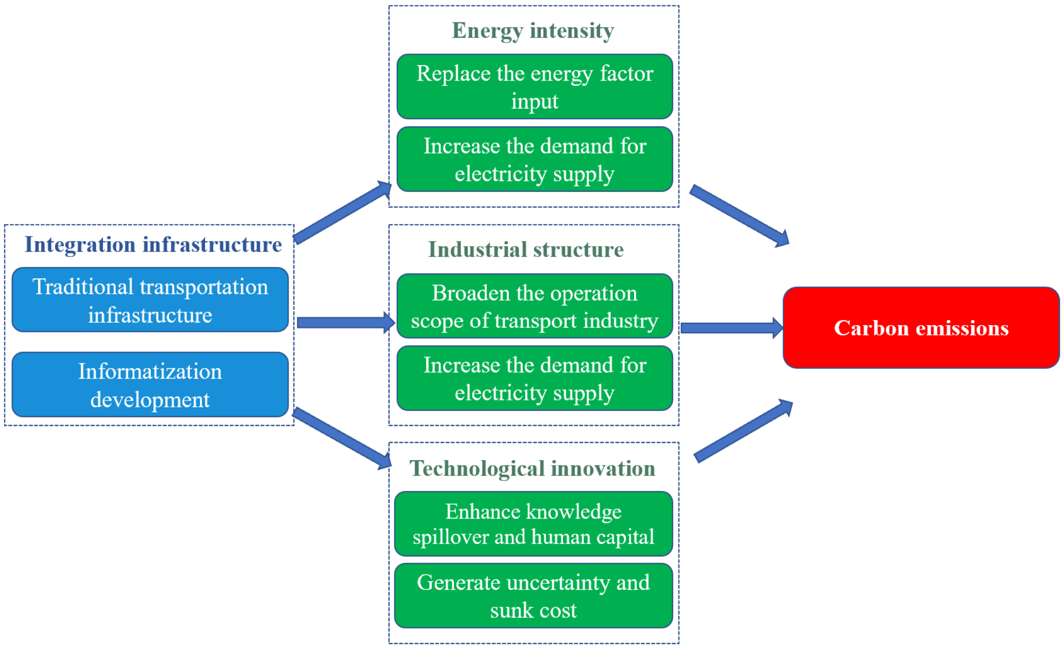


Figure 1. The impact mechanism.

3.2. Specific Methodologies

(1) The coupling coordination degree model

The coupling coordination degree model was applied to evaluate the development level of integrated infrastructure. The coupling degree derives from physics and has been widely adopted by economic research to express the degree of interdependence and interaction between two or more subsystems [62,63]. According to the identification of integrated infrastructure, two subsystems, the traditional transportation infrastructure subsystem (U_1) and the informatization development subsystem (U_2), were constructed. Then, the entropy method was applied to calculate the composite index of the two subsystems. Finally, the coupling coordination degree of the two subsystems was measured, which is used to characterize the development level of the integrated infrastructure. The index system is given in Table 1.

Table 1. The index system for assessing the integrated infrastructure.

System	Subsystems	Indicator	Unit	Weight
Integrated infrastructure	Traditional transportation infrastructure (U_1)	Length of railways in operation (x_1)	10,000 km	0.1224
		Length of highways (x_2)	10,000 km	0.1138
		Length of bus and trolley bus under operation (x_3)	km	0.2194
		Railway freight traffic (x_4)	10,000 tons	0.3936
		Highway freight traffic (x_5)	10,000 tons	0.1507
	Informatization development (U_2)	Capacity of mobile telephone exchanges (x_6)	10,000 subscribers	0.0687
		Base stations of mobile telephones (x_7)	10,000 unit	0.0754
		Length of optical cable lines (x_8)	km	0.0815
		Number of domain names (x_9)	10,000 unit	0.1812
		Number of webpages (x_{10})	10,000 pages	0.3172
		IPv4 addresses (x_{11})	10,000 unit	0.1949
		Broadband subscribers Port of Internet (x_{12})	10,000 unit	0.0811

In terms of the entropy method, first, the data were standardized to mitigate the impact of dimension and magnitude. Since all of the indices were positive, the standardized indices can be calculated as follows:

$$x_{ij}^* = \frac{x_{ij} - \min x_{ij}}{\max x_{ij} - \min x_{ij}}, i = 1, 2, \cdots, n; j = 1, 2, \cdots m \tag{1}$$

where x_{ij} represents the primitive values of index j for evaluated object i; x_{ij}^* stands for the standardized index; $\max x_{ij}$ and $\min x_{ij}$ refer to the maximum and minimum value of x_{ij}.

Then, we calculated the proportion of index j for evaluated object i:

$$f_{ij} = x_{ij}^* / \sum_{i=1}^{n} x_{ij}^* \tag{2}$$

where f_{ij} is the proportion of x_{ij}.

The information entropy of each index, e_j, is then calculated as:

$$e_j = -\frac{1}{\ln n} \sum_{i=1}^{n} f_{ij} \ln(f_{ij}), \quad 0 \le e_j \le 1 \tag{3}$$

where $\frac{1}{\ln n}$ represents the information entropy coefficient.

Based on the entropy, the weight of each index can be calculated as below:

$$w_j = 1 - e_j / \sum_{j=1}^{m} (1 - e_j) \tag{4}$$

Using the linear weighting method, the composite index of the subsystem can be obtained as follows:

$$U_k = \sum_{j=1}^{m} w_j x_{ij}^*, k = 1, 2 \tag{5}$$

U_1 and U_2 are the composite indices of the traditional transportation infrastructure and informatization development. The greater the value, the better the development of the subsystem.

The coupling degree is established as below:

$$C = \frac{\sqrt{U_1 \cdot U_2}}{1/2(U_1 + U_2)}, \quad C \in [0, 1] \tag{6}$$

where C is the coupling degree of traditional transportation infrastructure and informatization development, which characterizes the coupling status of the two subsystems. However, it cannot accurately depict the level of coordinated development between the two subsystems, since there might be cases of a high coupling degree with low subsystem levels [64,65]. To mitigate this problem, the coupling coordination degree was introduced.

