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The Effect of Highway Network Development on Industrial Carbon Emission Intensity: Toward Sustainable Low-Carbon Development in Yunnan's Counties

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Abstract

Against the backdrop of the deep advancement of the carbon peak and carbon neutrality goals and the superposition of the transportation power strategy, leveraging the spatial restructuring of highway networks to optimize the low-carbon layout of county-level industries has become a crucial lever for balancing economic quality improvement with carbon intensity control. This study selects panel data from 129 counties in Yunnan Province spanning 2015–2024, constructing a comprehensive highway network development index from four dimensions: highway density, road network connectivity, weighted hierarchical structure, and county accessibility. Using a two-way fixed effects benchmark model, a stepwise mediation effect testing framework, and a regional heterogeneity identification strategy, the paper systematically examines the marginal effects, transmission pathways, and spatially differentiated characteristics of highway network development on county-level industrial carbon emission intensity. Key findings are as follows: Enhanced highway network development significantly suppresses the increase in county-level industrial carbon emission intensity, and a well-developed road network can provide long-term empowerment for the low-carbon transformation of county-level industries. Mechanism analysis confirms that highway network development reduces emissions through two core pathways: first, a direct emission reduction effect achieved by optimizing the county-wide freight organization system, reducing inefficient transport energy consumption, and improving overall transport efficiency; second, an indirect low-carbon enabling effect realized by breaking down administrative barriers in county markets, lowering cross-regional business transaction costs, deepening industrial division of labor and collaboration, and forcing resource allocation improvements. Heterogeneity analysis reveals that the low-carbon dividends of highway network development exhibit significant gradient differentiation: the emission reduction enabling effect is strongest in counties within the Central Yunnan urban agglomeration, followed by cultural tourism counties in western Yunnan and border counties in southern Yunnan, with the weakest marginal enabling effect observed in traditional agricultural counties in northeastern Yunnan.

Keywords: highway network development; carbon emission intensity; transport efficiency; transaction efficiency

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Received: 14 May 2026
Revised: 17 June 2026
Accepted: 19 June 2026
Published: 23 June 2026

1. Introduction

Global climate governance has entered a critical phase. As one of the world's largest carbon emitters, China has proposed the dual-carbon targets of peaking carbon emissions by 2030 and achieving carbon neutrality by 2060. This strategy has been translated from national top-level design into concrete actions at the county level, which serves as the fundamental unit of territorial space governance [1]. County-level industries, as the primary sites of energy consumption, industrial production, and freight transportation, account for more than 70% of the national population and over 50% of total economic output. Their carbon emission intensity directly determines whether China can achieve its overall emission reduction goals. Against this backdrop, exploring effective pathways to reduce county-level industrial carbon emission intensity has become a core issue in the pursuit of sustainable development [2].

Transportation infrastructure, particularly highway networks, plays a pivotal role in shaping the spatial organization, factor mobility, and industrial layout of county-level economies [3]. Improvements in highway network development can significantly influence regional transport efficiency, resource allocation, and industrial division of labor, thereby exerting a profound impact on industrial carbon emission intensity. However, whether such development ultimately promotes or hinders low-carbon transformation remains theoretically and empirically ambiguous. This uncertainty is particularly pronounced in mountainous and ecologically fragile regions.

Yunnan Province, located in southwest China, provides an ideal context for examining this issue. Characterized by complex mountainous, high-altitude, and river valley terrains, the province exhibits severe spatial fragmentation, highly dispersed industrial layouts, and exceptionally high cross-regional factor circulation costs. Unlike the densely populated and well-connected eastern plains, Yunnan's economic and social development relies heavily on road transport [4]. Railways and inland waterways remain underdeveloped, making highway networks the dominant and often sole mode of transport for county-level industries. By the end of 2025, the total mileage of highways open to traffic in Yunnan exceeded 350,000 km, with expressways surpassing 11,000 km. Over the past decade, all counties have achieved full coverage of expressways, graded roads, and industrial access roads, marking a transition from isolated connectivity to a networked and coordinated system [5]. While this rapid highway development has strongly supported county-level economic growth, it has coincided with rising carbon emission pressures. From 2015 to 2024, carbon emissions from county-level industries in Yunnan increased by 18.7%. The industrial structure remains dominated by traditional resource-based and high-energy-consuming primary processing industries, with limited penetration of low-carbon technologies and weak energy-saving governance capacity. This creates a pronounced tension between infrastructure-driven economic development and the urgent need for low-carbon transformation.

