

Paving the Green Road: How Transportation Infrastructure Improves Corporate Energy Efficiency

Zhiyu Wei

Qixing Huang

QixingHuangxmu@163.com

Research Article

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Abstract: Transportation infrastructure serves as a critical driver of market integration and facilitates the efficient movement of production factors across regions. From a factor allocation perspective, this study investigates how transportation infrastructure construction shapes corporate energy efficiency. Empirical findings confirm that such infrastructure, particularly road networks, significantly enhances firms' energy efficiency. Key transmission mechanisms include improved factor allocation efficiency, optimized energy consumption structures, and induced technological innovation. Furthermore, the effects exhibit substantial heterogeneity depending on regional energy intensity and industrial characteristics, with more pronounced improvements observed in energy-intensive and highly industrialized areas. Additionally, infrastructure development contributes to reduced corporate pollution emissions, achieved through lower energy consumption and increased investment in pollution abatement technologies. These findings offer theoretical grounding and policy insights for optimizing transport infrastructure planning and advancing the green transformation of enterprises.

Keywords: Transportation Infrastructure Construction; Energy Efficiency; Factor Allocation

1. Introduction

24 With the acceleration of urbanization in developing countries, the transportation
25 industry has become increasingly important. The rational structuring of transportation
26 systems is a critical factor in achieving sustainable economic transformation and
27 remains a key responsibility of governments (Mężyk 2021). Convenient transportation
28 fosters the establishment and expansion of cities, while the construction of
29 transportation infrastructure plays a vital role in mitigating traffic congestion and
30 promoting regional development. Improvements in transportation facilities enhance
31 regional economic competitiveness by facilitating industrial agglomeration and
32 technological innovation, providing enterprises with a more accessible transportation
33 environment, and offering robust support for the high-quality development of
34 businesses (X. Wang et al. 2025).

35 China's transportation infrastructure has achieved remarkable progress since the
36 reform and opening-up period. In its early stages, the country's transportation system
37 was relatively underdeveloped: railway transport dominated for a long time, the road
38 network was of poor quality and limited coverage, and both ports and airports operated
39 on a small scale. Development across different transportation modes remained
40 fragmented and severely constrained. With rapid economic growth, China significantly
41 increased investment in transportation, gradually expanding infrastructure to meet the
42 demands of industrialization and foreign trade. The highway network began to take
43 shape, railways were upgraded for higher speeds, coastal ports were expanded, and the
44 construction of civil aviation airports accelerated. As a result, the scale and quality of
45 China's ground transportation network have grown dramatically. This network has not
46 only shaped the spatial distribution of economic activities but has also profoundly
47 influenced urbanization patterns, productivity, geographic mobility, trade flows, and
48 pricing (Davis et al. 2025a). The travel mode that combines multiple transportation
49 methods is regarded as a sustainable urban transportation solution(Huang and Ma 2026).
50 China has also made breakthrough achievements in transportation infrastructure. Its
51 operating mileage of high-speed rail, expressways, and urban rail transit ranks first

worldwide. A modern integrated transportation system has taken initial shape, providing significant momentum for rapid economic development. The main framework of the national comprehensive three-dimensional transportation network comprising the “six axes, seven corridors, and eight channels” is over 90% complete, substantially enhancing overall capacity, operational efficiency, and service quality. In 2019, China issued the Outline of Building a Strong Transportation Nation, which set forth the goal of establishing a unified, open, and competitively structured modern transportation market system, and largely completing China’s transformation into a global transportation power with three transportation networks and two transportation circles by 2035.

Transportation infrastructure provides conditions for regional integration, thereby enhancing energy efficiency and promoting economic growth(Hu et al. 2023; Zheng et al. 2025). Closely linked to business operations, transportation is also a key determinant of the sustainable development of enterprises. The optimization of transportation conditions can promote the free flow of production factors and enhance enterprise productivity, which has become a critical issue in China’s pursuit of high-quality economic development. The construction of transportation infrastructure helps dismantle administrative barriers and natural market divisions created by geographic constraints, enabling resource sharing and the interconnection of factors across regions. This process fosters broader market integration. In the context of building a unified national market, the expansion of transportation networks accelerates the cross-regional flow of labor, capital, technology, and other factors by improving regional accessibility and spatial connectivity. These improvements promote the reorganization of production factors, alleviate resource misallocation, and enhance the efficiency of resource allocation (Cao and Su 2024). Through this transformation, China’s growth model is shifting from an extensive pattern driven primarily by factor inputs to an intensive model driven by new forms of production factors.

79 With the continuous growth of the global economy and energy demand, improving
80 energy efficiency has become a central priority for governments and scholars
81 worldwide. During the early stages of China’s industrial development, the extensive
82 model of economic growth led to severe problems of environmental pollution and
83 energy shortages. The report of the 20th National Congress of the Communist Party of
84 China underscored the critical task of “accelerating the green transformation of
85 development models.” In recent years, the Chinese government has advanced into a
86 stage of green development, where improving energy efficiency has received
87 widespread attention as a key pathway to achieving low-carbon and sustainable growth
88 (Cai et al. 2019). China has now entered a crucial period in its effort to reach carbon
89 peaking. The 14th Five-Year Plan for the Modern Energy System sets a target of
90 reducing energy consumption per unit of GDP by 13.5% by 2025 compared with the
91 level in 2020.

92 Energy efficiency serves as a driving force for economic growth (Yu et al. 2018).
93 Improving energy efficiency is regarded as an important means for enterprises to
94 achieve sustainable development and enhance competitiveness, as it can lead to
95 significant cost savings and improved profitability (Bensouda et al. 2024). In fact, as a
96 crucial vehicle for the spatial flow of production factors, transportation infrastructure
97 has played a decisive role in promoting economic growth, facilitating regional resource
98 integration, and fostering coordinated development over more than forty years since the
99 reform and opening-up. With the continuous improvement of China’s transportation
100 infrastructure, trade costs have been substantially reduced, thereby improving the
101 access of inland regions to international markets and amplifying the welfare gain (Y.
102 Xu and Yang 2021). Against the backdrop of accelerating the establishment of a unified
103 domestic market, transportation infrastructure serves as a critical support for removing
104 regional barriers and promoting the free flow of production factors, which provides
105 significant development opportunities for enterprises.