The calculation formula of the coupling coordination degree is expressed as follows:

$$\begin{gathered} D = \sqrt{C \times T}, \\ T = \alpha U_1 + \beta U_2, \\ D \in [0, 1] \end{gathered} \tag{7}$$

where D is the coupling coordination degree of the system, which reflects the coordination development level between the traditional transportation infrastructure and informatization development. In our study, D was used to measure the development level of integrated infrastructure. The higher the value, the better the development of the integrated infrastructure. T is the comprehensive coordination index; α and β represent the contribution of traditional transportation infrastructure and informatization development, respectively. As informatization development is as important as traditional transportation infrastructure, we set $\alpha = \beta = 0.5$.

Existing studies mainly divide the coupling coordination degree into several categories [62,66]. Referring to the study of Zhao et al. [62], we divided the coupling coordination degree into five levels, which are presented in Table 2. $0 < D \leq 0.4$ suggests that the coordination between the subsystems is weak; $0.4 < D \leq 0.6$ is a state of transitional development; $0.6 < D \leq 1$ indicates a state where coordinated development is achieved.

Table 2. The classification of the coupling coordination degree.

Composite State	Coupling Coordination Degree	Classification
Synergy state	$0.8 < D \leq 1$	Advanced coordination
	$0.6 < D \leq 0.8$	High coordination
Transition state	$0.4 < D \leq 0.6$	Intermediate coordination
Imbalance state	$0.2 < D \leq 0.4$	Primary coordination
	$0 < D \leq 0.2$	Low coordination

(2) The regression models

Based on the purpose of our study, the panel regression model was constructed to test the impact of integrated infrastructure on carbon emissions. According to the existing studies, there are conflicting views regarding the direction of the relationship between traditional transportation infrastructure and carbon emissions, and the nonlinear relationship is often found for the relationship between informatization development and carbon emissions. Additionally, based on the mechanism analysis, the influencing channels through which the integrated infrastructure affects carbon emissions are complicated. Thus, the quadratic term for integrated infrastructure was introduced to the model to examine the possible nonlinear relationship between the integrated infrastructure and carbon emissions. The baseline model can be established as:

$$CO_{it} = \alpha_0 + \alpha_1 INF_{it} + \alpha_2 (INF_{it})^2 + \alpha_3 X_{it} + \varepsilon_{it} \quad (8)$$

where i and t represent the province and time; CO denotes carbon emissions; INF represents integrated infrastructure; X indicates the control variables; α denotes the parameter to be estimated; and ε is the error term, which is assumed to be independently and identically distributed.

To explore the impact mechanism of integrated infrastructure and carbon emissions, this paper also focused on the impact of integrated infrastructure on energy intensity, industrial structure, and technological innovation. The expressions are given below:

$$ENE_{it} = \beta_0 + \beta_1 INF_{it} + \beta_2 X_{it} + \varepsilon_{it} \quad (9)$$

$$STR_{it} = \lambda_0 + \lambda_1 INF_{it} + \lambda_2 X_{it} + \varepsilon_{it} \quad (10)$$

$$TEC_{it} = \gamma_0 + \gamma_1 INF_{it} + \gamma_2 X_{it} + \varepsilon_{it} \quad (11)$$

where ENE, STR, and TEC stand for the energy intensity, industrial structure, and technological innovation, respectively; β, λ, and γ are the coefficients to be estimated. The remaining variables share the same meaning as given above.

3.3. Variable Selection and Data

(1) Dependent variable: carbon emissions (CO). This variable is measured by the amount of carbon emissions in each province. In this study, we employed the emission factor method introduced by the 2006 International Panel on Climate Change (IPCC) Guidelines; that is, we used the amount of fuel burned and emission factors to estimate the carbon emissions [67]. This method is relatively simple and easy to operate, with relatively

low data requirements. Therefore, it is the most widely used emission factor method for estimating carbon emissions at present [68,69].

(2) Explanatory variable: integrated infrastructure (*INF*). According to the NDRC definition of integrated infrastructure, the coupling coordination degree of traditional transportation infrastructure and informatization development is employed to measure the integrated infrastructure.

(3) Control variables. According to the mechanism analysis, we incorporated three variables, energy intensity, industrial structure and technological innovation, into the model. Energy intensity (*ENE*) was measured by the electricity consumption per unit of gross domestic product (*GDP*). Industrial structure (*STR*) was calculated by the ratio of the value–added of the tertiary industry to that of the secondary industry. Technological innovation (*TEC*) was expressed by the number of invention patents that were granted. In addition, this study also introduced five other control variables that affect carbon emissions. Income level (*AGDP*) was measured using GDP per capita in constant 2004 prices. Agglomeration degree (*AGG*) was calculated by the amount of non–farm output per unit area. The degree of government intervention (*GOV*) was measured by the share of local general budget expenditure in GDP. Opening up (*FDI*) was expressed by the ratio of foreign direct investment to GDP. Human resource (*HUM*) was calculated by the number of students enrolled in high school and above, with each undergraduate, college, and high school student assigned a value of 3, 2, and 1, respectively.

The sample included data from 30 provinces in China (Tibet, Taiwan, Hong Kong, and Macao were excluded due to poor data accessibility) between 2013 and 2020. The data were mainly collected from the China Statistical Yearbook, China Energy Statistical Yearbook, China Statistical Yearbook of Environment, and provincial and municipal statistical yearbooks. Price–relevant data were converted to the constant 2013 price. Missing data were estimated using the linear interpolation method. Logarithm forms were taken for the explanatory variables to filter out the scale difference. Descriptive statistics of the variables are reported in Table 3.

Table 3. Descriptive statistics of the variables.

Variable	Mean	Std	Min	Max
CO	10.25	0.76	8.15	11.64
INF	0.38	0.13	0.10	0.72
ENE	2.19	0.52	1.28	3.68
AGDP	10.87	0.42	10.04	12.01
STR	0.25	0.36	−0.41	1.66
TEC	8.34	1.39	4.51	11.17
AGG	1.29	0.49	0.01	2.29
FDI	1.08	1.11	−3.06	5.83
GOV	−1.40	0.38	−2.12	−0.28
HUM	5.55	0.75	3.19	6.74

4. Evolutionary Characteristics of Integrated Infrastructure

In this study, the coupling coordination degree of informatization development and traditional transportation infrastructure was adopted to measure the integrated infrastructure.