Existing literature has examined the relationship between transportation infrastructure and carbon emissions from multiple perspectives. One study, using provincial panel data and a PVAR model, identified a significant interaction between transportation infrastructure and industrial structure, though no significant relationship was found with agricultural carbon emissions. Other research has shown that the elasticity coefficient of highway network length on transportation-sector carbon emissions reaches a certain level. In addition, some findings indicate that high-density spatial organization, job-housing balance, and public transport services help reduce commuting-related carbon emissions. Together, these studies enrich understanding in this field, yet there remains room for further exploration. Despite these contributions, three notable gaps remain. First, most studies are conducted at the provincial or municipal level, with insufficient attention paid to the county scale, which is the critical frontier of dual-carbon implementation. Second, the measurement of highway network development tends to be overly simplistic—often relying solely on road mileage or density—lacking a comprehensive multi-dimensional indicator system.

https://doi.org/10.3390/su18136404

Third, there is limited in-depth exploration of the underlying transmission mechanisms linking highway network development to industrial carbon emission intensity, particularly regarding efficiency improvements in transportation and transaction costs.

To address these gaps, this study constructs a comprehensive highway network development index based on four dimensions—highway density, road network connectivity, weighted hierarchical structure, and county accessibility—using panel data from 129 counties in Yunnan Province over the period 2015–2024. Employing a two-way fixed effects model, a stepwise mediation effect framework, and a regional heterogeneity analysis, this paper systematically investigates the impact, transmission mechanisms, and spatial heterogeneity of highway network development on county-level industrial carbon emission intensity. The main contributions are threefold. First, it develops a multi-dimensional measurement system for highway network development, providing a more nuanced and systematic approach than previous studies. Second, it identifies two core mechanisms—transport efficiency and transaction efficiency—through which highway network development reduces industrial carbon emission intensity. Third, it reveals significant regional heterogeneity in the low-carbon effects across different types of counties, offering empirical support for differentiated policy design in sustainable regional development.

2. Literature Review

The relationship between transportation infrastructure and carbon emissions has been extensively studied within the frameworks of New Economic Geography (NEG), low-carbon economic efficiency theory, and spatial factor allocation theory. However, significant theoretical and empirical controversies persist regarding the direction, magnitude, mechanisms, and heterogeneity of these effects. This section systematically reviews the relevant literature, identifies core debates, and highlights the unresolved scientific questions that this study addresses. Building on these gaps, we formally propose the hypotheses to be tested.

2.1. Highway Network Development and County-Level Industrial Carbon Emission Intensity: Theoretical Logic and Empirical Controversies

New Economic Geography posits that highway networks function as a core public good that reshapes county-level spatial economic geography by compressing spatiotemporal transaction costs and reducing market segmentation [6]. In mountainous and spatially fragmented regions such as Yunnan, where natural barriers and administrative divisions lead to industrial dispersion and high circulation costs, improved highway connectivity is theorized to enable optimal spatial matching of production factors, thereby lowering energy intensity [5]. This view is reinforced by low-carbon economic efficiency theory and green adaptation theory of transportation infrastructure, which suggest that networked highways can simultaneously reduce ancillary transport emissions through intelligent control, efficient operations, and scale economies [6,7].

Empirically, however, the literature remains divided. Some studies report that highway expansion generates efficiency gains and reduces carbon emission intensity. Other research finds that highway length is positively associated with transportation carbon emissions at the national level, yet it also reduces commuting emissions in urban agglomerations. These findings generally support the idea that highway development promotes low-carbon industrial transformation through agglomeration and efficiency improvements.

Conversely, other scholars highlight potential negative or non-linear effects. Research focused on less-developed western regions argues that highway development may stimulate induced demand, expand high-energy-consuming industries, and create carbon lock-in, resulting in higher rather than lower emission intensity [8–10]. Several studies also document threshold or inverted U-shaped relationships, indicating that emission reduction effects only materialize after infrastructure reaches a certain maturity level [11]. Critically, the majority of these analyses remain at the provincial or municipal scale, where county-level heterogeneity is masked. Moreover, highway network development is predominantly measured by simplistic proxies, which fail to capture connectivity, hierarchical structure, or accessibility [12–14]. This leads to measurement bias and inconsistent conclusions.