In view of the high costs associated with transportation infrastructure construction and the pressing need for Chinese enterprises to improve energy efficiency, conducting an in-depth analysis of the relationship between the two and the underlying mechanisms is of great significance for optimizing resource allocation across space and advancing high-quality economic development.

The academic literature on the economic effects of transportation infrastructure construction can generally be divided into two categories. One stream of research examines the impact of transportation infrastructure on macroeconomic development. Scholars argue that transportation infrastructure construction can stimulate economic growth by promoting market integration, facilitating trade, attracting investment, and enhancing the flow and allocation of production factors and resources (Banerjee et al. 2020; S. Chen et al. 2024; Mohmand et al. 2021; Nenavath 2021). Different transportation modes interact with each other, exhibiting synergistic effects in terms of economic efficiency between railways and highways, and substitution effects in terms of ecological efficiency (Yaqin Jiang et al. 2025). As research has deepened, some scholars have pointed out that transportation infrastructure exhibits network externalities, and its effect on promoting economic growth depends on connectivity, thereby showing a non-linear relationship with economic growth (Deng 2013). Transportation infrastructure reshapes the spatial allocation of resources and production factors, exerting regionally heterogeneous effects on macroeconomic growth (Bernard et al. 2019). Specifically, it makes a significant positive contribution to the economic growth of large cities, while having no notable impact on small and medium cities, thereby exacerbating China's economic disparities (Jin et al. 2020).

Another stream of literature investigates the impact of transportation infrastructure construction on total factor productivity. Some scholars, taking the National Trunk Highway System as a quasi-natural experiment, find that the improvement of transportation infrastructure can facilitate the flow of production factors across regions and the division of labor among enterprises, thereby enhancing total factor productivity

(M. Xu and Feng 2022). From the perspective of firm distribution, highway construction enhances firms' total factor productivity by diverting the economic activities of land-intensive industries from node regions to non-node regions. In high-income and upper-middle-income countries, road construction exerts negative effects on economic growth and unemployment, whereas road density has a positive impact on total factor productivity (Laborda and Sotelsek 2019). In terms of environmental consequences, the construction of transportation infrastructure can reduce the total amount of carbon emissions by enhancing the carbon emission efficiency of fossil energy used by enterprises (Su et al. 2025). In addition, some scholars have extended the scope of research to green total factor productivity. Previous studies have shown that the synergy between green the finance and fintech, low-carbon transportation and green finance can enhance green energy efficiency (J. Wang et al. 2024; J. Zhang and Sun 2025). Furthermore, there is evidence suggesting that energy audits and energy management systems are the key tools for enhancing the energy efficiency of enterprises (Toro et al. 2025). Credit constraints restrict the improvement of enterprises' energy efficiency (D. Zhang et al. 2025). Low-carbon city pilot projects can enhance energy efficiency (Niu et al. 2023).

Although the macroeconomic benefits and social impacts of surface transportation networks have received widespread attention, their effects on enterprises' energy efficiency at the micro level have been scarcely examined. The limited number of existing studies has nonetheless acknowledged the relationship between transportation infrastructure construction and energy efficiency. Scholars have found that the construction of urban road infrastructure can improve enterprises' energy efficiency (Z. Du et al. 2024). However, from a holistic perspective, no study has yet incorporated different types of transportation modes into an integrated analytical framework.

In terms of measuring energy efficiency, the assessment of total factor energy efficiency has also been widely applied with the main approaches including DEA and the Malmquist Productivity Index method at the macro level (K. Du and Lin 2017;

Durrani et al. 2025; Yuchen Jiang et al. 2025; Jing et al. 2025). In existing studies, scholars typically measure enterprises' energy efficiency by using either the total output value per unit of energy consumption or the total energy consumption per unit of output value (Z. Du and Hao 2025; Qi et al. 2023; Tang and Xu 2025). Du et al. (2025) innovatively estimate enterprises' energy efficiency using the order- α method.

Energy substitution is an important topic in energy economics research, which can be categorized into internal substitution and external substitution. The former primarily refers to the optimization of the energy structure, while the latter concerns the efficient allocation of social resources, including energy, capital, and labor. In terms of factor substitution, since Berndt and Wood (1975) raised the issue of capital substituting for energy, the question of energy substitution has attracted widespread attention from scholars. At present, capital occupies an absolutely central position and the substitution effects of either energy or labor for capital are not significant (Z. Zhang and Lin 2018). In addition, the substitution potential between labor and energy is relatively higher than that between capital and energy (Wesseh et al. 2013). Evidence suggests that approximately 45.77% of the variation in carbon intensity can be attributed to the substitution of capital for energy and labor for energy (K. Liu et al. 2018). The overall negative rate of change in the labor–energy substitution elasticity and the overall positive rate of change in the capital–energy substitution elasticity are the core factors driving the fluctuations in the rate of change of energy productivity (Q. Wang et al. 2017).

The potential marginal contributions of this paper are as follows. First, adopting a micro-level perspective, this study investigates the heterogeneous effects of various types of transportation infrastructure on energy efficiency, thereby broadening the research perspective on the impacts of transportation infrastructure. Second, from the viewpoint of factor allocation, this paper systematically examines the mechanisms through which transportation infrastructure influences enterprises' energy efficiency, including improving the structure of factor allocation, optimizing the energy structure,

and promoting technological innovation. This contributes to a more comprehensive understanding of the pathways through which transportation infrastructure affects energy efficiency and provides empirical evidence for clarifying the mechanism by which transportation empowers energy efficiency. Third, this study employs the order- α method to estimate enterprises' energy efficiency. Compared with traditional approaches, the order- α method is better suited for firm-level estimation, as it can account for cross-sector technological heterogeneity, thus more accurately reflecting real production conditions. In contrast to the commonly used partial efficiency indicators in the existing literatures such as ratios of energy to output or other inputs, the order- α approach offers a more robust measure. Fourth, this paper evaluates the environmental benefits of transportation infrastructure in enhancing enterprises' energy efficiency by systematically examining its role in controlling pollution emissions and the underlying mechanisms.