4.1. The Evolutionary Trend of Integrated Infrastructure and the Two Subsystems

In order to reveal the development level of the integrated infrastructure in each province over the study period, we present the composite index of integrated infrastructure by province for 2013, 2016, and 2020. The results are given in Table 4.

Table 4. The development level of integrated infrastructure.

Province/Municipality	2013	2016	2020	Province/Municipality	2013	2016	2020
Beijing	0.2899	0.3495	0.4345	Henan	0.3910	0.4772	0.5550
Tianjin	0.2192	0.2238	0.2785	Hubei	0.3249	0.3935	0.4514
Hebei	0.4322	0.4794	0.5802	Hunan	0.3446	0.4170	0.4789
Shanxi	0.4038	0.4307	0.5226	Guangdong	0.5875	0.6550	0.7196
Inner Mongolia	0.3624	0.3959	0.4735	Guangxi	0.2920	0.3535	0.4564
Liaoning	0.3802	0.4090	0.4671	Hainan	0.1023	0.1248	0.1709
Jilin	0.2423	0.2679	0.3317	Chongqing	0.2443	0.2904	0.3489
Heilongjiang	0.3226	0.3392	0.3935	Sichuan	0.3955	0.4666	0.5493
Shanghai	0.2544	0.2874	0.3078	Guizhou	0.2401	0.3034	0.3776
Jiangsu	0.4340	0.4966	0.5879	Yunnan	0.2985	0.3486	0.4338
Zhejiang	0.4286	0.5275	0.6154	Shaanxi	0.3384	0.3984	0.4781
Anhui	0.3625	0.4205	0.4882	Gansu	0.2112	0.2694	0.3288
Fujian	0.3359	0.4259	0.4518	Qinghai	0.1295	0.1472	0.1878
Jiangxi	0.3161	0.3504	0.4391	Ningxia	0.1214	0.1479	0.1909
Shandong	0.5195	0.5452	0.6531	Xinjiang	0.2539	0.3134	0.3765

First, it can be seen from the table that the composite index of integrated infrastructure in each province continued to improve over the period of analysis. In 2013, the composite indices of integrated infrastructure in most areas were between 0.2 and 0.4, while in 2020, only four areas were still below 0.3. Referring to the classification of the coupling coordination degree in Table 2, the composite index in more than half of the areas spanned two different coordination intervals due to the accelerating trend.

Second, there was no significant change in the ranking of the integration infrastructure levels across different provinces. The top three provinces with the highest level of integrated infrastructure were Guangdong, Shandong, and Zhejiang, and the bottom three were Ningxia, Qinghai, and Hainan, indicating a lock–in effect of “higher highs, lower lows”.

Third, the distribution of the level of integrated infrastructure in each area exhibited an “olive” shaped structure. According to the statistics in Table 4, only a small number of provinces or municipalities belonged to the synergy and imbalance state, while most provinces or municipalities belonged to the transition state, showing an olive–shaped distribution structure with a large middle part and two small ends.

Since there are huge development gaps among the eastern, central, and western regions of China, to illustrate the evolution tendency and compare the regional disparities of integrated infrastructure in China and in the three different regions, we averaged the composite index of integrated infrastructure, traditional transportation infrastructure, and informatization development for the whole country and each region over the period of analysis. Figures 2–4 demonstrate the regional differences in the integrated infrastructure, traditional transportation infrastructure, and informatization development from 2013 to 2020, respectively.

In terms of integrated infrastructure, there were significant similarities in the evolutionary trends in China and the three regions over the periods of analysis; that is, the composite indices of integrated infrastructure continued to grow at similar rates. The difference was that there were significant regional differences in the level of integrated infrastructure. Eastern China showed the highest level of integrated infrastructure between 2013 and 2020, rising from 0.36 to 0.48, followed by Central China, with a stable increase from 0.34 to 0.46. Both developed faster than the national average. Western China had the lowest level of integrated infrastructure, which increased from 0.26 to 0.38. The ranking was in accordance with the economic development level in each region.

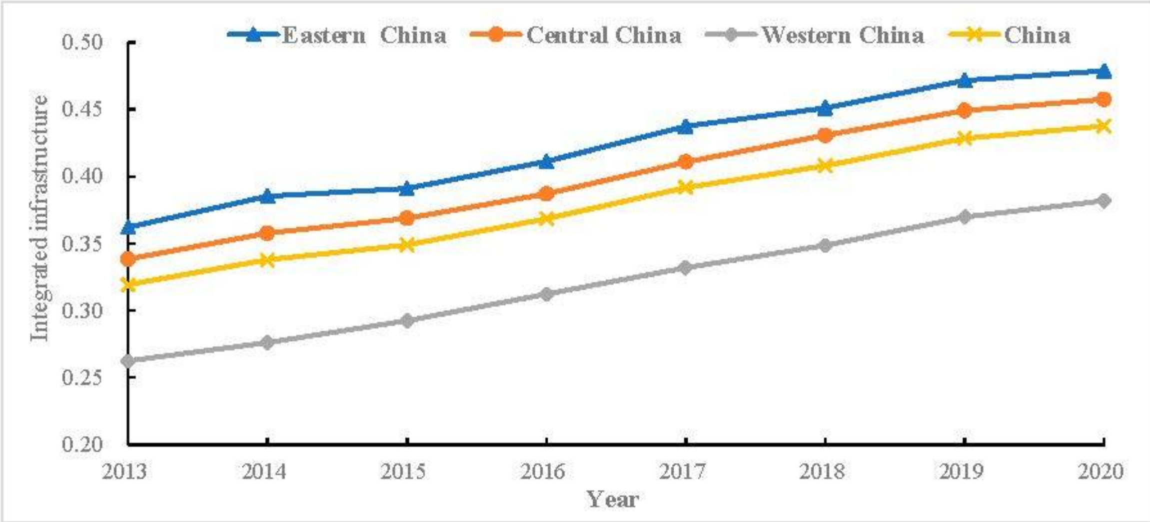


Figure 2. Integrated infrastructure in China and three different regions from 2013 to 2020.

