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Transportation Infrastructure and Digital Economy—Evidence from Chinese Cities

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Abstract: In this research, the influences of railways, roads, waterways, and civil aviation on the digital economy were analyzed using traffic, urban, and enterprise data in the integrated transport system. Regression was performed through the generalized spatial least square method (GS2SLS) in the empirical section to solve the endogeneity problem. It was verified that transportation infrastructure can promote the digital economy. While the development of railways, waterways, and roads is expected to rise by 1%, the digital economy will be increased by 0.0049, 0.0048, and 0.0031, respectively, and civil aviation's effect is not significant. The robustness test results were still remarkable. From the industry level of cities, it was found that transportation infrastructure mainly promotes the development of the digital economy by upgrading the industrial structure. At the enterprise level, promoting entrepreneurship and facilitating the digital transformation of enterprises have become the main driving forces for the development of the digital economy, and strengthening labor flow is a vital promotion mechanism at the factor level of cities. In addition, a significant single-threshold effect is observed in promoting the digital economy by transportation infrastructure. In the cities that cross the threshold of the economic development level, the progress in the digital economy increases from 0.0027 and 0.0035 to 0.0059 and 0.0061 for 1% development of railways and roads; the promotion of the digital economy by transportation infrastructure is more evident in cities with a permanent-residents population of more than 3 million. Developing the digital economy and transport infrastructure is essential for economic recovery and sustainable development.

Keywords: transportation infrastructure; digital economy; GS2SLS; threshold model; China

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1. Introduction

The successful closing of the 20th National Congress of the Communist Party of China (CPC) marked the beginning of a new journey of social development in China, in which six power goals like "traffic power" and "digital China" were defined. China has permanently attached great importance to transportation infrastructure. The ancient "Zheng He is Sailing to the West", the contemporary "Belt & Road Initiative" and "Silk Road in the Air", and the famous saying "If you want to get rich, build roads first" today reflect that transportation infrastructure has always been regarded as a ballast stone for economic development in China. With the advent of the digital age, the deep integration of the digital economy and the real economy has become crucial for high-quality economic development in the new era. It is regarded as a new kinetic energy for economic growth. In the foreseeable future, transportation infrastructure and the digital economy will become critical factors in building China into a modern and powerful socialist state.

China has been praised as an "infrastructure maniac" by the media all over the world. For the first time in the 19th National Congress of the Communist Party of China (CPC) to "strengthen the construction of a transportation power", China's transportation infrastructure has achieved leap-forward development. Today, China is an undisputed transportation power. The complete transportation infrastructure makes China a leader in transportation, which has excellent internal advantages compared with other developing

countries. Simultaneously, researching the impact of China's transportation infrastructure on the development of the digital economy proves advantageous for numerous developing nations' digital economic progress, drawing from the wealth of Chinese experience.

As a pivotal factor of production with significant spatial mobility, transportation infrastructure has consistently played a decisive role in propelling economic growth, fostering regional resource integration, coordinating development, and mitigating carbon emissions [1–7]. Therefore, in the era of the digital economy, can transportation infrastructure continue to exert its influence and propel the development of the digital economy? This constitutes the central query of this discourse. Examining the specifics, China has witnessed rapid development in the digital economy over the past decade. Since 2012, the annual growth rate of China's digital economy has averaged 15.9%; in 2021, the scale of the digital economy reached CNY 45.5 trillion, registering a nominal year-on-year growth of 16.2%. The digital economy has played a crucial role in altering enterprise operational models, fostering development through information transparency, refining institutional environments, and blurring the boundaries of economic activities [8,9]. Additionally, scholars have observed that digital technologies such as artificial intelligence primarily enhance the efficiency of factor allocation and production in enterprises, particularly in high-tech industries [10]. In this context, the digital economy primarily facilitates relative substitution rather than absolute substitution of capital and labor based on efficiency in configuration [11]. Furthermore, the digital economy can enhance urban resilience and has significant positive spatial spillover effects, further promoting sustainable urban development [12].

There is a strong link between the rise of the digital economy and sustainable development in several ways, including resource efficiency, environmental protection, the spread of clean technologies, and support for sustainable economic growth. The application of digital technology can significantly improve the efficiency of resource utilization. Through big data analytics and IoT technologies, businesses can better monitor and manage the use of resources, thereby reducing waste and increasing efficiency. Undeniably, the digital economy's development mainly relies on "new infrastructure" with 5G base stations, UHV, big data centers, artificial intelligence, and industrial internet as the core. The research objective of this paper is centered on exploring the role of transportation infrastructure, traditionally considered conventional infrastructure, in the realm of the digital economy. What functions can transportation infrastructure serve in the context of the digital economy? What are the underlying mechanisms of their interaction? Regrettably, a substantial body of the literature has analyzed the impact of transportation infrastructure on economic development, encompassing the overall factor productivity of enterprises [13], specialization of labor [14], exports [15], and innovation [16], among other aspects. No research has yet delved into a comprehensive examination of its detailed impact and underlying mechanisms on the development of the digital economy. Recognizing that railways, highways, waterways, and aviation constitute the backbone of China's integrated transportation system, this paper, for the first time, scrutinizes the impact mechanisms and variations in the role of transportation infrastructure on the digital economy from four dimensions.

The relationships of four kinds of transportation infrastructure—railways, roads, waterways, and civil aviation—with the digital economy were explored using the integrated transport system and traffic data, urban data, and enterprise data. In this research, the generalized spatial least square method (GS2SLS) was used for regression to deal with the endogeneity problem. Robustness tests were carried out, including using the post cities in the Ming Dynasty and the average gradient of cities as instrumental variables, replacing the spatial matrix, and excluding municipalities directly under the central government and provincial capitals. The conclusions remained robust. The main findings are as follows. First, transportation infrastructure can promote the digital economy, with railways playing the most significant role, followed by waterways, roads, and civil aviation in succession. From the industrial level of cities, it was found that transportation infrastructure mainly promotes the development of the digital economy by upgrading the industrial structure. At the enterprise level, promoting entrepreneurship and facilitating the digital transformation

of enterprises have become the main driving forces for development. At the factor level, enhancing labor flow is a vital promotion mechanism. Third, the promoting effect of transportation infrastructure on the digital economy is more evident in the cities that cross the economic development level threshold and the cities with a permanent-resident population of more than 3 million.

The potential marginal contributions of this research are described as follows. First, the influences of railways, roads, waterways, and civil aviation on the digital economy were analyzed, which enriched the research results regarding the economic effects of transportation infrastructure in the digital age. Secondly, the action mechanism of transportation infrastructure in the digital economy was explained from three aspects: industry, enterprise, and city factor. Third, the further analyses had specific policy reference significance, being helpful for local governments to check and fill gaps and promote the construction of transportation infrastructure. Due to the limited data availability at the county level, this study did not extend its focus to the county level. A more micro and specific exploration of the mechanisms through which transportation infrastructure influences the development of the digital economy could be achieved with data support at the county level. Presently, research on the development of the digital economy tends to be macroscopic, lacking studies specific to particular regions. There is also a need for more attention to the development of specific core industries within the digital economy. These areas represent potential directions for future research.

2. Theoretical Analysis and Hypothesis

2.1. Transportation Infrastructure and Digital Economy

The core function of transportation infrastructure is to reduce the inter-regional traffic cost and integrate the production factors and trading markets in each region. Enterprises proliferate through lower trade costs and increase the market potential in their regions, thus promoting regional economic development [17]. Specifically, transportation infrastructure reduces the flow cost of production factors such as capital and labor. At the enterprise level, the efficiency of complex information communication is enhanced mainly by promoting face-to-face transportation. In the digital age, transportation infrastructure significantly positively impacts increasing employment in the tertiary industry [18]. It accelerates enterprises' understanding of digital technology by reducing communication and technical barriers [19], which is beneficial to developing the digital economy. Because of the backward areas of the digital economy, transportation infrastructure will help them imitate the development path of areas with a developed digital economy. After having a specific development foundation, transportation infrastructure will further help backward areas expand the scale of the digital economy and realize the balanced development of the digital economy. On the other hand, transportation infrastructure can improve the timeliness, accuracy, and completeness of information obtained by service enterprises, consolidate their competitive advantages in organizational management and production decisions [20], and boost the development of the digital economy.