The remainder of this paper is organized as follows. Section 2 presents the research data, Section 3 introduces the research model, Section 4 reports the main empirical results, and Section 5 provides the conclusions and policy implications.

2. Data description

2.1. Transportation infrastructure

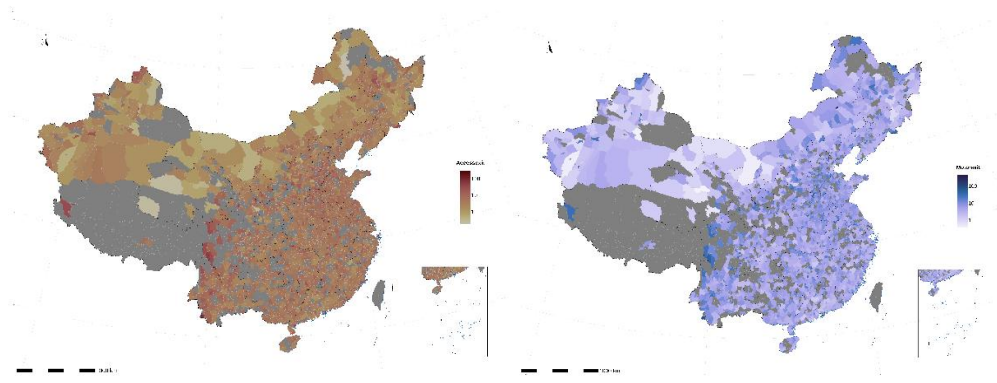
2.1.1. Measurement method

Drawing on the study of Davis et al. (2025), this paper measures comprehensive transportation level (*accessexit1*) by the number of accessible exits of all transportation modes within a county; road transportation level (*motorexit*) by the number of accessible road exits; railway transportation level (*railstation*) by the number of railway stations; high-speed rail transportation level (*highroute*) by the number of high-speed rail lines; and waterway transportation level (*waterroute*) by the number of navigable water routes.

Previous studies on transportation in China have often focused on a single mode of transport or on relatively short time periods, and have lacked information on transportation access points. The database employed in this study represents the most comprehensive and longest-spanning GIS database on surface transportation in China to date. Specifically, the database integrates OpenStreetMap digital maps with digitized information from historical paper maps through a multi-source data fusion approach. It further undergoes rigorous topological correction and speed attribute annotation, thereby systematically documenting the annual changes in various types of surface transportation networks in China from 1993 to 2020. This innovative approach to data construction not only significantly enhances the precision and reliability of the dataset but also ensures spatiotemporal consistency, resulting in a refined GIS database that covers multiple transportation modes over a long time span. The database further distinguishes between transportation routes and actual access points, providing critical support for accurately assessing the effective accessibility of transportation networks and serving as an essential foundation for this study.

2.1.2. Basic information

The database reveals a remarkable expansion of China's transportation networks between 1993 and 2020, with the total national network length increasing from 184,000 kilometers to 563,000 kilometers. Fig. 1 (a) and 1(b) illustrate the construction of overall transportation infrastructure and road transportation infrastructure in China, respectively. As shown in Fig. 1, transportation infrastructure is most developed in the eastern coastal regions, particularly in the Yangtze River Delta, the Pearl River Delta, and the Beijing–Tianjin–Hebei region, where transportation exits are dense with high accessibility and intercity linkages are close, and the overall level of infrastructure development is advanced. By contrast, transportation infrastructure in the central region remains at a moderate level, while in the western region, complex geographical conditions have resulted in relatively weaker transportation infrastructure.



(a) Overall transportation infrastructure (b) Road transportation infrastructure

Fig. 1. Transportation infrastructure development in China in 2020

2.2. Energy efficiency

2.2.1. Measurement method

Existing literature commonly measures energy efficiency using energy consumption per unit of industrial output. However, this indicator fails to account for technological heterogeneity across industries, making direct comparisons between different sectors less meaningful. Moreover, when the relative price of energy changes compared with other inputs, some indicators may fluctuate due to factor substitution, even if actual energy efficiency remains unchanged (K. Du et al. 2025). We follow Tauchmann (2012) and employ the partial frontier analysis method, order- α , to estimate enterprises' energy efficiency. The order- α approach identifies comparable peers and measures the distance between a firm and the efficiency frontier, thereby providing a more objective assessment of energy efficiency while effectively avoiding the drawbacks of single-factor energy efficiency evaluations. Compared with Data Envelopment Analysis (DEA) or the Stochastic Frontier Approach (SFA), this method also alleviates concerns about measurement errors arising from firm-level outputs. As for enterprises' energy inputs including coal consumption, fuel oil consumption, and natural gas consumption. We convert them into standard coal equivalents using standard conversion coefficients.

2.2.2 Basic information

To better evaluate the changing trends in enterprises' energy efficiency, we calculate the annual average energy efficiency of firms nationwide as well as across the eastern, central, and western regions, and plot the temporal trends of energy efficiency. As shown in Fig. 2, energy efficiency nationwide exhibits a certain degree of fluctuation but demonstrates an overall upward trajectory over time. In particular, since the promulgation of the new Environmental Protection Law in 2015, stricter regulations on enterprises' production activities have led to a marked improvement in energy efficiency, which reached its peak of 0.293 in 2020. The eastern region demonstrates relatively high stability and growth potential in terms of energy efficiency. The central region has shown strong growth momentum since 2015, gradually catching up with the east. By contrast, the western region maintains a relatively low overall level of energy efficiency, accompanied by substantial volatility.

In Fig. 3, we compare the energy efficiency of firms with different levels of energy consumption, pollution intensity, energy intensity, and marketization, in order to better assess the heterogeneity of energy efficiency across firm types. Specifically, firms characterized by low energy consumption, non-heavy pollution, low energy intensity, and location in regions with a higher level of marketization exhibit relatively higher energy efficiency.