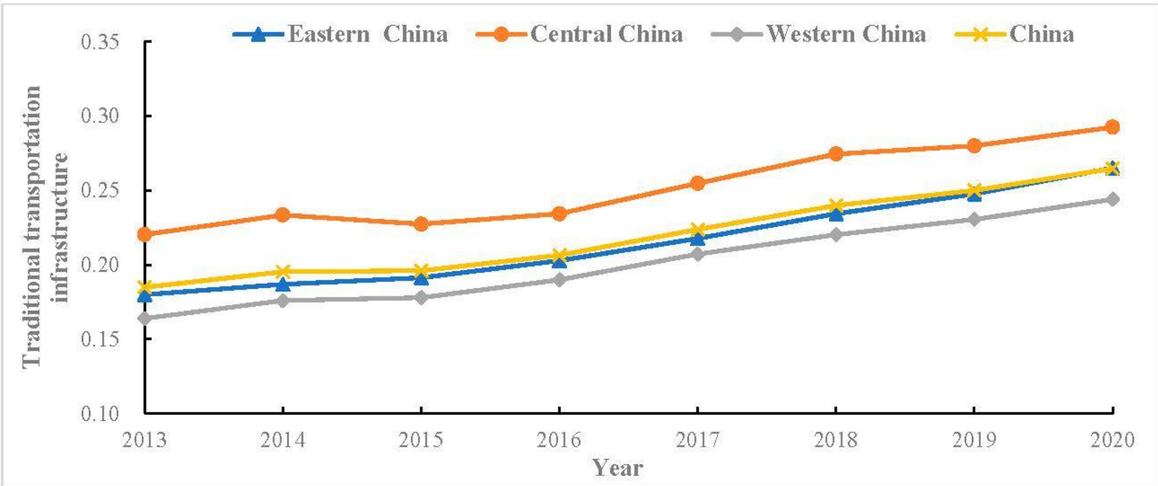


Figure 3. Traditional transportation development in China and three different regions from 2013 to 2020.

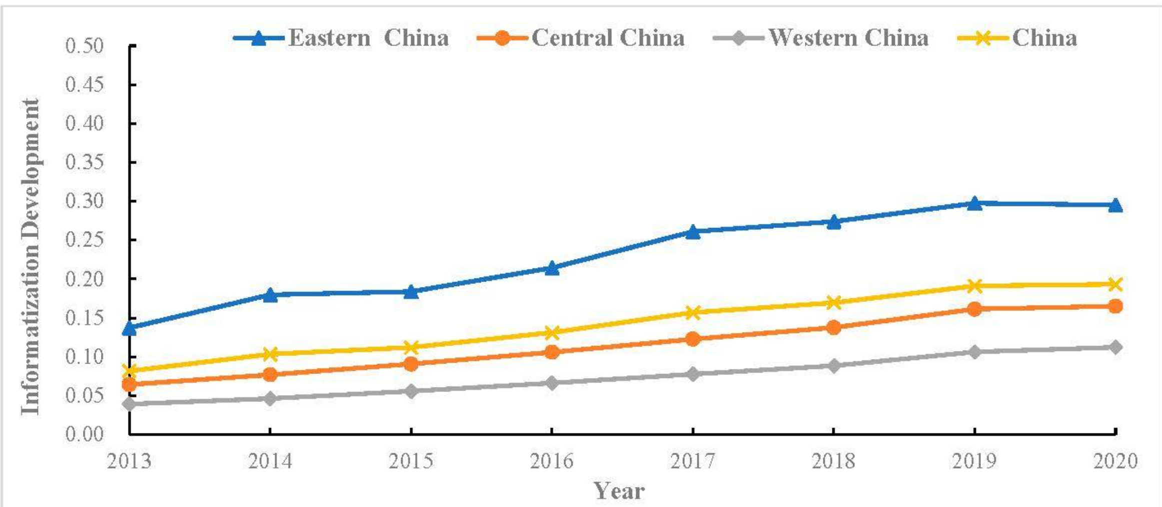


Figure 4. Informatization development in China and three different regions from 2013 to 2020.

The levels of traditional transportation infrastructure in China and the three regions experienced a fluctuating increase over the analysis period. The level of traditional transportation infrastructure in Central China was the highest, followed by Eastern and Western China. Regarding the traditional transportation infrastructure in Central China, a fluctuating feature was displayed between 2013 and 2015. After that, it resumed its growth trend and reached 0.29 in 2020. The traditional transportation infrastructure in Eastern China increased at a slow pace between 2013 and 2015, which accelerated after 2015 and reached 0.27 in 2020. Western China shared a similar trend to Eastern China, whose traditional transportation infrastructure increased from 0.16 to 0.24.