Based on the above analysis, we propose the following contrasting hypothesis:

Hypothesis 1 (H1): *Transportation infrastructure can promote the development of the digital economy.*

2.2. Mechanism Analysis

2.2.1. Industry Level

Sachs et al. (1999) [21] and Yang and Zhang (2003) [22] posit that exogenous comparative advantage, endogenous specialization in the economy, and transaction efficiency determine the division of labor and trade patterns between regions. Transportation infrastructure enhances transaction efficiency, expediting the division of labor and specialization between regions. According to the theory of gradient economics, the convenience of specialization and transactions facilitates industrial agglomeration, propelling the formation of industrial clusters and the continuous accumulation of favorable factors. Simultaneously, in

line with the gradient economics theory, the industrial agglomeration and division of labor brought about by transportation infrastructure may also yield "spillover effects", wherein regions with a relatively backward industrial structure can leverage their comparative advantages to attract some industries from other cities or further strengthen the development of advantageous industries through knowledge spillover and technological exchange. China's economy focuses on transforming and upgrading the industrial structure from quantitative to qualitative changes. However, the economic law shows that changes in the industrial structure will cause a "structural slowdown" and slow economic growth. Transportation infrastructure cultivates new demands by strengthening inter-regional economic linkage [23], accelerating the development of service industries with strong spatial spillover effects such as finance, catering, education, and medical care, increases the output value of the tertiary industry [24], and realizing the advanced industrial structure. The upgrading of the industrial structure is mainly achieved through personnel exchanges, field visits, and patent authorization [25]. Transportation infrastructure can strengthen the above economic activities and expand the development scale of the digital economy.

On the other hand, China's irrational industrial structure is also an essential factor that inhibits economic development. Transportation infrastructure can facilitate each region to reasonably develop related industries that match its factor endowment through the optimization effect of resource allocation. That is, enterprises will locate R&D, management, and other departments in developed regions with market, technological, and talent advantages and locate production departments in backward regions [26]. Meanwhile, with the progress in transportation infrastructure, economic activities will first flow into areas with higher returns [27] to realize a rational industrial structure and boost the development of the digital economy.

Based on the above analysis, we propose the following contrasting hypothesis:

Hypothesis 2 (H2): *At the industry level of cities, transportation infrastructure promotes the development of a digital economy by upgrading and rationalizing the industrial structure.*

2.2.2. Enterprise Level

Enhancing transportation infrastructure and refining the transportation system can directly facilitate the spatial mobility of factors among various regions and cities. This influence affects enterprise behavior and the quantity, prices, and returns on production inputs. Consequently, it has a consequential impact on developing the digital economy in the respective regions. External environmental conditions are an essential factor affecting the entrepreneurship of small and microenterprises [28]. Convenient talent exchange and logistics conditions provided by transportation infrastructure can increase the cognitive level of residents, help potential entrepreneurs to have a better awareness of risk assessment for entrepreneurial projects, and cultivate entrepreneurs' optimistic expectations [29], which is not only conducive to an increase in regional employment but also can lead to regional entrepreneurial activities at the same proportion [30]. Meanwhile, transportation infrastructure provides more regional entrepreneurial opportunities and promotes entrepreneurial activities by improving market accessibility and accelerating the process of market integration [13]. Active entrepreneurial activities are an essential endogenous driving force for high-quality development [9], which can provide necessary support for developing China's digital economy. On the other hand, transportation infrastructure helps in the digital transformation of enterprises, and by improving regional proximity, it can reduce the cost spent by digital enterprises in market exploitation, providing more opportunities for enterprises in neighboring areas to get in touch with digital technology. Its compressed spatial-temporal effect can also quickly bring entrepreneurs into contact with cutting-edge digital technology, which is beneficial to the spread of invisible knowledge, thus improving the digitalization and intelligence level of enterprises and boosting the development of the digital economy.

Based on the above analysis, we propose the following contrasting hypothesis:

Hypothesis 3 (H3): *At the enterprise level, transportation infrastructure promotes the development of the digital economy by promoting entrepreneurship and the digital transformation of enterprises.*

2.2.3. Factor Level

Endogenous growth theory explores the labor change effects of transportation infrastructure, affirming that infrastructure construction can reduce trade costs, promote trade development, and stimulate economic growth. This, in turn, increases employment opportunities in the secondary and tertiary sectors, fostering labor mobility between industries and regions. Accelerating the flow of factors is a significant effect induced by transportation infrastructure. A complete transportation network improves the willingness of the labor force in cross-regional activities by reducing the cross-regional transit time [31]; additionally, acquiring new employees will also enable enterprises to learn cutting-edge technologies and knowledge faster [16]. Further, progress in transportation infrastructure will make the time-sensitive, high-skilled labor force more willing to work across regions, which meets the talent requirements for developing the digital economy. At the same time, transportation infrastructure promotes personnel flow, which is beneficial to shortening the technological gap between enterprises and meeting the technical requirements of developing the digital economy. On the other hand, for digital enterprises that are still in their infancy, the problem they face is often the weak intelligence foundation, the key to which is increasing contact with enterprises possessing developed digital technologies [32]. Transportation infrastructure can reduce the spatial-temporal distance between two sides, help digital enterprises in the starting phase by strengthening the labor flow, and promote the regional development of the digital economy.

Based on the above analysis, we propose the following contrasting hypothesis:

Hypothesis 4 (H4): *At the factor level of cities, transportation infrastructure promotes the development of a digital economy by strengthening the labor flow.*

3. Empirical Tests

3.1. Sample Selection and Data Sources

China's railways, roads, waterways, and civil aviation have developed rapidly in the recent decade. From 2012 to the end of 2021, the accumulated fixed investment in railways reached CNY 7 trillion, the operating mileage reached 150,000 km, and the freight volume in 2021 was 4.774 billion tons. The density of road networks reached 55 km/100 km^2, and the total mileage of rural roads increased from 3,564,000 km at the end of 2011 to 4,466,000 km at the end of 2021. The mileage of inland waterways opened to traffic reached 128,000 km, with 2659 berths of 10,000 tons and above. The accumulated fixed investment in civil aviation reached CNY 800 billion, with 250 transport airports (Data source: national news network, http://www.scio.gov.cn/xwfbh/xwbfbh/wqfbh/47673/48346/index.htm, accessed on 18 August 2023).

On the other hand, digital inclusive finance is a meaningful way to realize the deep integration of digital technology and financial services, which can effectively measure the development level of industrial digitalization. The latest data sample interval spans from 2011 to 2020. To sum up, the research interval of samples was finally determined as 2011–2013 after considering the construction progress in China's transportation infrastructure and the availability of critical data.

The traffic data included four aspects: railways, roads, waterways, and civil aviation. The data mainly came from the National Bureau of Statistics, China Urban Statistical Yearbook, Compilation of Railway Statistical Data, National Railway Administration, the China Civil Aviation Statistical Yearbook, and the Civil Aviation Administration of China. Digital inclusive finance data were derived from the Digital Inclusive Finance Index (2011–2020) compiled by the Digital Finance Research Center of Peking University (Data source: Digital Finance Research Center of Peking University, https://idf.pku.edu.cn/yjcg/zsbg/513800.htm,

accessed on 10 August 2023). Enterprise data were mainly acquired from Tianyancha, Qichacha, and CSMAR databases.

The remaining data mainly came from the National Bureau of Statistics, the China Statistical Yearbook over the years, the China Regional Economic Statistical Yearbook, the China Labor Statistical Yearbook, the China Urban Statistical Yearbook, the CEIC China Economic Database, local statistical yearbooks, and local statistical bulletins. Due to the severe data missing in some cities, the panel data of 229 cities from 2011 to 2020 were finally formed.

3.2. Variable Description

3.2.1. Explained Variable

Digital Economy (ECO). Bukht and Heeks (2018) [33] thought that the digital economy mainly includes three aspects: the digital industry represented by information and telecommunications services, platform economy, and e-commerce; the narrow layer of the digital economy; and the broad layer of the digital economy. CAICT divides the digital economy into digital industrialization, digital governance, digital value, and industrial digitalization (Data source: CAICT, http://www.caict.ac.cn/kxyj/qwfb/bps/202207/t20220708_405627.htm, accessed on 20 August 2023). Despite the different definitions given by scholars to the digital economy, it is consistently accepted that the digital economy is closely related to the development of the internet. At the same time, digital inclusive finance is an essential means of realizing the digitalization of the service industry. Regarding the research by Zhao Tao et al. (2020) [9], the development level of the digital economy in cities was measured from two levels—internet and digital inclusive finance. The development level of the internet was measured from four angles: the popularization rate of the internet and mobile phones, the proportion of employees in related industries, and the per capita output. The measurement indexes included the number of internet broadband access users per 100 people, the number of mobile phone users per 100 people, the proportion of employees in computer services and software industry to employees in urban units, and the per capita total amount of telecommunications services. The digital inclusive finance index represented the development level of digital inclusive finance. The above five indexes were all positive. In this research, the entropy method was adopted, and the final score was used as a characterization index to measure the development level of the digital economy in cities. The specific calculation steps are as follows:

First, standardization was performed as follows:

$$x'_{\theta ij} = \frac{x_{\theta ij} - min\{x_j\}}{max\{x_j\} - min\{x_j\}} \tag{1}$$

where $max\{xj\}$ and $min\{xj\}$ stand for this index's maximum value and minimum value in all years, respectively, and $x'_{\theta ij}j$ denotes the standardized value of the j-th index of the province θ in the year i.