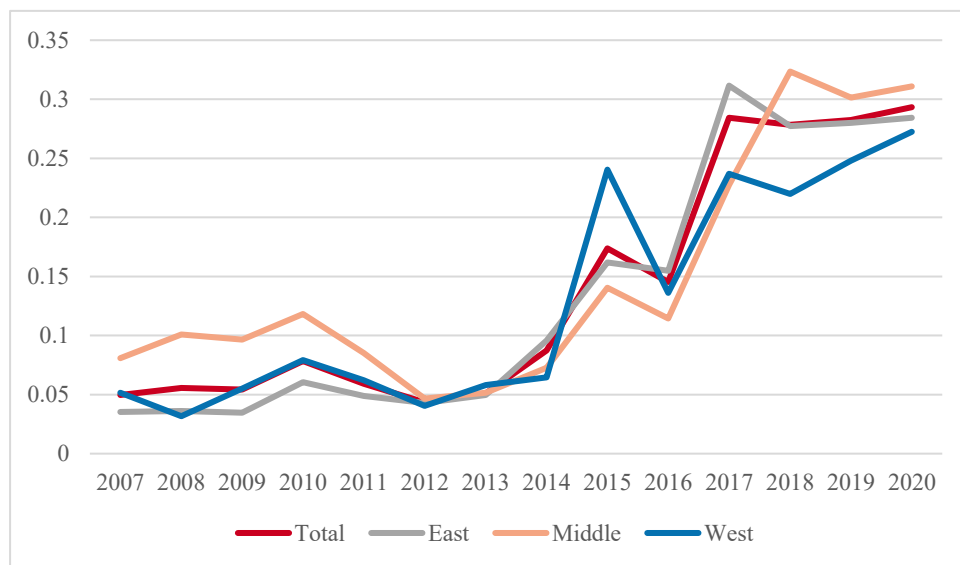


Fig. 2. Temporal trends of enterprises' energy efficiency in China over 2007-

2020

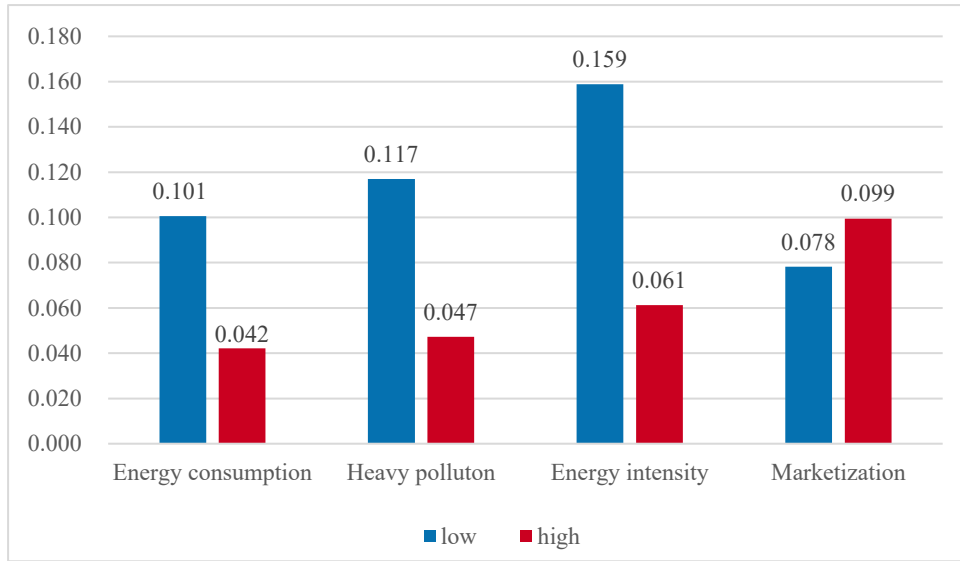


Fig. 3. Energy efficiency of different types of firms in China

2.3. Supplementary data

We also obtained supplementary data for analysis. The city-level characteristics mainly include regional GDP and the shares of the secondary and tertiary industries in regional GDP, which are drawn from the China City Statistical Yearbook and local statistical bureaus. The frequency of environment-related terms collected from municipal government work reports is used to measure the intensity of environmental regulation. Firm-level control variables are obtained from the National Tax Survey data.

In addition, for the mechanism analysis, we measure firms' capital input by their year-end total assets, labor input by the average annual number of employees, and energy input by total energy consumption. The energy structure is measured by the share of coal consumption. Firms' technological innovation level is measured by innovation investment per unit of energy consumption.

This paper conducts the basic processing of the sample data through the following steps: first, excluding samples with severe missing values in key variables; and second,

winsorizing all continuous variables at the 1% level in both tails. Table 1 reports the summary statistics of the variables.

309

Table 1

Descriptive statistics.

Variable	N	Mean	p50	SD	Min	Max
Panel A: firm-level variables						
<i>Efficiency</i>	1884000	0.0910	0	0.252	0	1
<i>Efficiency_order95</i>	1884000	0.0910	0	0.252	0	1
<i>Size</i>	1884000	10.15	10.07	2.131	5.384	16.32
<i>Roa</i>	1883000	0.0200	0.00700	3.436	-281.0	1606
<i>Capital</i>	1875000	0.247	0.187	0.572	0	534.2
<i>Lev</i>	1884000	0.687	0.656	6.772	0	5582
<i>Staff</i>	1493000	4.087	4.043	1.610	1.099	8.988
<i>Cashflow</i>	1875000	0.0540	0	3.074	-374.8	1423
<i>ATO</i>	1882000	1.724	0.938	24.91	0	16895
<i>Energy_comsuption</i>	1884000	6762	5.715	41366	0	361633
<i>Capital_energy</i>	1762000	1559	1.013	122293	0	81880000
<i>Labour_energy</i>	1762000	1.112	0.00200	63.14	0	46455.000
<i>Coal</i>	1884000	0.230	0	0.378	0	1
<i>NOx</i>	459753	1025	0	85242	-848059	33090000
<i>SO2</i>	461421	2906	0	697852	0	274700000
<i>Patent</i>	1089000	49613	0	1564000	0	178100000
<i>Intensity</i>	1830000	0.037	0	0.203	0	9.663
Panel B: City-level variables						
<i>RealGDP</i>	1576000	4089	2616	4328	61.84	32733
<i>Industry</i>	1570000	1.243	1.191	0.540	0.0740	10.60
<i>Environment</i>	1506000	0.005	0.005	0.002	0	0.0200
<i>Terrain_variety</i>	1519000	269.2	128	387.2	2	5791
Panel C: County-level variables						
<i>Accessexit1</i>	1519000	11311	5807	43210	199.6	2762000
<i>Motorexit</i>	1519000	18327	7562	70797	739.4	2762000
<i>Railstation</i>	1513000	14642	8418	30554	199.6	1325000
<i>Highroute</i>	1519000	9128	5492	12427	13.85	304255
<i>Waterroute</i>	1519000	84288	12561	290057	12.80	2595000
<i>Accessexit2</i>	1519000	10602	4529	43570	98.83	2769000