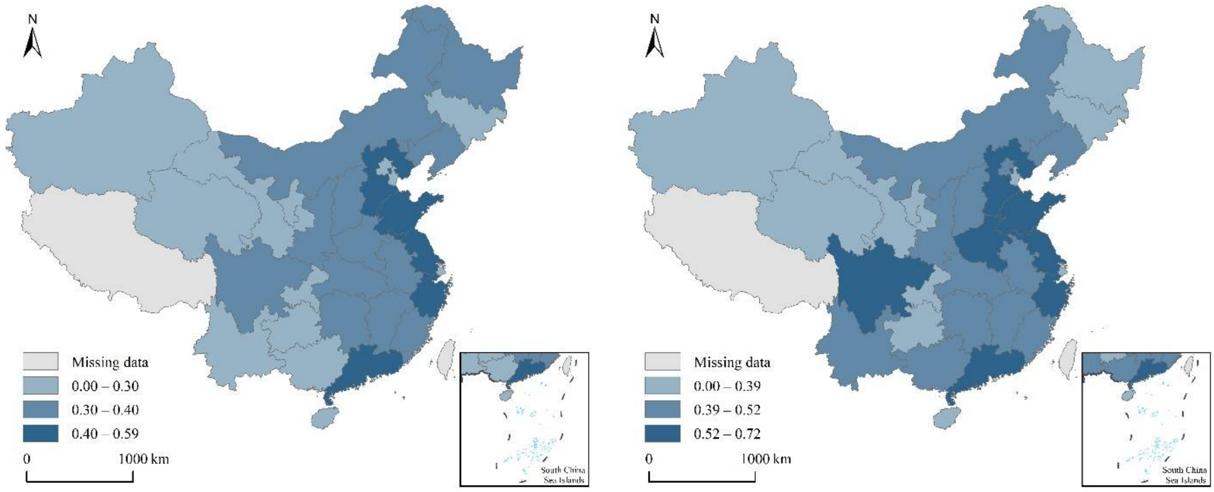
Regarding informatization development, the level of informatization development in China and the three regions all continued to rise during the period of analysis, while the regional heterogeneity in the growth rate was obvious. Eastern China displayed the highest level of informatization development and the fastest growth rate between 2013 and 2020, rising from 0.14 to 0.30. It is also noteworthy that only the informatization development in Eastern China was above the national average. The level and growing speed of informatization development in the central and western regions lagged behind those in the whole country and eastern region. The level of informatization development in Central China increased from 0.06 to 0.17 during the period of analysis, and that in Western China increased from 0.04 to 0.11, suggesting a significant gap with Eastern China. A possible explanation for this regional difference is that informatization development requires the right kind of professional talent, which calls for a higher level of regional technology and human capital. Compared with the other two regions, the economic foundation of the eastern region is solid, and the high degree of openness to the outside world has attracted a number of high–quality talent, providing the necessary conditions for informatization development.

Comparing Figures 2–4, Eastern China is the national leader in informatization development, and its level of traditional transportation infrastructure is higher than the national average, which explains why its composite index of integrated infrastructure was the highest among the three regions. Meanwhile, there was a large gap between the level of informatization development in the central and western regions and that in the eastern regions. The traditional transportation infrastructure in Central China is well–developed, so its integrated infrastructure index was second only to the eastern region. Both the level of informatization development and traditional transportation infrastructure were lower than the national average, so the integrated infrastructure index was the lowest. It is also notable that for Eastern China, the level of informatization development was higher than that of traditional transportation infrastructure, whereas the opposite case was observed for the whole country, Central, and Western China, with higher levels of traditional transportation infrastructure and lower levels of informatization development.

4.2. The Spatial Distribution of Integrated Infrastructure and the Two Subsystems

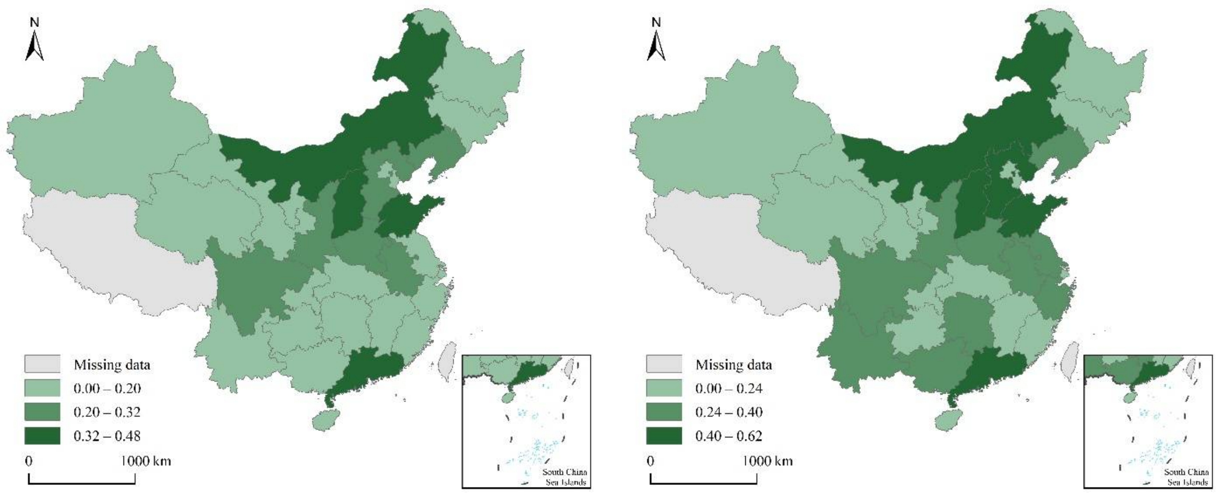
To unveil the spatial–temporal distribution characteristics of the integrated infrastructure, this study mapped the spatial distribution of integrated infrastructure, traditional transportation infrastructure, and informatization development in 2013 and 2020 with the help of ArcGIS software and the vector diagram of China's administrative divisions, which are presented in Figures 5–7.

According to Figure 5, the composite index of integrated infrastructure is characterized by significant spatial differentiation, being high in the east and low in the west. From 2013 to 2020, some western provinces such as Yunnan, Guangxi, and Sichuan significantly caught up, while Heilongjiang, which is located in northeast China, lagged behind.



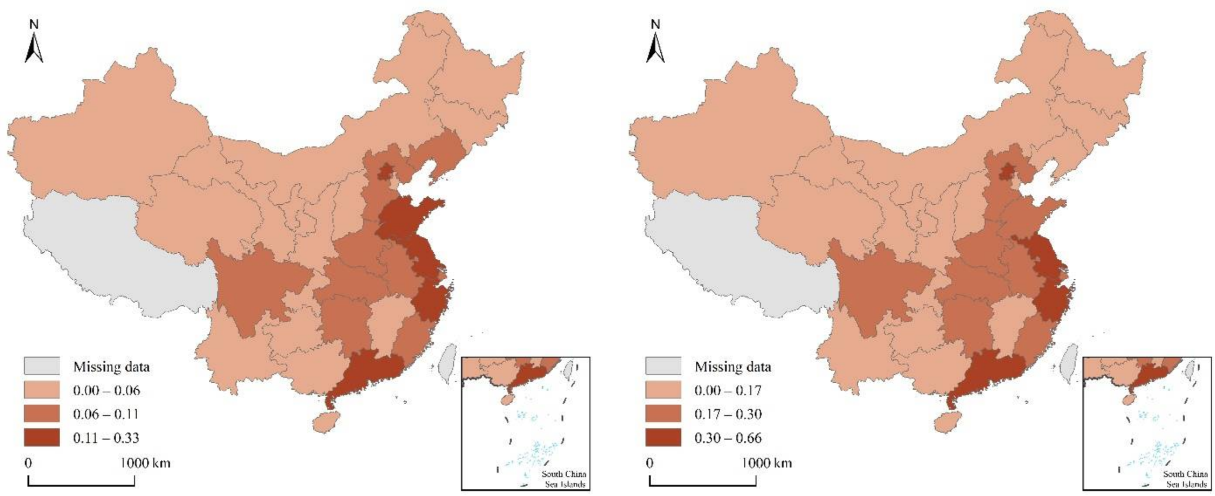
(**a**) (**b**)