Second, the proportion of the j-th index in the year i was calculated as below:

$$\rho_{\theta ij} = \frac{x'_{\theta ij}}{\sum_{\theta=1}^{k}\sum_{i=1}^{m} x'_{\theta ij}} \tag{2}$$

where m is the number of years of samples. The entropy of the j-th index was solved as follows:

$$e_j = -\frac{1}{In(m)}\sum_{i=1}^{m}\left(\rho_{\theta ij} * In\left(\rho_{\theta ij}\right)\right) \tag{3}$$

The information redundancy of the j-th index was expressed as $f_j = 1 - e_j$. Furthermore, the index weight was calculated based on the information redundancy, as below:

$$w_j = \frac{f_j}{\sum_{j=1}^{n} f_j} \tag{4}$$

Finally, the digital economy index of each province over the years was acquired by multiplying the standardized index with the index weight as follows:

$$Eco_{\theta i} = \sum_{j=1}^{n} (w_j * x'_{\theta ij}) \tag{5}$$

3.2.2. Core Explanatory Variables

Transportation infrastructure. Based on the availability of urban data and the comprehensiveness of the research, the construction level of urban transportation infrastructure was measured from four angles: railways (RW), roads (HW), waterways (WW), and civil aviation (AP). In the research of Tang S et al. (2021) [34], the passenger turnover of four kinds of transportation infrastructure was taken as an index to characterize the construction level of transportation infrastructure. In this research, logarithms were taken from the above indexes to mitigate the heteroscedasticity of the data in the model.

3.2.3. Mechanism Variable

Rationalization of industrial structure (RS). There is a mismatch in production factors in Chinese cities, which must be solved to achieve high-quality economic development. Referring to the method of Gan C H et al. (2011) [35], the rationalization level of the industrial structure in cities was measured using the Theil index, which could not only reflect the proportion of industries in national economic development but also reflect the coupling degree between the labor force and industrial structure. The specific calculation steps are as follows:

$$RS = \sum_{i=1}^{n} (a_i/a) In\left(\frac{a_i/b_i}{a/b}\right) = \sum_{i=1}^{n} (a_i/a) In\left(\frac{a_i/a}{b_i/b}\right), n = 1, 2, 3 \tag{6}$$

where RS stands for Theil index, and a and b for the output value and the number of employees of various industries, respectively. When the industrial structure is in equilibrium, $ai/a = bi/b$, $RS = 0$. It is worth noting that RS is a negative index. The smaller its value, the more rational the industrial structure.

Advancement of the industrial structure (HS). Economic development has been deeply integrated with the internet, and the efficiency of information transmission in various industries has been continuously improved. The development of producer services, including finance and insurance, has promoted the technological upgrading of the secondary industry. That is, upgrading the industrial structure has enabled the secondary and tertiary industries to enjoy the development dividend. Based on the method of Liu M F et al. (2022) [36], the advanced level of the industrial structure in cities was measured by using the ratio of the output value of the tertiary industry to that of the secondary industry.

Entrepreneurial activity (SE). Active entrepreneurial activities provide high-quality soil for economic development. Based on the research of Bai J H et al. (2022) [37], the population of each city served as a standardized base number, and the number of new businesses per 100 people was used as an index to measure the entrepreneurial activity of each city. In this research, the logarithm was taken from the above index.

Digital transformation (DIG). As an essential link in the development of the digital economy, digital transformation can effectively improve the total factor productivity and organizational resilience of enterprises, and it is also an important channel for enterprises to

integrate into the digital development of industries. According to the practice of Wu F et al. (2021) [38], the keyword frequency of digital economy in the annual report of listed companies was taken as the characterization index to measure the digital transformation of enterprises (Keywords: artificial intelligence, business intelligence, image understanding, investment decision support system, intelligent data analysis, intelligent robot, machine learning, deep learning, semantic search, biometric technology, face recognition, voice recognition, identity authentication, autonomous driving, natural language processing, big data, data mining, text mining, data visualization, heterogeneous data, credit reporting, augmented reality, mixed reality, virtual reality. Multi-party secure computing, brain like computing, green computing, cognitive computing, converged architecture, billion-level concurrency, EB-level storage, internet of Things, cyber-physical systems, blockchain, digital currency, distributed computing, differential privacy technology, smart financial contract, mobile internet, industrial internet, mobile internet, internet medical care, e-commerce, mobile payment, third-party payment, NFC payment, smart energy, B2B, B2C, etc. Networking, smart wear, smart agriculture, intelligent transportation, intelligent medical care, intelligent customer service, smart home, intelligent investment, intelligent travel, intelligent environmental protection, smart grid, intelligent marketing, digital marketing, unmanned retail, internet finance, digital finance, Fintech, financial technology, quantitative finance, open bank.), and 27,714 pieces of valid data were formed, which were matched to cities according to their establishment addresses. The average value represented the digital transformation level of enterprises in each city. In this research, the logarithm was taken from the above index.

Labor flow (LB). China's transportation network has been continuously improved, expanding the scope of labor flow and realizing the specialized division of labor, which has boosted high-quality economic development in China. In this research, the practice of Gao B et al. (2021) [39] was referenced to measure the labor flow level of each city based on the proportion of the employment number in the total population of each city.

3.2.4. Control Variables

The development of the digital economy is inseparable from the progress in emerging technologies such as big data and cloud computing. The iteration and updating of technologies mainly depend on R&D capital investment and highly skilled talents. The R&D investment (RD) and education level (EDU) were selected as control variables. R&D investment (RD) was measured by the total amount of R&D investment in each city, and the education level (EDU) was measured by the number of college students per 10,000 people. Logarithmic transformations were applied to the indicators above in this study to mitigate the heteroscedasticity of the data in the model.

3.3. Multicollinearity

Each explanatory variable was subjected to the multicollinearity test to avoid the multicollinearity problem. See Table 1 below, where AP's variance inflation factor (VIF) is 2.01, while the VIF for the remaining explanatory variables is below 2. This ensures that the econometric results are not unduly influenced by multicollinearity among the variables [40].

Table 1. Variance inflation factor.

	RW	HW	WW	AP	RS	HS	SE	DIG	LB	RD	EDU
VIF	1.71	1.50	1.10	2.01	1.27	1.57	2.52	1.33	1.85	1.93	1.69

3.4. Descriptive Statistics

The descriptive statistical results of variables are shown in Table 2 below. The maximum value and minimum value of the digital economy reached 0.881 and 0.013, respectively, indicating that the development of the digital economy among cities in China was unbalanced. The standard deviations of railways, roads, waterways, and civil aviation were all relatively large, reaching 1.441, 1.085, 1.558, and 1.638, respectively, manifesting that the

construction level of transportation infrastructure in different cities was quite different at this stage and reflecting the importance of studying different transportation infrastructure to the development of the digital economy.

Table 2. Descriptive statistics.

Variable	Obs.	Mean	Std. Dev.	Max	Min
Eco	2290	0.131	0.100	0.881	0.013
RW	2290	6.034	1.441	10.30	0.693
HW	2290	8.379	1.085	12.57	2.303
WW	2290	3.748	1.558	9.636	0.000
AP	2290	4.351	1.638	10.28	0.137
RS	2290	0.266	0.217	3.430	0.0001
HS	2290	1.012	0.545	5.348	0.113
SE	2290	4.657	0.632	7.544	2.769
DIG	2290	2.466	0.789	5.700	0.043
LB	2290	0.143	0.136	1.473	0.024
RD	2290	12.15	1.756	17.06	1.386
EDU	2290	4.937	0.944	7.166	1.386

3.5. Econometric Strategy

3.5.1. Econometric Model

The development of the digital economy in China presents a strong spatial macro-linkage, indicating that cities with a high development level of digital economy will be learned and imitated by their associated cities. At the same time, the elevated level of transportation-infrastructure construction will further strengthen the economic ties between cities through the exchange of technology and talent. Based on this, the spatial correlation of the digital economy was controlled for regression using GS2SLS, and the benchmark model was constructed as follows:

$$Eco_{ij} = \alpha_0 + \alpha_1 \cdot RW_{ij} + \alpha_2 \cdot HW_{ij} + \alpha_3 \cdot WW_{ij} + \alpha_4 \cdot AP_{ij} + \beta X_{ij} + \chi Y_{ij} + \varphi_{ij} \quad (7)$$

where i represents the year and j is the province; Eco_{ij} denotes the explained variable—digital economy; RW_{ij}, HW_{ij}, WW_{ij}, and AP_{ij} stand for railway, road, waterway, and civil aviation indexes, respectively; X_{ij} is the mechanism variable; Y_{ij} stands for the control variable; α, β, and χ are estimation parameters; φ_{ij} is the random disturbance term.