312

3. Empirical model and methodology

To examine the impact of transportation infrastructure construction on firms' energy efficiency, this paper constructs the following two-way fixed effects model.

$$Y_{it} = \beta intra_{kt} + \alpha \sum X_{it} + \gamma \sum Z_{ct} + \delta_i + \mu_t + \varepsilon_{it} \quad (1)$$

Here, the subscripts i , c , k , and t denote firm, city, county, and year, respectively. Y_{it} represents the energy efficiency of firm i in year t , measured by energy consumption per unit of output. $intra_{kt}$ denotes the level of transportation infrastructure construction in the county where the firm is located. All continuous variables are log-transformed. The coefficient of primary interest in this study is β which is expected to be positive according to the theoretical discussion above.

To mitigate omitted variable bias in the econometric model, the control variables included in this paper are divided into firm-level and city-level controls. X denotes a set of firm-level control variables, including firm size (*Size*), return on assets (*Roa*), fixed asset ratio (*Capital*), asset turnover (*ATO*), leverage (*Lev*), number of employees (*Staff*), and cash flow ratio (*Cashflow*). Z denotes a set of city-level control variables, including real GDP (*RealGDP*), industrial structure (*Industry_structure*), and environmental regulation (*Environment*). δ_i and μ_t represent firm fixed effects and year fixed effects, respectively, while ε_{it} is the error term. Standard errors are clustered at the county level.

4. Results and discussion

4.1. Baseline regression

The regression results of transportation infrastructure construction on enterprises' energy efficiency are presented in Table 2. Column (1) reports the regression of comprehensive transportation infrastructure on enterprises' energy efficiency. The results indicate that the construction of transportation infrastructure significantly

promotes enterprises' energy efficiency. The estimated coefficient of $\ln_accessit1$ is 0.009. Given that the mean value of Efficiency is 0.091, this implies that a one-unit increase in the level of transportation infrastructure leads to an approximately 9.89% improvement in enterprises' energy efficiency.

The regression result in Column (2) is significantly positive, indicating that road construction markedly enhances enterprises' energy efficiency. In contrast, the results in Columns (3)-(5) suggest that the construction of conventional railways, high-speed railways, and waterways does not exert a significant effect on enterprises' energy efficiency.

Highways, as the most fundamental and widely spread modern transportation infrastructure, play a crucial role in efficiently connecting various modes of transportation and enhancing the overall efficiency of the transportation network. They hold an irreplaceable position within the integrated transportation system. According to the "2024 Statistical Bulletin on the Development of the Transportation Industry" published by the Ministry of Transport, by the end of 2024, the total length of highways in China has reached 5.49 million kilometers, with an increase of 1.12 million kilometers over the past 10 years. In 2024, highways handled a total of 418.8 billion tons of commercial freight, accounting for 73.6% of the country's total commercial freight volume.

The construction and operation of highways have had a profound impact on regional economic and social development. Compared with other modes of transportation, road transport offers greater flexibility, convenience, and widespread coverage, making it the primary mode of transportation. Road transport provides "door-to-door" services, offers flexible scheduling, accommodates small shipment volumes, and can operate on various types of roads, thereby covering a broad service area. Economically, road transport has low initial investment, minimal risk, and strong adaptability. Furthermore, the continuity of road transport ensures the smoothness of the transportation process, reduces the need for transshipment, and allows for stable,

round-the-clock operation, unaffected by natural conditions. Given that road transport holds a dominant share of freight volume in Chinese enterprises, it is more effective than other forms of transportation in improving the energy efficiency of enterprises.

Table 2

Baseline regression.

Variable	(1)	(2)	(3)	(4)	(5)
	<i>ln_accessexit1</i>	<i>ln_motorexit</i>	<i>ln_railstation</i>	<i>ln_highroute</i>	<i>ln_waterroute</i>
<i>Efficiency</i>	0.0094*** (0.0034)	0.0064** (0.0027)	-0.0007 (0.0027)	0.0016 (0.0017)	0.0003 (0.0030)
Company FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes
r2_a	0.4277	0.4277	0.4277	0.4277	0.4277
N	932984	932984	932984	932984	932984

Notes: Standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Variables listed in the row headers represent the explanatory variables, while those in the column headers represent the dependent variables.

4.2. Robustness tests

4.2.1. Replace the explanatory variables

To ensure the robustness of variable measurements, this paper replaces the traffic infrastructure construction indicators calculated at the postal region level with those calculated at the administrative region level. As shown in Column (1) of Table 3, the regression results after the replacement still indicate that traffic infrastructure construction significantly contributes to the improvement of corporate energy efficiency.

4.2.2. Change the clustering hierarchy

To avoid selection bias in the clustering hierarchy, this paper adjusts the clustering level from the district and county level to the city level. As shown in Column (2) of Table 3, after this adjustment, the baseline conclusion of the paper remains robust.

4.2.3. Exclude special years

Due to the significant impact of the major public health event in 2020 on the normal operations of enterprises, this paper excludes the data from 2020 and re-conducts the regression to ensure the accuracy and reliability of the research results. As shown in Column (3) of Table 3, the core explanatory variables remain positively significant.

4.2.4. Exclude the samples of directly administered municipalities

Due to the important political and economic status of directly administered municipalities, as well as their more developed transportation infrastructure, this paper excludes the data from Beijing, Shanghai, Tianjin, and Chongqing and re-conducts the regression. As shown in Column (4) of Table 3, the results remain robust.

4.2.5. Replace the dependent variable

This paper calculates energy efficiency using the 95th percentile and performs robustness checks by using alternative percentiles to address outliers. As shown in Column (5) of Table 3, after these adjustments, the baseline conclusion of the paper remains robust.