Figure 5. The distribution of integrated infrastructure in 2013 and 2020. (**a**) 2013; (**b**) 2020.



(**a**) (**b**)

Figure 6. The distribution of traditional transportation development in 2013 and 2020. (**a**) 2013; (**b**) 2020.



(**a**) (**b**)

Figure 7. The distribution of informatization development in 2013 and 2020. (**a**) 2013; (**b**) 2020.

As revealed in Figure 6, the provinces with well–developed transportation infrastructure are mainly concentrated in the central and western regions, while the level of traditional transportation infrastructure in the eastern coastal regions lags behind. Yunnan and Guangxi, located in the southwestern region, experienced significant developments in transportation infrastructure during the period of analysis, which is the main reason for the growth in their integration infrastructure.

Figure 7 shows that the most developed areas for informatization development are Beijing, Guangdong, Zhejiang, Jiangsu, and other eastern coastal provinces. From 2013 to 2020, the relative rankings among provinces remained unchanged, except for a northeastern province, Liaoning, which lagged behind.

The eastern region has a better foundation for integrated infrastructure, but traditional transportation infrastructure has expanded relatively slowly due to its limited land resources. Some southwestern provinces such as Yunnan and Guangxi made substantial improvements in both traditional transportation infrastructure and informatization development over the period of analysis. Additionally, some inland provinces such as Ningxia and Qinghai lagged behind in the development of integrated infrastructure and the subsystems.

5. The Impact of Integrated Infrastructure on Carbon Emissions

5.1. The Results of the Baseline Model

The impact of integrated infrastructure on carbon emissions was examined based on Equation (8), and the results are presented in Table 5. The Hausman test rejects the original hypothesis at the 1% level, so the choice of the fixed effects model seems more desirable. A stepwise regression method was adopted, where only the key explanatory variable, INF, was included in model 1, and the control variables were gradually added in models 2–9.

Table 5. Results of the impact of integrated infrastructure on carbon emissions.

Variable	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8	Model 9
INF	1.716 ***	2.710 ***	1.477 **	1.681 **	1.676 **	2.133 **	2.142 **	2.173 ***	1.659 ***
	(3.84)	(6.23)	(2.25)	(2.48)	(2.47)	(2.55)	(2.56)	(2.59)	(2.72)
INF^2	−1.050 **	−1.794 ***	−1.196 **	−1.242 **	−1.264 **	−1.282 **	−1.303 **	−1.322 **	−1.517 ***
	(−2.03)	(−3.70)	(−2.23)	(−2.31)	(−2.35)	(−2.30)	(−2.34)	(−2.37)	(−3.13)
ENE		0.485 ***	0.523 ***	0.503 ***	0.530 ***	0.487 ***	0.479 ***	0.480 ***	0.567 ***
		(6.56)	(7.01)	(6.60)	(6.37)	(6.37)	(6.24)	(6.23)	(7.63)
AGDP			0.202 **	0.202 **	0.188 **	0.228 ***	0.214 ***	0.232 ***	0.026
			(2.48)	(2.49)	(2.25)	(4.83)	(4.25)	(4.09)	(0.32)
STR				−0.065	−0.080	−0.095 *	−0.106 **	−0.120 **	−0.103 *
				(−1.22)	(−1.41)	(−1.91)	(−2.06)	(−2.17)	(−1.88)
TEC					0.020	0.022	0.023	0.019	0.025
					(0.79)	(0.97)	(1.00)	(0.82)	(1.14)
AGG						0.181 ***	0.184 ***	0.186 ***	0.217 ***
						(5.44)	(5.50)	(5.53)	(6.99)
FDI							0.011	0.009	−0.008
							(0.87)	(0.71)	(−0.61)
GOV								0.052	0.060
								(0.71)	(0.82)
HUM									0.278 ***
									(3.33)
_cons	9.765 ***	8.446 ***	6.542 ***	6.529 ***	6.473 ***	5.447 ***	5.613 ***	5.503 ***	6.417 ***
	(106.45)	(38.80)	(8.21)	(8.20)	(8.09)	(8.83)	(8.69)	(8.27)	(7.63)
Obs	240	240	240	240	240	240	240	240	240
R–sq	0.233	0.365	0.384	0.388	0.390	0.505	0.507	0.509	0.544
F statistics	31.65 ***	39.72 ***	32.07 ***	26.02 ***	21.75 ***	29.63 ***	25.99 ***	23.10 ***	23.86 ***

Note: *t* values in parentheses; ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

The results from the table show that the coefficient of *INF* was significantly positive and the coefficient of INF^2 was significantly negative. This estimation result suggests that the development of integrated infrastructure might increase carbon emissions at the early stage, and that as the level of integrated infrastructure increases, it is able to reduce emissions. In other words, there is an inverted U–shaped relationship between the integrated infrastructure and carbon emissions.