3.5.2. Spatial Weight Matrix

The spatial weight matrices mainly used in spatial econometric research are the adjacency matrix and the distance matrix, in which the latter is divided into geographical distance and economic distance. The geographical distance matrix mainly includes traffic distance and geographical-location distance, which are composed of the reciprocal of inter-regional high-speed kilometers and the reciprocal of the linear distance of geographical locations. The economic distance matrix consists of the reciprocal of the inter-regional difference in per capita GDP. This research selected the economic distance matrix as the spatial weight matrix in regression. In the part of the robustness test, a nested spatial weight matrix was constructed for regression.

3.5.3. Endogeneity Processing

In reality, cities taking the lead in developing the digital economy have a high level of economic development. The central government, as a construction planner, often has a greater preference for these areas and strengthens the investment in transportation infrastructure in these areas. The site selection and construction of transportation infrastructure are non-random, leading to endogeneity due to self-selection deviation.

Given this, regression was performed in this research by selecting the generalized spatial two-stage least square method, which was capable of consistent parameter estima-

tion based on controlling the heteroscedasticity of the model, dealing with the endogeneity problem of critical variables, and correcting the spatial interaction of missing variables in the model (Arraiz et al., 2010) [41]. The third-order spatial lag term of transportation infrastructure was selected as the instrumental variable to avoid weak instrumental variables in the regression. In the follow-up robustness test part, post-cities in the Ming Dynasty and the average gradient of cities were chosen as instrumental variables for 2SLS-based regression to ensure the scientificity of research conclusions.

4. Results

4.1. Baseline Regression

The baseline regression results are listed in Table 3 below. Columns (1)–(4) are the individual regressions of various transportation infrastructure. The Hausman test results were significant at 1%, so we used the fixed effects model to regress. In all regressions, the F-test statistics were more significant than the empirical value of 10, indicating the absence of weak instrumental variables. W *Eco coefficients were all significantly positive, proving a significant spatial spillover effect in the digital economy. The railway and road regression coefficient was significantly positive at 10% in the independent regression. The regression coefficient of the waterway was significantly positive at 1%. The regression coefficient of civil aviation was not significant. Hypothesis 1 (H1) is confirmed. The regression coefficient for civil aviation is negative but not statistically significant. This is primarily attributed to the late development of civil aviation in China.

Table 3. Baseline regression.

	(1)	(2)	(3)	(4)
	FE	**FE**	**FE**	**FE**
W × Eco	0.7594 **	0.7472 *	0.8119 *	0.8415 *
	(0.369)	(0.422)	(0.417)	(0.436)
RW	0.0049 *			
	(0.002)			
HW		0.0031 *		
		(0.002)		
WW			0.0048 ***	
			(0.002)	
AP				−0.0010
				(0.001)
RS	−0.0038	−0.0043	−0.0037	−0.0042
	(0.006)	(0.006)	(0.006)	(0.006)
HS	0.0069 *	0.0083 **	0.0073 **	0.0074 **
	(0.003)	(0.003)	(0.003)	(0.003)
SE	0.0130 ***	0.0156 ***	0.0137 ***	0.0142 ***
	(0.002)	(0.003)	(0.004)	(0.003)
DIG	0.0044 **	0.0055 ***	0.0049 ***	0.0049 ***
	(0.002)	(0.002)	(0.002)	(0.002)
LB	0.0256	0.0304 *	0.0271	0.0279
	(0.018)	(0.018)	(0.017)	(0.018)
EDU	−0.0011	−0.0012	−0.0010	−0.0009
	(0.002)	(0.002)	(0.002)	(0.002)
RD	0.0011	0.0013	0.0012	0.0013
	(0.001)	(0.001)	(0.001)	(0.001)
F Test	18.40	18.25	18.83	17.94
	(0.000)	(0.000)	(0.000)	(0.000)
Hausman Test	562.96	427.61	549.71	595.66
	(0.000)	(0.000)	(0.000)	(0.000)
Observations	2290	2290	2290	2290
R-squared	0.215	0.212	0.202	0.172

Notes: All regressions include a constant. *, **, ***: significant at 10%, 5%, 1%; standard errors are clustered at the city level.

Additionally, civil aviation construction has a lagged promoting effect on economic development [34]. Regular flight services on fixed routes were only restored in 1950, with the introduction of the route from Tianjin via Wuhan to Chongqing. Simultaneously, the current shortage of airspace resources in China has led to a significant issue of flight delays.

The industrial structure's rationalization coefficient remained negative but insignificant among the mechanism variables. The advancement of the industrial structure, entrepreneurial activity, and digital transformation coefficient of enterprises were all significantly positive. The labor flow coefficient was significantly positive in Column (2), and the other regression coefficients were all positive but insignificant. The rationalization of the industrial structure could have significantly promoted the digital economy's development. A possible reason is that developed regions will fully use advantageous industries to structurally transform, squeezing the space for industrial structural transformation in late-developing regions. The development of the digital economy was not promoted by labor flow, which was mainly ascribed to the long-term high degree of labor market segmentation in China leading to the unbalanced labor supply and demand in some regions and impeding its promoting effect on the development of the digital economy.

Among the control variables, the R&D investment coefficient was positive but insignificant. The education level coefficient remained negative but not significant. The main reason is a big gap in the number of colleges and universities in different cities in China, which inhibits the balanced development of the urban economy.

4.2. Robustness Test

4.2.1. Regression of Instrumental Variables

In this research, the endogeneity problem in the econometric model could be effectively solved through regression using GS2SLS, but to ensure the scientificity and rigorousness of our research conclusions, post-cities in the Ming Dynasty and the average gradient of cities were further chosen as the instrumental variables of transportation infrastructure for regression. The reasons are explained as follows. The post stations were constructed for military purposes in the Ming Dynasty, and the construction foundation was mainly affected by the original local geological conditions due to the then-technical restrictions, and the original geological conditions were highly related to the construction of transportation infrastructure, that is, such post-cities met the conditions for serving as an instrumental variable as analyzed from two angles: homogeneity and correlation. As a geographical environment condition, the average gradient of cities was little correlated with the digital economy, and at the same time, it affected the construction of transportation infrastructure. The higher the average gradient, the more difficult it was to build transportation infrastructure. In this part, the road index was selected as the representative variable of transportation infrastructure. Because the two indexes—post-cities in the Ming Dynasty and the average gradient of cities—did not change with time, their interaction term with the time dummy variable was used as the instrumental variable. See Table A1 for the specific regression. The F-test statistics were always more significant than the empirical value of 10. The regression results showed that the coefficient of transportation infrastructure was still significantly positive.

4.2.2. Replacement of Space Matrix

In this research, the spatial weight matrix used in the baseline regression was the spatial matrix of economic distance. To comprehensively investigate the spatial correlation between regions further, a nested spatial matrix considering both economic distance and geographical distance was constructed by reference to the research of Shao S et al. (2022) [42], namely, $W2 = 0.5_{\text{Weconomyc distance}} + 0.5W_{\text{geographical distance}}$. The specific results are listed in Table A2, from which each coefficient did not differ obviously from the baseline regression result.

4.2.3. Exclusion of Municipalities Directly under the Central Government

Compared with ordinary prefecture-level cities, municipalities directly under the central government and provincial capital cities presented a higher comprehensive development level, leading demonstration positions in transportation, economy, and other aspects, and would receive more policy inclinations from the central government, accounting for 13.1% of 229 city samples in this research. Regression was performed again based on excluding the data of such municipalities directly under the central governance to avoid their influence on the regression results. The results are listed in Table A3, in which no evident changes in regression coefficients were observed.

4.2.4. Change in the Order of Spatial Lag Term

The spatial lag term was set as three periods to avoid weak instrumental variables in the baseline regression. The spatial lag term was further set as a 2-period lag for regression again, with the specific results seen in attached Table A4. All F-test statistics were greater than 10, and regression coefficients showed no significant changes compared to the baseline regression results.