4.2.6. Instrumental Variables Method

To address the endogeneity issue, we construct an interaction term by multiplying terrain richness with the national average level of transportation infrastructure, which is used as an instrumental variable. Column (1) of Table 4 presents the results of the first-stage analysis using the Two-Stage Least Squares (2SLS) method. The Kleibergen-Paap rk LM statistic rejects the null hypothesis at the 1% significance level, indicating that the instrumental variable satisfies the identification condition. Moreover, the Kleibergen-Paap Wald rk F statistic passes the weak instrument test with a value exceeding the 10% critical threshold. The first-stage regression shows that the instrumental variable is significantly correlated with regional transportation infrastructure, satisfying the relevance test. As shown in Column (2) of Table 4, the coefficient of the core explanatory variable in the second-stage regression is

416 significantly positive, indicating that the promoting effect remains valid after
 417 addressing endogeneity.

418

419 **Table 3**

420 Robustness tests.

Variable	(1)	(2)	(3)	(4)	(5)
	<i>Efficiency</i>	<i>Efficiency</i>	<i>Efficiency</i>	<i>Efficiency</i>	<i>Efficiency</i>
<i>ln_accessexit2</i>	0.0058** (0.0024)				
<i>ln_accessexit1</i>		0.0094** (0.0038)	0.0093*** (0.0034)	0.0086** (0.0036)	0.0094*** (0.0034)
Company FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes
r2_a	0.4277	0.4277	0.4207	0.4313	0.4277
N	932984	932984	924034	842453	932984

421 Notes: Standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

422

423 **Table 4**

424 Instrumental Variables Method.

Variable	(1)	(2)
	<i>ln_motorexit</i>	<i>Efficiency</i>
<i>Terrain_variety</i>	0.0495*** (0.0026)	
<i>ln_motorexit</i>		0.0175** (0.0080)
Company FE	Yes	Yes
Year FE	Yes	Yes
Controls	Yes	Yes
Kleibergen-Paap rk LM (P value)	224.0730 (0.0000)	
Kleibergen-Paap Wald rk F	358.0432	

[critical value]	[16.3800]	
N	932984	932984

Notes: The same as table 3.

4.3. Mechanism Analysis

So far, we have demonstrated that the construction of transportation infrastructure enhances the energy efficiency of enterprises. However, the factors driving this improvement in energy efficiency remain uncertain. Here, we explore several possible mechanisms, including the improvement of factor structure, optimization of energy structure, and promotion of technological innovation.

The optimization of factor structure is not only an important source of economic growth but also plays a crucial role in enhancing energy efficiency. Enterprises serve as key carriers for the flow and allocation of factors, where labor, capital, and energy interact and can substitute for each other in the production process. The different configurations of these three factors can, to some extent, influence the energy efficiency of enterprises. In economic production, substituting energy with production factors such as capital has a significant impact on improving energy efficiency. It is an essential pathway for sustainable economic development and the establishment of long-term energy-saving and emission reduction mechanisms (Yang et al. 2011). In the operation of a market economy, the flow of production factors follows the law guided by marginal productivity, where factors move from less efficient areas to more efficient ones in order to achieve optimal resource allocation and maximize benefits. This process reflects the profit-seeking nature of production factors. When the acquisition cost of production factors is too high, it restricts the expansion and high-quality development of enterprises. Reducing the costs of output delivery and input procurement helps enterprises expand markets and promote consumption (Y. Wang 2022). According to the factor market substitution theory, price is a key driving factor for the substitution of production factors. When the input costs of production factors change, rational

producers tend to substitute expensive production factors with relatively cheaper ones, given the existing technological conditions.

The spontaneous adjustment of market mechanisms is not omnipotent. Market segmentation has long been a key factor restricting the efficient allocation of resources and the smooth circulation of markets. The construction of transportation infrastructure effectively breaks down long-standing market segmentation, promotes market integration, and fosters a healthy industrial ecosystem. Comprehensive transportation infrastructure breaks down geographical boundaries and industry barriers between regions, allowing the market to play a decisive role in resource allocation. This enables the better cross-regional configuration and optimization of production factors such as labor, capital, energy, and technology. The construction of transportation infrastructure effectively addresses issues of resource misallocation in enterprises and plays a fundamental and strategic role in the process of factor structure adjustment (Mengyu et al. 2023). A well-developed transportation network enables the seamless connection of different combinations of production factors across the production-to-consumption chain, significantly improving the efficiency with which enterprises acquire production factors. As transportation infrastructure improves, the market mechanism can function more effectively, achieving a Pareto improvement in resource allocation.

At present, China's regional factor markets lag significantly behind product markets, which exacerbates distortions in factor prices, reduces the efficiency of factor allocation, and has resulted in a dual crisis of overcapacity and energy shortages Liu. Transportation has significantly improved the accessibility of cities, altering the flow patterns of capital and labor (Z. Chen et al. 2023). Enterprises are able to more freely choose the optimal allocation of production factors, providing strong support for improving energy efficiency. The construction of transportation infrastructure has improved the transportation conditions along the line, creating a favorable investment environment and promoting capital flow. According to production theory, the use of energy-saving technologies can be reflected through the capital substitution effect for

energy (Stern and others 2004). When capital and energy exhibit a substitutive relationship, under given technological conditions, increased capital investment helps achieve energy-saving policy objectives. Convenient transportation improves the operational efficiency and competitiveness of cities, providing a channel for the flow of high-tech human capital. This attracts more talent, driving the substitution of energy by human capital in turn.

The long-standing high transportation costs have been a major obstacle to the widespread adoption of clean energy. Excessive energy transportation costs lead enterprises to overly rely on local energy resources, limiting their ability to procure and utilize high-quality energy from distant sources. The optimization of regional transportation networks improves the accessibility of enterprises, resulting in a significant cost-reduction effect (Shirley and Winston 2004). With the continuous improvement of transportation networks, efficient connections between transportation modes such as railways, highways, and maritime transport have significantly enhanced the flexibility and convenience of energy procurement and transportation for enterprises. As the transportation costs of clean energy continue to decrease, enterprises' reliance on traditional energy sources such as coal can be reduced, thereby lowering energy consumption (Lee et al. 2023). Firms are able to choose energy supply sources with greater flexibility, leading to a more diversified composition of energy consumption. With the widespread adoption of clean energy, the energy structure of firms has been further optimized, effectively alleviating energy misallocation and thereby creating favorable conditions for improving energy efficiency (X. Liu et al. 2025).