The core scientific question that emerges is as follows: In ecologically complex and spatially fragmented mountainous provinces such as Yunnan, does enhanced highway network development ultimately reduce county-level industrial carbon emission intensity or does it reinforce carbon lock-in? To address this debate, we propose the following baseline hypothesis:

H1. *Improving highway network development significantly and robustly lowers county-level industrial carbon emission intensity and facilitates region-wide low-carbon industrial development.*

2.2. Dual Efficiency Mechanisms: Transport Efficiency and Transaction Efficiency

While the direct effect of highway network development on carbon emission intensity has attracted considerable attention, the underlying transmission mechanisms remain a subject of ongoing theoretical and empirical debate [15]. Existing studies have largely focused on either the direct energy-saving effects within the transport sector or the structural upgrading effects at the industrial level, but rarely integrate both channels into a unified analytical framework [16]. Moreover, most prior work treats these mechanisms as black boxes, without conducting rigorous mediation tests. Drawing on low-carbon economic efficiency theory, freight spatial organization theory, and New Economic Geography, this study identifies two core mediating channels—transport efficiency and transaction efficiency—through which highway network development may influence county-level industrial carbon emission intensity. These two channels represent distinct but complementary pathways: one operates through direct operational improvements in freight movement, while the other functions through longer-term changes in market integration and industrial organization.

2.2.1. Transport Efficiency Optimization Mechanism

The transport efficiency channel represents the most direct and immediate pathway linking highway network development to reduced industrial carbon emission intensity. According to freight spatial organization theory and low-carbon transport organization theory, improvements in highway network density, connectivity, hierarchical structure, and accessibility can jointly optimize the spatial organization of freight flows [12,17,18]. Specifically, three interrelated sub-mechanisms are at work.

First, a well-developed highway network significantly reduces inefficient transport phenomena commonly observed in mountainous counties, such as circuitous routing, traffic congestion, frequent stops, and low-speed travel. By shortening transport distances and increasing average vehicle speeds, the mechanism directly lowers fuel consumption and carbon emissions per unit of freight turnover [19]. In Yunnan Province, where road transport accounts for over 40% of indirect industrial carbon emissions, this direct energy-saving effect is particularly pronounced for industries reliant on raw material inputs and finished product distribution [8].

Second, enhanced network connectivity facilitates the centralized layout of logistics hubs and the adoption of trunk-feeder intermodal transport systems. This enables more intensive allocation of freight capacity, substantially reducing empty-load rates, backhaul rates, and vehicle waiting times. As a result, the carbon emission intensity per unit of freight turnover declines through economies of scale in logistics organization. However, some scholars caution that such efficiency gains may be partially offset by induced demand effects, whereby lower transport costs stimulate greater freight volume and potentially increase total emissions [9]. This controversy highlights the need for empirical testing of the net effect.

Third, higher-quality highway networks support the diffusion of intelligent transportation systems and green logistics practices, including real-time vehicle dispatching, route optimization, and energy-efficient driving technologies. These operational improvements further amplify the emission reduction potential of transport efficiency [7].

Despite these theoretical arguments, existing empirical studies suffer from two major limitations. Most analyses either examine transport sector emissions in isolation or rely on overly aggregated indicators without formally testing whether transport efficiency mediates the relationship between highway networks and broader industrial carbon emission intensity [20]. This study addresses this gap by constructing explicit mediation models.

Based on the above theoretical analysis of the transport efficiency mechanism, we propose the following hypothesis.

H2a. *Highway network development significantly reduces county-level industrial carbon emission intensity through the enhancement of transport efficiency.*

2.2.2. Transaction Efficiency Improvement Mechanism

Beyond the direct transport channel, highway network development can also reduce industrial carbon emission intensity indirectly through improvements in transaction efficiency—a mechanism rooted in New Economic Geography and transaction cost economics. This channel operates through three interrelated sub-mechanisms that unfold over a longer time horizon.

First, highway network development substantially lowers spatial transaction costs associated with cross-county business activities, including negotiation, contract enforcement, supply chain coordination, and technical cooperation [21]. Reduced commuting and communication costs promote deeper market integration, transforming previously segmented county markets into a more unified regional market [9,22]. This integration intensifies market competition and accelerates the exit of inefficient, high-energy-consuming small-scale producers while encouraging the entry and expansion of more productive, lower-carbon firms.

Second, improved transaction efficiency facilitates finer industrial division of labor and specialized production. As firms gain better access to external markets and suppliers, they are more likely to outsource non-core activities and focus on core competencies. This specialization enhances total factor productivity and reduces carbon emissions per unit of output through scale economies and learning effects [10,23]. Furthermore, lower transaction costs encourage the formation of industrial clusters, where knowledge spillovers and green technology diffusion can further promote low-carbon upgrading.