5. Mechanism Analysis

The benchmark test proved that transportation infrastructure can significantly promote the development of the digital economy. Based on the theoretical deduction above, the action mechanism of transportation infrastructure in the digital economy was further analyzed in this section and verified from three levels: industry, enterprise, and city factor. On this basis, an econometric model with interactive items was constructed:

$$Eco_{ij} = \beta_0 + \beta_1 \cdot Trans_{ij} + \beta_2 \cdot Trans_{ij} \cdot Machanism_{ij} + \beta_3 \cdot Control_{ij} + \varphi_{ij} \quad (8)$$

Transit represents the four kinds of transportation infrastructure: railway, road, waterway, and civil aviation; $Machanism_{ij}$ is the mechanism variable, $Control_{ij}$ is the control variable, and φ_{ij} is the random disturbance term.

5.1. Industry Level

At the industry level, the action mechanism of transportation infrastructure in the digital economy was tested from two aspects: rationalizing the industrial structure and upgrading the industrial structure.

5.1.1. Rationalization of the Industrial Structure

Table 4 shows the regression results of rationalization of the industrial structure. The interaction-term coefficient of the road was significantly positive, meaning that the road will significantly inhibit the rationalization of the regional industrial structure. Generally speaking, transportation infrastructure still needs to promote the development of the digital economy by rationalizing the industrial structure. The possible reasons are described as follows. First, the effects of transportation infrastructure on urban industrial structure are mainly the division effect and convergence effect. In the case of a similar urban development level, the division effect is dominant, and the industrial structure will be polarized. On the contrary, it is a convergence effect, and the industrial structure will be more similar, which is beneficial to advancing the urban industrial structure but not necessarily conducive to rationalizing it. Secondly, although roads have become the most mature transportation network in China, the regional barriers and market segmentation between cities have been aggravated because of the segmented road operation and management model, thus hindering the rationalization of the urban industrial structure.

Table 4. Rationalization of the industrial structure.

	(1)	(2)	(3)	(4)
	FE	**FE**	**FE**	**FE**
W × Eco	0.6877 *	0.6856	0.7719 *	0.7714 *
	(0.378)	(0.429)	(0.397)	(0.460)
Trans	0.0048 *	0.0038 **	0.0049 ***	−0.0006
	(0.003)	(0.002)	(0.002)	(0.002)
Trans × Machanism	−0.0062	0.0198 ***	0.0061	−0.0082 *
	(0.005)	(0.005)	(0.005)	(0.005)
HS	0.0063 *	0.0089 **	0.0073 **	0.0067 *
	(0.004)	(0.004)	(0.004)	(0.004)
SE	0.0132 ***	0.0158 ***	0.0135 ***	0.0143 ***
	(0.003)	(0.003)	(0.003)	(0.003)
DIG	0.0045 **	0.0057 ***	0.0052 ***	0.0049 ***
	(0.002)	(0.002)	(0.002)	(0.002)
LB	0.0240	0.0253	0.0268	0.0271
	(0.018)	(0.018)	(0.018)	(0.018)
EDU	−0.0011	−0.0017	−0.0010	−0.0010
	(0.002)	(0.002)	(0.002)	(0.002)
RD	0.0010	0.0013	0.0012	0.0013
	(0.001)	(0.001)	(0.001)	(0.001)
F Test	18.42	20.08	18.96	18.12
	(0.000)	(0.000)	(0.000)	(0.000)
Observations	2290	2290	2290	2290
R-squared	0.216	0.189	0.193	0.188

Notes: All regressions include a constant. *, **, ***: significant at 10%, 5%, 1%; standard errors are clustered at the city level.

5.1.2. Advancement of the Industrial Structure

Table 5 shows the regression results regarding the advancement of the industrial structure. The interaction-term coefficient of transportation infrastructure remained positive, among which the coefficient of waterway was significant at the level of 1% and that of civil aviation was significant at the level of 5%, indicating that transportation infrastructure can stimulate the development potential of the service industry, expand the proportion of its output value, and promote the development of the digital economy. The insignificant impact of highways and railways can be attributed to significant imbalances in developing China's urban digital economy. Furthermore, there is substantial room for railway construction in China's central and western regions, which has yet to effectively stimulate the advancement of industrial structures in these areas. While highways can facilitate factor mobility and accelerate the flow of goods, the prevalent phenomenon of "each city for itself" in highway management among cities remains severe. The absence of a unified management system has led to low administrative efficiency, resulting in a positive but statistically insignificant coefficient for highways.

Table 5. Advancement of the industrial structure.

	(1)	(2)	(3)	(4)
	FE	**FE**	**FE**	**FE**
W × Eco	0.7626 **	0.8480 **	0.9197 **	0.8717 **
	(0.353)	(0.416)	(0.375)	(0.431)
Trans	0.0049 *	0.0023	0.0048 ***	0.0001
	(0.002)	(0.002)	(0.002)	(0.002)
Trans × Machanism	0.0007	0.0007	0.0052 ***	0.0028 **
	(0.002)	(0.002)	(0.002)	(0.001)
RS	−0.0018	−0.0019	−0.0014	−0.0025
	(0.006)	(0.006)	(0.006)	(0.006)

Table 5. *Cont.*

	(1)	(2)	(3)	(4)
	FE	**FE**	**FE**	**FE**
SE	0.0152 ***	0.0178 ***	0.0158 ***	0.0153 ***
	(0.003)	(0.003)	(0.003)	(0.003)
DIG	0.0053 ***	0.0063 ***	0.0059 ***	0.0058 ***
	(0.002)	(0.002)	(0.002)	(0.002)
LB	0.0245	0.0280	0.0248	0.0257
	(0.002)	(0.002)	(0.002)	(0.002)
EDU	−0.0012	−0.0012	−0.0011	−0.0012
	(0.002)	(0.002)	(0.002)	(0.002)
RD	0.0011	0.0012	0.0015	0.0014
	(0.001)	(0.001)	(0.001)	(0.001)
F Test	17.98	17.71	19.88	18.09
	(0.000)	(0.000)	(0.000)	(0.000)
Observations	2290	2290	2290	2290
R-squared	0.210	0.189	0.195	0.192

Notes: All regressions include a constant. *, **, ***: significant at 10%, 5%, 1%; standard errors are clustered at the city level.

5.2. Enterprise Level

At the enterprise level, the action mechanism of transportation infrastructure in the digital economy was tested from entrepreneurial activity and digital transformation.

5.2.1. Entrepreneurial Activity

Table 6 shows the regression results of entrepreneurial activity. The interaction-term coefficients of the four types of transportation infrastructure were all significantly positive, and the significance level remained at 1%, meaning that transportation infrastructure can promote the development of the digital economy by enhancing entrepreneurship.

Table 6. Entrepreneurial activity.

	(1)	(2)	(3)	(4)
	FE	**FE**	**FE**	**FE**
W × Eco	0.7737 **	0.7349 *	0.8883 ***	0.7502 *
	(0.386)	(0.383)	(0.344)	(0.418)
Trans	0.0055 **	−0.0007	0.0045 **	0.0041 **
	(0.003)	(0.002)	(0.002)	(0.002)
Trans × Machanism	0.0044 ***	0.0038 ***	0.0041 ***	0.0049 ***
	(0.001)	(0.001)	(0.001)	(0.001)
RS	−0.0040	−0.0055	−0.0061	−0.0048
	(0.007)	(0.007)	(0.007)	(0.007)
HS	0.0121 ***	0.0136 ***	0.0141 ***	0.0093 ***
	(0.003)	(0.003)	(0.003)	(0.003)
DIG	0.0084 ***	0.0087 ***	0.0087 ***	0.0077 ***
	(0.002)	(0.002)	(0.002)	(0.002)
LB	0.0284	0.0331 *	0.0300 *	0.0276
	(0.018)	(0.018)	(0.018)	(0.018)
EDU	−0.0009	−0.0003	−0.0005	−0.0009
	(0.002)	(0.002)	(0.002)	(0.002)
RD	0.0014	0.0011	0.0017	0.0015
	(0.001)	(0.001)	(0.001)	(0.001)
F Test	17.32	16.11	17.85	18.02
	(0.000)	(0.000)	(0.000)	(0.000)
Observations	2290	2290	2290	2290
R-squared	0.200	0.152	0.180	0.204

Notes: All regressions include a constant. *, **, ***: significant at 10%, 5%, 1%; standard errors are clustered at the city level.

5.2.2. Digital Transformation

Table 7 shows the regression results of digital transformation. The interaction-term coefficient of transportation infrastructure was positive, and the significance levels of railway, waterway, and civil aviation were 10%, 5%, and 1%, respectively, proving that transportation infrastructure can facilitate the digital transformation of urban enterprises and boost the development of the digital economy. Compared to other transportation infrastructure, such as railways, highways exhibit the least significant role in promoting the connectivity of economic activities between cities and enterprises [43]. This limited significance impedes the effective learning of digital knowledge and technologies by enterprises from other technological entities, thereby failing to enhance the digital transformation capabilities of the enterprises significantly. Consequently, while positive, the highway interaction coefficient is not statistically significant.