Existing evidence indicates that promoting technological innovation can significantly improve energy efficiency(Wu et al. 2024; Xiao et al. 2025). Production technology is essentially tacit knowledge, which is difficult to transfer between different locations (Teece 1977). Transportation infrastructure expands the scope for enterprises to search for and match innovative factors, broadening their reach from limited internal spaces to more distant external innovation actors, thereby accelerating

knowledge spillover (Agrawal et al. 2017). With the improvement of transportation networks, the flow of technological factors becomes smoother, enabling enterprises to collaborate more efficiently with other companies or technical institutions. Technological innovation can enhance energy efficiency through technology adoption and independent innovation (R. Zhang and Fu 2022). Enterprises can quickly absorb advanced external technologies through technology adoption, reducing innovation risks and costs. On the other hand, independent innovation enables enterprises to develop core technologies with independent intellectual property, enhancing their long-term competitiveness (Shao and Wang 2022). These two approaches complement and promote each other, jointly improving existing energy production and utilization methods, thereby driving the improvement of energy efficiency.

Subsequently, we empirically examine how the construction of transportation infrastructure contributes to improving corporate energy efficiency by stimulating the adjustment of factor structure, energy combination, and technological innovation effects.

4.3.1. Adjust factor structure

In this section, we explore whether the construction of transportation infrastructure enhances corporate energy efficiency by improving the factor structure. Due to the legacy of the planned economy era, significant misallocation problems persist across regions and industries in China, primarily manifested in capital misallocation and labor misallocation (Hao et al. 2020). Traditional economic theory typically assumes that the flow of production factors across geographical spaces occurs instantaneously, and therefore does not consider any transportation costs for these factors. However, in reality, the transportation costs of production factors cannot be zero. The improvement of transportation conditions creates favorable conditions for the movement of production factors, enabling smoother flow. The development of transportation infrastructure breaks regional barriers, promotes regional integration, and makes the flow of capital and labor more convenient, creating favorable conditions for energy substitution. The reduction in capital and labor input costs strengthens the

substitutability for energy factors. When enterprises face high energy costs, they tend to adopt energy-efficient production methods, increasing the input of other production factors, such as capital and labor, to reduce reliance on energy. As shown in Columns (1) and (2) of Table 5, the construction of transportation infrastructure has facilitated the substitution of energy factors with capital and labor, improving the configuration of factor structure.

4.3.2. Adjust energy structure

This section explores whether the construction of transportation infrastructure enhances energy efficiency by optimizing the energy structure of enterprises. Energy input distortion refers to the situation where enterprises become overly dependent on certain energy sources due to factors such as high energy transportation costs, price opacity, or imperfect markets, while neglecting more sustainable and environmentally friendly alternatives.

China's energy structure has been dominated by coal for a long time, with coal accounting for approximately 55.3% of primary energy consumption in 2024. Currently, China is promoting the transition from traditional energy sources to clean energy, gradually reducing its dependence on fossil fuels. This shift aims to lower energy consumption while reducing environmental pollution, and the energy structure is showing a trend of diversification.

With the optimization of transportation networks, long-distance transportation has become more efficient, allowing higher-quality energy resources, such as coal, to flow to enterprises at lower transportation costs, effectively replacing lower-quality local energy. The improvement of transportation infrastructure not only reduces the transportation costs of fossil fuels but also creates conditions for the promotion and utilization of clean energy. Previously, influenced by the differences in the distribution of energy resources and the limitations of transportation accessibility, enterprises' energy structure has predominantly relied on coal. This paper measures the energy structure of enterprises by the proportion of coal consumption in total energy

consumption. The regression results, as shown in Column (3) of Table 5, indicate that the construction of transportation infrastructure significantly reduces the proportion of coal consumption in enterprises, thereby optimizing the energy structure.

4.3.3. Promote technological innovation

This paper further examines the role of transportation infrastructure construction in promoting technological innovation. Technological innovation is measured by the logarithm of the sum of average external research and development and technical service expenses along with other intangible assets per unit of energy consumption. As shown in Column (4) of Table 5, the regression results indicate that the construction of transportation infrastructure significantly enhances the level of technological innovation in enterprises.

Table 5

Mechanism Analysis.

Variable	(1) <i>Capital_energy</i>	(2) <i>Labour_energy</i>	(3) <i>Coal_p</i>	(4) <i>ln_Patent</i>
<i>ln_accessexit1</i>	0.1310*** (0.0419)	0.0224*** (0.0078)	-0.0140*** (0.0054)	0.0900** (0.0378)
Company FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes
r2_a	0.5094	0.3108	0.6229	0.2702
N	800026	800026	932984	693123

Notes: The same as table 3.

4.4. Heterogeneity analysis

4.4.1. Energy intensity

The construction of transportation infrastructure can increase the energy consumption and output of energy-intensive industries in China (Tan et al. 2018). On this basis, we further explore the heterogeneous impact of transportation infrastructure construction on enterprises with different levels of energy intensity. Energy-intensive enterprises typically require large amounts of energy resources to support their

production activities. These enterprises' production methods heavily rely on the continuous supply of energy and its low-cost acquisition, making them more sensitive to energy supply. In this context, the availability of energy and transportation costs become key factors influencing the competitiveness of enterprises.

When firms are influenced by climate change considerations in formulating their business and/or financial strategies, they are more likely to achieve breakthroughs in optimizing energy efficiency (Nguyen 2024). The convenience of transportation directly impacts the efficiency and cost of energy transportation. With the improvement of transportation networks, high-quality energy resources can be more easily transported from production areas to demand areas. This not only reduces the transportation costs of energy but also ensures the stability and sustainability of energy supply, allowing energy-intensive enterprises to acquire the energy they need at lower costs, thereby improving energy utilization efficiency. This paper measures the energy intensity of enterprises by the energy consumption per unit of economic output. The regression results in Columns (1) and (2) of Table 6 show that the effect of transportation infrastructure construction is more significant for energy-intensive enterprises.