With the inclusion of a set of control variables, the sign and significance of our coefficients of interest remained stable, which ascertains the robustness of our results. Specifically, according to model 9, the coefficient of the linear term of integrated infrastructure was positively significant at the 1% level, while that of the quadratic term was negatively significant at the 1% level, which indicates that pollution emissions can be exacerbated when the level of integrated infrastructure is low; when the level of integrated infrastructure is higher than the turning point, 0.547, the development of integrated infrastructure can curb pollution emissions. As illustrated in Table 4, the composite indices of integrated infrastructure in most provinces were still below the turning point by 2020, indicating that the development of integrated infrastructure might accelerate carbon emissions for most provinces.

5.2. Robustness Checks

There may be endogeneity issues arising from the two–way reverse causality among the core variables included in our study. In particular, both transportation infrastructure and information technology can affect local economic activities and change people's habits, thus affecting regional carbon emissions. In return, regional carbon emissions also affect the distribution of transportation and information industries. To mitigate the potential biases of reverse causality, the two–stage least squares–instrumental variable (2SLS–IV) method was adopted to estimate the model. The selection of a proper instrumental variable is critical when constructing the model. This should be directly related to the key explanatory variable but not to the dependent variable [70]. Referring to the study of Che and Wang [71] and Dou and Gao [61], we chose the volume of post and telecommunications business in 1984 to construct an instrumental variable for integrated infrastructure. The reasons for this are as follows. First, both the construction and application of traditional transportation infrastructure and information infrastructure are closely related to the historical postal and telecommunication business volume. Moreover, regions with higher historical postal and telecommunications operations are also more likely to stimulate demand for transportation infrastructure construction and information technology development, satisfying the variable correlation condition. Second, relative to the ever–increasing economic activities, the volume of post and telecommunications business in 1984 had a negligible impact on carbon emissions in the current era, which satisfies the exogeneity requirement of instrumental variables.

Apart from the above, due to the presence of a comprehensive index in the model, there might be endogeneity problems arising from measurement bias. Therefore, we also examined the robustness of our results in the use of alternative variables and samples. First, to eliminate the mismeasurement caused by statistical errors in a single variable, the model was re–estimated by replacing the core explanatory variables with the coupling degree. Second, in order to exclude the interference of potential extreme values on the model results, a 5% trimmed dataset was used. Moreover, the sample was re–estimated after excluding the data of four municipalities including Beijing, Tianjin, Shanghai, and Chongqing.

The results of the robustness checks are given in Table 6. Models 1–2 present the results on the 2SLS model; models 3–4 display the estimation results of replacing the core explanatory variables; models 5 and 6 are the results based on a 5% trimmed dataset and the exclusion of municipality samples, respectively.

Table 6. Results of the robustness checks.

Variable	2SLS–IV		INF = Coupling Degree		Sample Adjustment	
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
INF	4.655 ***	4.452 **	2.527 **	1.698 **	2.085 ***	1.860 ***
	(6.79)	(2.28)	(2.52)	(2.05)	(3.37)	(2.76)
INF^2	−4.670 ***	−4.089 ***	−1.237 *	−0.998 *	−2.105 ***	−1.710 ***
	(−5.73)	(−3.79)	(−1.87)	(−1.80)	(−4.11)	(−3.40)
Control variable	N	Y	N	Y	Y	Y
Obs	240	240	240	240	216	208
F statistics	35.95 ***	22.78 ***	9.44 ***	23.00 ***	24.97 ***	24.18 ***

Note: *t* values in parentheses; ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

According to Table 6, the linear term of *INF* is positive and statistically significant, while the quadratic is negatively significant, suggesting that the nonlinear relationship between integrated infrastructure and carbon emissions is sufficiently pronounced. The results from Table 6 do not differ from those in Table 5 in a statistically significant way, proving the robustness of the baseline model.

5.3. Further Analysis

Based on the above analysis, it was found that integrated infrastructure significantly affects carbon emission. To further identify how integrated infrastructure affects carbon emissions, this study discusses the influencing channels through which an integrated infrastructure affects carbon emissions based on the discussion in Section 3.1. In other words, the effects of integrated infrastructure in relation to energy intensity, industrial structure, and technological innovation were tested. The results are provided in Table 7.

Table 7. Results of the impact mechanism.

Variable	DEPVAR = STR		DEPVAR = ENE		DEPVAR = TEC	
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
INF	2.800 ***	1.136 ***	−0.759 ***	0.893 ***	7.075 ***	1.020
	(21.31)	(3.19)	(−7.97)	(3.33)	(20.92)	(1.13)
Control variable	N	Y	N	Y	N	Y
Obs	240	240	240	240	216	208
R–sq	0.685	0.796	0.132	0.460	0.677	0.805
F statistics	454.07	86.86	63.55	18.99	437.47	92.06

Note: *t* values in parentheses; *** indicates significance at the 1% level.

According to model 2, the coefficient of integrated infrastructure is positively significant at the 1% level, indicating that integrated infrastructure exerts a driving influence on the industrial structure. This means that integrated infrastructure can promote the development of the tertiary industry, which might lead to lower carbon emissions [45].

As revealed from model 4, integrated infrastructure yields a positive and statistically significant effect on the energy intensity at the 1% level, which suggests that integrated infrastructure can enhance energy intensity. In other words, the development of integrated infrastructure is conducive to higher energy consumption per unit output, which might enhance emissions.

From model 6, integrated infrastructure is shown to have a positive but very weak influence on technological innovation, which documents that integrated infrastructure might boost technological innovation, although the effect is trivial.

6. Discussion

In this study, the evolutionary trend of integrated infrastructure was assessed. It was found that the level of integrated infrastructure continued to improve from 2013 to 2020, which is consistent with national policies that promote the construction of new infrastructure. In addition, due to the late start of integrated infrastructure, most provinces are still in a state of transitional development, and the number of provinces that reached a synergy state of coordination is limited. It is also revealed from the trend analysis that Eastern China took the lead in informatization development, while Central and Western China had a better foundation in traditional transportation infrastructure, which is in accordance with previous studies [72]. A possible explanation for this is that the eastern region has a well–developed economy and produced sufficient data [73], while its land and energy are seriously insufficient. Moreover, urban planning in the eastern region has been basically perfected, which limits the further expansion of traditional transportation infrastructure. However, the central and western regions have plenty of renewable energy and vast land, and most cities are still in the early stages of urbanization, so transportation infrastructure experiences rapid development. In 2022, China has approved projects to build eight national computing hubs and approved plans on 10 national–data center clusters, mostly in the central and western provinces such as Gansu and Ningxia. The project might bridge the gap between eastern and western regions in computing resources and facilitate the development of integrated infrastructure.