Table 7. Digital transformation.

	(1)	(2)	(3)	(4)
	FE	**FE**	**FE**	**FE**
W × Eco	0.8329 **	0.8562 **	0.8762 **	0.9433 **
	(0.369)	(0.422)	(0.389)	(0.415)
Trans	0.0051 **	0.0021	0.0042 **	0.0002
	(0.002)	(0.002)	(0.002)	(0.002)
Trans × Machanism	0.0017 *	0.0002	0.0019 **	0.0027 ***
	(0.001)	(0.001)	(0.001)	(0.001)
RS	−0.0041	−0.0052	−0.0044	−0.0043
	(0.007)	(0.007)	(0.007)	(0.007)
HS	0.0086 **	0.0105 ***	0.0097 ***	0.0087 **
	(0.004)	(0.004)	(0.004)	(0.004)
SE	0.0163 ***	0.0188 ***	0.0173 ***	0.0169 ***
	(0.003)	(0.003)	(0.003)	(0.003)
LB	0.0254	0.0289	0.0278	0.0284
	(0.002)	(0.002)	(0.002)	(0.002)
EDU	−0.0016	−0.0014	−0.0014	−0.0015
	(0.002)	(0.002)	(0.002)	(0.002)
RD	0.0015	0.0016	0.0015	0.0017
	(0.001)	(0.001)	(0.001)	(0.001)
F Test	18.14	17.29	18.58	18.59
	(0.000)	(0.000)	(0.000)	(0.000)
Observations	2290	2290	2290	2290
R-squared	0.234	0.219	0.220	0.207

Notes: All regressions include a constant. *, **, ***: significant at 10%, 5%, 1%; standard errors are clustered at the city level.

5.3. Factor Level

At the factor level, the action mechanism of transportation infrastructure in the digital economy was tested from labor flow.

Labor Flow

Table 8 presents the regression results of labor flow. The interaction-term coefficient of transportation infrastructure was positive, and the significance level of railway, waterway, and civil aviation was 1%, verifying that transportation infrastructure can strengthen the labor flow between cities and promote the development of the digital economy. The insignificance of the coefficient for highways can be attributed to the highly uneven density of the highway network as well as passenger and freight traffic between Chinese cities. Highway operation and toll management are typically under the jurisdiction of different local governments. There are numerous toll stations and relatively high toll fees on highways between cities, which, to a certain extent, increase the cost of labor mobility and result in inefficient resource allocation.

Table 8. Labor flow.

	(1)	(2)	(3)	(4)
	FE	**FE**	**FE**	**FE**
W × Eco	0.7997 **	0.7416 *	0.7257 *	0.8963 **
	(0.364)	(0.400)	(0.406)	(0.436)
Trans	0.0053 **	0.0028	0.0058 ***	0.0011
	(0.002)	(0.002)	(0.002)	(0.002)
Trans × Machanism	0.0524 ***	0.0007	0.0491 ***	0.0439 ***
	(0.010)	(0.005)	(0.010)	(0.008)
RS	−0.0019	−0.0037	−0.0035	−0.0029
	(0.006)	(0.006)	(0.006)	(0.006)
HS	0.0065 *	0.0079 **	0.0069 *	0.0064 *
	(0.004)	(0.004)	(0.004)	(0.004)
SE	0.0127 ***	0.0157 ***	0.0132 ***	0.0131 ***
	(0.003)	(0.003)	(0.003)	(0.003)
DIG	0.0043 **	0.0053 ***	0.0054 ***	0.0048 **
	(0.002)	(0.002)	(0.002)	(0.002)
EDU	−0.0006	−0.0009	−0.0007	−0.0004
	(0.002)	(0.002)	(0.002)	(0.002)
RD	0.0010	0.0013	0.0011	0.0014
	(0.001)	(0.001)	(0.001)	(0.001)
F Test	21.23	17.96	21.06	21.17
	(0.000)	(0.000)	(0.000)	(0.000)
Observations	2290	2290	2290	2290
R-squared	0.282	0.155	0.251	0.273

Notes: All regressions include a constant. *, **, ***: significant at 10%, 5%, 1%; standard errors are clustered at the city level.

5.4. Summary

The above results show that transportation infrastructure promotes the development of the digital economy in cities through four paths: upgrading the industrial structure, promoting entrepreneurship, facilitating the digital transformation of enterprises, and strengthening labor flow. In addition to rationalizing the industrial structure, the remaining research hypotheses (H2–H4) have been verified.

6. Further Analyses

The relationship between transportation infrastructure and the digital economy has been explained above, among which railways and roads, as the main transportation forces in China, still need to be present in the central and western regions, most of which are economically backward areas. Then, can transportation infrastructure promote the development of the digital economy in economically backward cities? What are the differences between different types of cities?

6.1. Economic Development Level

6.1.1. Estimation of Threshold Effect

Based on the level of economic development level, a threshold model was adopted to confirm whether there is a threshold effect on the promoting effect of transportation infrastructure on the digital economy and to identify which cities have a more apparent promoting effect:

$$Eco_{ij} = \chi_0 + \chi_1 \cdot Trans_{ij}\left(GDP_{ij} \le \gamma\right) + \chi_2 \cdot Trans'_{ij}\left(GDP_{ij} > \gamma\right) + \chi_3 \cdot X_{ij} + \varphi_{ij} \quad (9)$$

$Trans_{it}$ represents railway and road; GDP_{ij} denotes the threshold variable, namely economic development level, characterized by per capita GDP; X_{ij} represents the remaining explanatory variables.

Figure 1 shows the threshold estimation of railways' and roads' economic development level (per capita GDP). Table 9 exhibits the test results of the threshold effect. The model passed the single threshold test, and the threshold values of railways and roads were similar. All the above results were obtained after 500 times repeated sampling by Bootstrap.

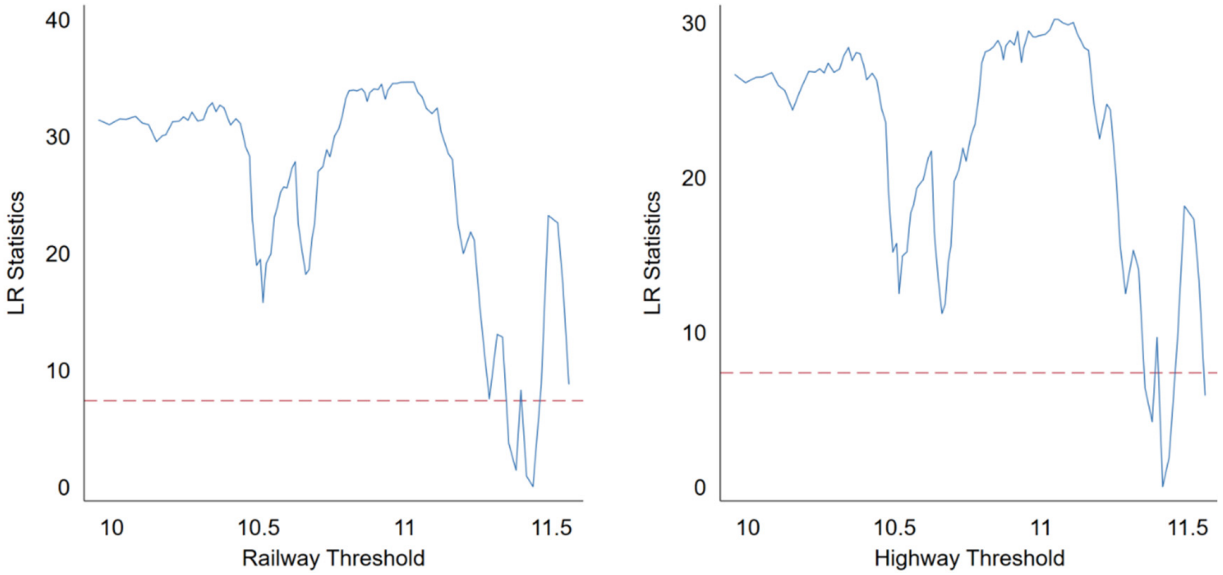


Figure 1. Threshold of economic development level.

Table 9. Test of threshold effect.