4.4.2. Industrialization level

Industrial agglomeration is a major theoretical foundation of new economic geography. Localized economies refer to the benefits that enterprises can derive from the economic activities of other firms in the same industry within a specific region, which in turn drives the clustering of firms in the same industry in that area, fostering industrial growth. When enterprises cluster together, efficiency improvements can be achieved through labor concentration, knowledge spillovers, and outsourcing (Krugell and Rankin 2012).

Within the framework of profit maximization, enterprises tend to exhibit agglomeration effects during the site selection process, as they benefit from shared tangible infrastructure and intangible resources such as technology and market

information (Weber 1929). For example, the proximity of thermal power and energy storage companies reduces the cost of technical communication, fosters technological cooperation, and facilitates the exchange of energy management expertise. A well-developed transportation network promotes regional market integration, enabling enterprises to more easily expand production scales, achieve economies of scale, and optimize production processes, thereby improving resource utilization efficiency (Y. Wang 2022).

Regions with higher levels of industrialization tend to attract a large number of energy-intensive and high-energy-consuming enterprises. These enterprises form efficient collaborative networks through close cooperation, which is conducive to achieving economies of scale and enhancing the market competitiveness of both industries and enterprises. The synergies between enterprises realize through resource sharing, technological innovation, supply chain integration, and the positive interaction between market competition and cooperation, leading to significant economies of scale, which amplifies the positive impact of transportation infrastructure construction, resulting in a notable improvement in energy efficiency. This paper measures the industrialization level of a region by the ratio of the secondary sector to the tertiary sector. The regression results in Columns (3) and (4) of Table 6 show that the effect of transportation infrastructure construction is more pronounced for enterprises located in regions with a higher degree of industrialization.

Table 6

Heterogeneity analysis.

Variable	(1)	(2)	(3)	(4)
	$\ln_accessexit_{it}$	$\ln_motorexit_{it}$	$\ln_accessexit_{it}$	$\ln_motorexit_{it}$
	$\times Intensity_{it}$	$\times Intensity_{it}$	$\times Industry_{ct}$	$\times Industry_{ct}$
<i>Efficiency</i>	0.0062** (0.0028)	0.0053** (0.0022)	0.0190** (0.0080)	0.0129** (0.0060)
Company FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes

r2_a	0.4320	0.4320	0.4278	0.4278
N	900759	900759	932984	932984

Notes: The same as table 2.

4.5. Further analysis

4.5.1. Reduce pollution

Improving energy efficiency has long been regarded as one of the key strategies for reducing pollution emissions. By optimizing energy utilization, not only can energy waste be effectively reduced, but emissions of greenhouse gases and harmful substances can also be significantly lowered. As shown in Columns (1) and (2) of Table 7, the construction of transportation infrastructure has reduced enterprises' NO_x and SO₂ emission levels. This is mainly due to the improvements in the transportation network, which make the transportation process more efficient, reduce the time and transportation costs associated with the flow of energy resources, promote the substitution of traditional fossil fuels with new low-carbon fuels, further reducing pollution emissions.

4.5.2. Reduce energy consumption

By improving energy efficiency, enterprises can significantly reduce their dependence on energy resources while maintaining output levels, thereby lowering overall energy consumption. As shown in Column (3) of Table 7, the construction of transportation infrastructure has significantly reduced the energy consumption of enterprises.

4.5.3. Increase pollution control efforts

The improvement of transportation infrastructure not only enhances transportation efficiency but also reduces logistics and warehousing costs, alleviating the financial pressure on enterprises so as to create more favorable conditions for enterprises to invest in pollution control. Enterprises are able to allocate funds to pollution management, thereby better achieving sustainable operations and environmental compliance. As shown in Column (4) of Table 7, with the advancement of

transportation infrastructure construction, enterprises' investment in pollution control has significantly increased. The final piece of evidence indicates that the reduction in pollution emissions is not only a direct result of lower energy consumption but is also closely linked to the increased efforts of enterprises in pollution management.

Table 7

Further analysis.

Variable	(1) <i>ln_NOx</i>	(2) <i>ln_SO2</i>	(3) <i>ln_Energy_Consumption</i>	(4) <i>ln_Pollution_Control</i>
<i>ln_accessexitl</i>	-0.1307* (0.0685)	-0.1266* (0.0683)	-0.1184*** (0.0441)	0.1445** (0.0676)
Company FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes
r2_a	0.6730	0.6844	0.6994	0.6130
N	249266	250434	932984	250170

Notes: The same as table 3.

5. Research conclusions

As transportation infrastructure continues to improve and the process of regional integration advances, it is foreseeable that the optimization and interconnectedness of transportation networks will profoundly and continuously impact the flow of factors, resource allocation efficiency, and performance levels of enterprises. In the new development landscape, where enterprises face dual pressures of energy transition and energy conservation and emission reduction, this paper provides an in-depth analysis of the specific mechanisms through which transportation infrastructure enhances corporate energy efficiency from the perspective of factor allocation. Additionally, it explores the heterogeneous impact of transportation infrastructure on enterprises based on regional and enterprise characteristics. The findings offer valuable insights for enterprises and provide empirical evidence for government departments to further improve the construction of transportation infrastructure.

Based on the 2007–2020 National Enterprise Tax Survey data from China, this paper investigates the impact of transportation infrastructure construction on corporate energy efficiency. Overall, the main empirical findings of this study are as follows. First, the construction of transportation infrastructure significantly improves corporate energy efficiency. Among different types of transportation infrastructure, only road transportation construction has a significant positive effect on energy efficiency, while other types of transportation infrastructure show no significant impact. Second, improving factor allocation, optimizing energy structure, and promoting technological innovation are key mechanisms through which transportation infrastructure construction enhances energy efficiency. Third, in regions with higher energy intensity and higher levels of industrialization, the impact of transportation infrastructure construction on improving energy efficiency is more pronounced. Fourth, further analysis reveals that transportation infrastructure construction enables enterprises to reduce energy consumption and increase their investment in pollution control, ultimately leading to a reduction in pollution emissions.

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