According to the results of the regression model, an inverted U–shaped relationship exists between integrated infrastructure and carbon emissions, suggesting that integrated infrastructure can provide a new impetus to green development, thus alleviating pollution emissions. The results are in line with existing studies taking transportation infrastructure [4], ICT [33], and new infrastructure [2] as objects. A possible reason for this is that, at the early development stage, the construction of integrated infrastructure might consume a substantial amount of energy due to the construction and operation of data centers and other information facilities. Along with the expansion of integrated infrastructure investment, big data, artificial intelligence, and other information technology continues to spread, which not only promotes the intelligent development of traditional transportation infrastructure, but also deepens the interface between the transport industry and information technologies, leading the transport industry development pattern in intensive and green directions, and thereby magnifying the emission reduction effect. Currently, the integrated infrastructure indices in most provinces are still below the turning point, suggesting the urgency of accelerating integrated infrastructure investment.

Further analysis revealed that integrated infrastructure enhances energy intensity, which is in line with some previous findings that the construction of infrastructure can result in excessive energy consumption [16,74]. A possible reason is that infrastructure construction can lead to the concentrated production of firms, which inevitably increases energy consumption [75]. Since the construction of integrated infrastructure is still in its early stage, the adoption of information technology such as 5G base stations and data centers into traditional transportation infrastructure may significantly accelerate energy consumption. As the increase in economic return is difficult to observe in the short–term, the energy intensity will enhance. Therefore, the issue of excessive energy consumption should be taken seriously during the expansion of integrated infrastructure.

In addition, the development of integrated infrastructure is conducive to the agglomeration of tertiary industry, which is consistent with the studies of Guo et al. [50] and Ren et al. [52]. This might be because the employment of information technology can introduce new products and new business models into traditional transportation infrastructure, thus driving the development of related service industries [49] such as modernized finance and R&D consulting. This will help to promote the greener and cleaner transformation of traditional transportation infrastructure.

Furthermore, it is notable that integrated infrastructure fails to spur technological innovation, which seems to be inconsistent with existing studies [34,45]. A possible explanation for this is that although the spillover effect of integrated infrastructure encourages innovation [55], the overwhelming new information inhibits the employees' innovation capabilities [58]; the positive effect is offset by the negative one, resulting in an insignificant relationship.

7. Conclusions and Policy Implications

With the unprecedented surge in information technology, the study of integrated infrastructure, which is characterized by the integration of traditional transportation infrastructure and informatization development, has gradually gained momentum. This study aimed to evaluate the evolutionary trends of integrated infrastructure and examine the impact of integrated infrastructure on carbon emissions. Using data from 30 Chinese provinces as the research sample, this study designed an index system and constructed a coupling coordination degree model to assess the development level of integrated infrastructure, on which basis the evolutionary trends and regional differences in integrated infrastructures were discussed. Then, the regression model was applied to empirically test the nonlinear effect of integrated infrastructure on carbon emissions. Moreover, the impacts of integrated infrastructure in relation to energy intensity, industrial structure, and technological innovation were examined to further identify the mechanisms by which integrated infrastructure affects carbon emissions. The major conclusions are as follows:

First, the levels of integrated infrastructure, traditional transportation infrastructure, and informatization development continued to improve over the period of analysis and showed a feature of "higher highs, lower lows". Meanwhile, the distribution of integrated infrastructure exhibited an "olive" shaped structure, with few provinces reaching the state of synergy. In addition, the regional disparities in integrated infrastructure, traditional transportation infrastructure, and informatization development were significant.

Second, there was an inverted–U–shaped relationship between integrated infrastructure and carbon emissions. The integrated infrastructure might exacerbate emissions at a low level; when the level of integrated infrastructure surpasses the turning point of 0.547, the development of integrated infrastructure can curb carbon emissions.

Third, the development of integrated infrastructure enhanced energy intensity, which might hamper emission reductions. However, integrated infrastructure was conducive to the development of tertiary industry, which can lead to lower carbon emissions. Meanwhile, the effect of integrated infrastructure on technological innovation was insignificant.

Based on the conclusions, we addressed the following policy implications:

First, as there are huge gaps in terms of information technology, economic development, and transportation infrastructure among different regions, integrated infrastructure construction should be in accordance with the actual situation of a given region, and cooperation among different regions is encouraged. The Eastern provinces are encouraged to support the informatization development of the Central and Western provinces by offering computing resources and advanced information technology. In return, the Central and Western provinces can utilize the land and energy resources to support the operation of intelligent transport in the Eastern provinces.

Second, integrated infrastructure has a mitigating effect on carbon emissions, and can be used as an important tool to empower green development. In particular, the industrial–structure–upgrading effect of integrated infrastructure can be utilized to promote pollution control. It is important to introduce 5G, data centers, and other new generation information technology into the traditional transport industry and provide technical and platform support for the digitalization and intelligent transformation of the traditional transport industry, thus allowing for the industry to continuously optimize its production and operation, improve energy utilization and pollution control measures, and accelerate green transformation.

Third, in the process of integrated infrastructure development, optimizing the energy structure should be taken seriously. More specifically, energy–saving and emission–reducing technologies should be employed during the construction and operation of integrated infrastructure to improve energy efficiency. At the same time, the government should strengthen the overall distribution of integrated infrastructure, promote the decommissioning and upgrade of high–energy–consuming facilities, optimize the reuse of resources, and avoid duplicate construction.

The current study provides a statistical reference for the relationship between integrated infrastructure and carbon emissions. However, extensions are necessary in future work. Since the concept and scope of integrated infrastructure was not clarified until 2018, relevant research is scarce and limited literature is available for reference and comparison. Additionally, due to data availability, the period of analysis of the current study was limited. In follow–up studies, we will try to enrich the discussion by combining some fresh case studies. In addition, we will try to extend the analysis period by introducing new variables.

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