Variable	Threshold Effect Value	*p* Value	95% C.I.
Railway	11.4372	0.010	[11.4057, 11.4657]
Road	11.4153	0.018	[11.3795, 11.4372]

From the regression results in Table 10, an apparent single-threshold effect was observed in the promoting effect of transportation infrastructure on the digital economy. As seen in Column (1), the magnitude and significance level of the promoting effect of railways on the digital economy did not experience evident changes after the threshold was passed; the influence coefficient grew from 0.0027 to 0.0059, and the significance level never passed the test, being elevated to 5%. The results in Column (2) showed that after the threshold was passed, the promoting effect of roads on the digital economy increased from 0.0035 to 0.0061, and the significance level was 1% after the threshold was exceeded. Therefore, transportation infrastructure can promote the digital economy regardless of the economic development level. The promoting effect will be substantially enhanced in cities whose economic development exceeds the threshold.

Table 10. Estimation of threshold effect.

	(1)	(2)
	Railway	**Road**
Trans (GDP $\leq \gamma$)	0.0027	0.0035 **
	(0.002)	(0.001)
Trans′ (GDP $> \gamma$)	0.0059 **	0.0061 ***
	(0.003)	(0.002)
RS	−0.0028	−0.0034
	(0.007)	(0.007)

Table 10. *Cont.*

	(1)	(2)
	Railway	**Road**
HS	0.0071 **	0.0093 **
	(0.004)	(0.004)
SE	0.0115 ***	0.0140 ***
	(0.003)	(0.003)
DIG	0.0045 **	0.0057 ***
	(0.002)	(0.002)
LB	0.0176	0.0205
	(0.018)	(0.018)
EDU	−0.0011	−0.0013
	(0.002)	(0.002)
RD	0.0008	0.0010
	(0.001)	(0.001)
F test	21.62	21.10
	(0.000)	(0.000)
Observations	2290	2290
R-squared	0.087	0.085

Notes: All regressions include a constant. **, ***: significant at 5%, 1%; standard errors are clustered at the city level.

6.1.2. Dynamic Distribution of Cities

With the road threshold as the standard, Table 11 lists the dynamic distribution of cities whose economic development level was more significant than the threshold value in 2011, 2016, and 2020. In 2011, the economic development value of 12 cities was above the threshold, and the number of such cities increased to 35 in 2016 and to 49 in 2020. Judging from the distribution of provinces and cities, municipalities directly under the central government and eastern and central provinces accounted for the majority. Judging from the functions of cities, most were industrial and commercial cities, and a few were resource-based cities. It could be seen that in addition to the traditional economically developed cities, some resource-based cities in the central and western regions could also take advantage of the development of the digital economy and use transportation infrastructure to carry out industrial transformation, making the digital economy a new kinetic energy for economic development.

Table 11. Dynamic distribution of cities.

Year	Cities	Province
2011	Baotou, Ordos, Dalian, Daqing, Wuxi, Suzhou, Dongying, Guangzhou, Shenzhen, Foshan, Jiayuguan, Karamay	Inner Mongolia (2), Liaoning (1), Heilongjiang (1), Jiangsu (2), Shandong (1), Guangdong (3), Gansu (1), Xinjiang (1)
2016	Beijing, Tianjin, Hohhot, Baotou, Wuhai, Ordos, Dalian, Daqing, Shanghai, Nanjing, Wuxi, Changzhou, Suzhou, Nantong, Yangzhou, Zhenjiang, Hangzhou, Ningbo, Shaoxing, Zhoushan, Xiamen, Jinan, Qingdao, Zibo, Dongying, Yantai, Weihai, Wuhan, Changsha, Guangzhou, Shenzhen, Zhuhai, Foshan, Zhongshan, Karamay	Beijing, Tianjin, Inner Mongolia (4), Liaoning (1), Heilongjiang (1), Shanghai, Jiangsu (7), Zhejiang (4), Fujian (1), Shandong (6), Hubei (1), Hainan (1), Guangdong (5), Xinjiang (1)
2020	Beijing, Tianjin, Tangshan, Baotou, Wuhai, Ordos, Dalian, Panjin, Shanghai, Nanjing, Wuxi, Changzhou, Suzhou, Nantong, Yangzhou, Zhenjiang, Taizhou, Hangzhou, Ningbo, Jiaxing, Huzhou, Shaoxing, Zhoushan, Hefei, Wuhu, Ma 'anshan, Fuzhou, Xiamen, Sanming, Quanzhou, Longyan, Nanchang, Jinan, Qingdao, Dongying, Yantai, Weihai, Zhengzhou, Wuhan, Yichang, Ezhou, Changsha, Guangzhou, Shenzhen, Zhuhai, Foshan, Dongguan, Jiayuguan, Karamay	Beijing, Tianjin, Hebei (1), Inner Mongolia (3), Liaoning (2), Shanghai, Jiangsu (8), Zhejiang (6), Anhui (3), Fujian (5), iangxi (1), Shandong (5), Henan (1), Hubei (3), Hunan (1), Guangdong (5), Gansu (1), Xinjiang (1)

Notes: The numbers in parentheses represent the number of cities.

6.2. Permanent-Residents Population

The permanent-resident population of a city is closely related to its development level. According to the <Tabulation on 2020 China population census by county>, the 229 cities were divided into megacities, supercities, type I big cities, type II big cities, and other cities, and the fixed effect model was used to analyze their differences (Megacity: more than 10 million permanent-residents population. Supercity: permanent-residents population of 5 million to 10 million. Type I big city: permanent-residents population of 3 million to 5 million. Type II big city: permanent-residents population of 1 million to 3 million. Other city: less than 1 million permanent-residents population).

According to the regression results in Table 12, it can be found that the promoting effect of transportation infrastructure on the digital economy has significant differences in cities with different permanent-resident populations. In megacities, the effect of roads is most significant; in supercities and type I big cities, the promoting effect of the railway is more prominent. In type II cities, highways act as inhibition. Different cities have different demand and accumulation levels of transport infrastructure, which leads to the differences in the role of different transport infrastructures in developing the city's digital economy. In particular, roads in type II big cities will inhibit the development of the digital economy, which means local governments need to accelerate overall planning to improve the transportation efficiency of the road network.

Table 12. Permanent-residents population of cities.

	(1)	(2)	(3)	(4)	(5)
	Megaciy	**Supercity**	**Type I Big City**	**Type II Big City**	**Other City**
RW	−0.0236	0.1188 ***	0.0573 ***	0.0045	−0.0002
	(0.027)	(0.031)	(0.017)	(0.005)	(0.002)
HW	0.0284 **	0.0009	−0.0155	−0.0084 **	0.0025
	(0.012)	(0.018)	(0.011)	(0.003)	(0.001)
RS	0.3106	0.0743	−0.0105	−0.0040	0.0057
	(0.204)	(0.189)	(0.124)	(0.019)	(0.004)
HS	−0.0158	0.0417	−0.0163	0.0184 **	−0.0009
	(0.045)	(0.048)	(0.020)	(0.008)	(0.003)
SE	0.1570 ***	−0.0057	0.0084	−0.0143 **	0.0062 *
	(0.044)	(0.024)	(0.033)	(0.005)	(0.003)
DIG	0.1671	−0.0189	0.0193	0.0008	0.0028 *
	(0.125)	(0.042)	(0.030)	(0.003)	(0.001)
LB	−0.0211	−0.0959	−0.2339 *	0.0865	0.1151 ***
	(0.103)	(0.083)	(0.123)	(0.058)	(0.024)
EDU	−0.0563 *	−0.0038	−0.0079	0.0059	0.0042 *
	(0.033)	(0.028)	(0.017)	(0.005)	(0.002)
RD	0.1369 ***	0.0545 ***	−0.0104	0.0018	−0.0022 **
	(0.041)	(0.015)	(0.010)	(0.002)	(0.001)
Year FE	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes
Observations	70	140	140	640	1300
R-squared	0.742	0.316	0.506	0.175	0.223

Notes: All regressions include a constant. *, **, ***: significant at 10%, 5%, 1%; standard errors are clustered at the city level.

7. Conclusions

Nearly 40 years of economic take-off has caused China to leave an indelible mark in the history of human development. How to further tap into the new kinetic energy of economic development has become a top priority. The development of the digital economy is crucial to economic recovery and sustainable development. Based on this, starting from the integrated transport system, railways, roads, waterways, and civil aviation relationships with the digital economy were figured out using traffic, urban, and enterprise data. The use of city-level data in this study has certain limitations, as it does not delve into the

level of enterprise behavior to investigate how transportation infrastructure influences the development of the digital economy. While this is a regrettable aspect of the present study, it also serves as a direction for future research.

The main conclusions are as follows. First, transportation infrastructure can promote the digital economy, among which the railway plays the most significant role, followed by waterways, roads, and civil aviation successively. Second, from the industrial level of cities, it was found that transportation infrastructure mainly promotes the development of the digital economy by upgrading the industrial structure. At the enterprise level, promoting entrepreneurship and facilitating the digital transformation of enterprises have become the main driving forces for development. At the factor level, enhancing labor flow is a vital promotion mechanism. Third, there is a significant single-threshold effect in the promoting effect of transportation infrastructure on the digital economy, especially in cities whose economic development level exceeds the threshold, and the promotion of the digital economy by transportation infrastructure is more evident in cities with a permanent-resident population of more than 3 million.

The research conclusions not only enrich the research results regarding the economic effects of transportation infrastructure in the digital age but also make up for the potential shortcomings of previous studies, in which different types of transportation infrastructure were not analyzed, and provide new ideas for the government to promote the construction of transportation infrastructure. First of all, the construction of a complete modern integrated transport system should be accelerated. The 20th National Congress of the Communist Party of China (CPC) was a crucial five-year period for China to build itself into a socialist modern power in an all-round way. Facing an external environment full of risks and uncertain internal environments, how to further improve transportation infrastructure and tap into the development potential of the digital economy is a crucial link to ensuring stable economic development. Local favorable conditions should be combined to accelerate the construction of transportation infrastructure which conform to development needs, avoiding a high "sunk cost" due to repeated construction as far as possible. Meanwhile, local governments should introduce relevant policies supporting the development of the digital economy, promote the coordinated development of cities through the spatial spillover effect of the digital economy, and further dig into the market potentials of the digital economy, making it a new kinetic energy for China's economic development. Secondly, local governments should "untie" the service industry based on risk control by combining local development progress and guiding the healthy development of the service industry by improving the inter-regional differences in public welfare and building a reasonable factor price system and a perfect policy system.

Meanwhile, local governments should match the enterprises taking the lead in the digital economy with the backward enterprises through point-to-point assistance and also help backward enterprises to realize digital transformation using the experience and technologies of leading enterprises. On the other hand, by introducing entrepreneurial incentive policies, local governments should reduce the cost of trial and error for entrepreneurs, provide them with sufficient space for trial and error as well as high-quality soil for their entrepreneurial activities, and boost the development of the digital economy. Finally, measures should be adjusted according to local conditions, and the mutual strong points of cities should be learned to offset weaknesses to promote their coordinated development. Cities whose economic development level is lower than the threshold show apparent differences in factor endowment characteristics, and the intercity market barriers should be broken by perfecting the urban supply chain construction to build a development environment with rich levels and information sharing. For cities whose economic development level is above the threshold, the top priority should be given to driving the joint development of surrounding cities. Different cities should seize this opportunity, and local governments must coordinate transport infrastructure construction plans to make the digital economy a new driving force for urban development.

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Appendix A. Robustness Test

Table A1. Regression of instrumental variables.

	(1)	(2)
	Post-Cities	**Average Gradient of Cities**
HW	0.0293 ***	0.0285 ***
	(0.008)	(0.007)
RS	−0.0046	−0.0047
	(0.006)	(0.006)
HS	0.0203 ***	0.0200 ***
	(0.005)	(0.005)
SE	0.0317 ***	0.0312 ***
	(0.006)	(0.006)
DIG	0.0115 ***	0.0113 ***
	(0.002)	(0.002)
LB	0.0523	0.0516
	(0.045)	(0.044)
EDU	−0.0032	−0.0032
	(0.002)	(0.002)
RD	0.0017 *	0.0016 *
	(0.001)	(0.001)
F Test	16.48	17.54
	(0.000)	(0.000)
City FE	Yes	Yes
Observations	2290	2290
R-squared	0.861	0.860

Notes: All regressions include a constant. *, ***: significant at 10%, 1%; standard errors are clustered at the city level.

Table A2. Replacement of space matrix.

	(1)	(2)	(3)	(4)
	FE	**FE**	**FE**	**FE**
W × Eco	2.3635 ***	2.8885 ***	2.6798 ***	2.9082 ***
	(0.399)	(0.402)	(0.427)	(0.457)
RW	0.0039			
	(0.003)			
HW		0.0028 *		
		(0.002)		
WW			0.0044 **	
			(0.002)	
AP				−0.0032 *
				(0.002)

Table A2. *Cont.*

	(1)	(2)	(3)	(4)
	FE	**FE**	**FE**	**FE**
RS	−0.0005	−0.0001	0.0001	0.0002
	(0.006)	(0.006)	(0.006)	(0.006)
HS	0.0053	0.0061 *	0.0055	0.0063 *
	(0.003)	(0.003)	(0.003)	(0.003)
SE	0.0078 **	0.0087 ***	0.0076 **	0.0089 ***
	(0.003)	(0.003)	(0.003)	(0.003)
DIG	0.0024	0.0028	0.0026	0.0028
	(0.002)	(0.002)	(0.002)	(0.002)
LB	0.0273	0.0317 *	0.0285	0.0297 *
	(0.002)	(0.002)	(0.002)	(0.002)
EDU	−0.0002	−0.0001	−0.0001	0.0003
	(0.002)	(0.002)	(0.002)	(0.002)
RD	0.0004	0.0003	0.0004	0.0005
	(0.001)	(0.001)	(0.001)	(0.001)
F Test	22.79	24.69	23.82	23.08
	(0.000)	(0.000)	(0.000)	(0.000)
Observations	2290	2290	2290	2290
R-squared	0.164	0.131	0.142	0.081

Notes: All regressions include a constant. *, **, ***: significant at 10%, 5%, 1%; standard errors are clustered at the city level.

Table A3. Exclusion of municipalities directly under the central government.

	(1)	(2)	(3)	(4)
	FE	**FE**	**FE**	**FE**
W × Eco	0.6030 *	0.5004	0.5491	0.5518
	(0.328)	(0.373)	(0.368)	(0.386)
RW	0.0041 *			
	(0.002)			
HW		0.0048 ***		
		(0.002)		
WW			0.0035 **	
			(0.002)	
AP				−0.0013
				(0.002)
RS	−0.0035	−0.0039	−0.0035	−0.0038
	(0.005)	(0.005)	(0.005)	(0.005)
HS	0.0073 **	0.0094 ***	0.0074 **	0.0079 **
	(0.003)	(0.003)	(0.003)	(0.003)
SE	0.0120 ***	0.0156 ***	0.0128 ***	0.0134 ***
	(0.003)	(0.003)	(0.003)	(0.003)
DIG	0.0027 *	0.0041 **	0.0032 **	0.0033 **
	(0.002)	(0.002)	(0.002)	(0.002)
LB	0.0008	0.0071	0.0021	0.0028
	(0.002)	(0.002)	(0.002)	(0.002)
EDU	−0.0007	−0.0010	−0.0006	−0.0005
	(0.002)	(0.002)	(0.002)	(0.002)
RD	0.0004	0.0006	0.0005	0.0006
	(0.001)	(0.001)	(0.001)	(0.001)
F Test	14.54	15.15	14.59	13.79
	(0.000)	(0.000)	(0.000)	(0.000)
Observations	1990	1990	1990	1990
R-squared	0.112	0.145	0.130	0.105

Notes: All regressions include a constant. *, **, ***: significant at 10%, 5%, 1%; standard errors are clustered at the city level.

Table A4. Change in the order of spatial lag term.

	(1)	(2)	(3)	(4)
	FE	**FE**	**FE**	**FE**
W × Eco	0.9197 **	0.6275	0.6784	0.6688
	(0.387)	(0.432)	(0.425)	(0.448)
RW	0.0049 *			
	(0.002)			
HW		0.0031 *		
		(0.002)		
WW			0.0048 ***	
			(0.002)	
AP				−0.0009
				(0.002)
RS	−0.0038	−0.0043	−0.0038	−0.0042
	(0.006)	(0.006)	(0.006)	(0.006)
HS	0.0067 *	0.0084 **	0.0074 **	0.0074 **
	(0.004)	(0.004)	(0.004)	(0.004)
SE	0.0129 ***	0.0156 ***	0.0138 ***	0.0143 ***
	(0.003)	(0.003)	(0.003)	(0.003)
DIG	0.0043 **	0.0055 ***	0.0050 ***	0.0049 ***
	(0.002)	(0.002)	(0.002)	(0.002)
LB	0.0257	0.0303 *	0.0269	0.0277
	(0.002)	(0.002)	(0.002)	(0.002)
EDU	−0.0011	−0.0012	−0.0010	−0.0009
	(0.002)	(0.002)	(0.002)	(0.002)
RD	0.0011	0.0013	0.0012	0.0013
	(0.001)	(0.001)	(0.001)	(0.001)
F Test	18.56	18.13	18.68	17.77
	(0.000)	(0.000)	(0.000)	(0.000)
Observations	2290	2290	2290	2290
R-squared	0.205	0.219	0.209	0.182

Notes: All regressions include a constant. *, **, ***: significant at 10%, 5%, 1%; standard errors are clustered at the city level.

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