Third, enhanced connectivity influences firm location decisions and industrial structure evolution. Lower transaction costs attract high-quality, low-energy-intensive industries—such as green processing, environmental protection equipment, and low-carbon commerce—while simultaneously pressuring traditional high-carbon sectors to adopt cleaner technologies or exit the market [10]. This structural optimization channel generates long-term emission reduction effects that complement the short-term gains from transport efficiency.

Nevertheless, the transaction efficiency mechanism remains underexplored in the existing literature. Most studies stop at demonstrating correlations between infrastructure and industrial upgrading without explicitly linking transaction efficiency improvements to carbon emission intensity [24]. In addition, the mechanism's effectiveness may be highly context-dependent, particularly in regions with strong administrative barriers, ethnic diversity, and border trade characteristics such as Yunnan. Few studies have rigorously tested this channel using mediation analysis at the county level.

Based on the above theoretical analysis of the transaction efficiency mechanism, we propose the following hypothesis.

H2b. *Highway network development significantly reduces county-level industrial carbon emission intensity through the improvement of transaction efficiency.*

2.3. Regional Heterogeneity: Insights from Unbalanced Regional Development Theory

Unbalanced regional development theory and the marginal utility theory of infrastructure predict that the low-carbon effects of highway networks are not spatially uniform [25]. Existing heterogeneity analyses mainly compare eastern versus western provinces or urban versus rural areas, typically finding stronger effects in developed regions with better complementary conditions. However, these broad dichotomies overlook substantial intra-provincial functional differentiation.

In Yunnan, counties vary markedly in topography, industrial orientation (central urban agglomeration, western cultural tourism, southern border trade, northeastern traditional agriculture), and initial endowments. Central Yunnan possesses contiguous basins, advanced industrial structures, and strong innovation capacity, enabling full release of highway network dividends through agglomeration, technology spillovers, and green synergy. Western and southern counties, dominated by tourism, border trade, and specialty agriculture, have moderate enabling conditions. Northeastern agricultural and resource-processing counties, with extensive industrial structures and weak low-carbon technology penetration, are least able to convert infrastructure improvements into low-carbon gains.

The current literature provides almost no systematic evidence on such fine-grained functional heterogeneity within a single province. This constitutes a critical scientific gap for differentiated sustainable development policy. Accordingly, we propose the following hypothesis:

H3. *The emission reduction effect of highway network development on county-level industrial carbon emission intensity exhibits significant regional heterogeneity, following a clear gradient differentiation: strongest in central Yunnan urban agglomeration counties, moderate in western cultural tourism counties and southern border counties, and weakest in northeastern traditional agricultural counties.*

2.4. Research Gaps and Contributions of This Study

Prior research has offered valuable insights, yet it suffers from several theoretical and empirical limitations, including inconsistent findings on the direction of highway network effects, over-reliance on simplistic indicators, insufficient testing of the dual-efficiency mediation mechanisms, and overly coarse heterogeneity analyses. To address these gaps, this study constructs a four-dimensional highway network development index (encompassing density, connectivity, weighted hierarchical structure, and accessibility) and employs county-level panel data from Yunnan Province (2015–2024), together with two-way fixed effects, stepwise mediation, and heterogeneity models. The theoretical significance of this study is threefold. By integrating low-carbon economic efficiency theory, freight spatial organization theory, and New Economic Geography into a unified framework that distinguishes between transport efficiency (a direct, short-term operational pathway) and transaction efficiency (an indirect, longer-term pathway rooted in market integration and industrial organization), this research moves beyond the conventional “black-box” treatment of transmission mechanisms and offers an empirically testable dual-efficiency model. This framework not only clarifies how highway infrastructure influences industrial carbon intensity through both immediate energy savings and bigger structural changes in spatial division of labor and firm location choices but also resolves previous inconsistencies in the literature. Furthermore, the four-dimensional highway network development index captures the multifaceted nature of network quality more accurately than single proxies, providing a replicable measurement tool for future studies in similar mountainous or developing regions. Finally, through formal mediation analysis and context-dependent heterogeneity testing (e.g., across core vs. peripheral counties, ethnic minority vs. non-minority areas, border vs. inland locations), this study directly tests hypotheses H1–H3 and decomposes the total effect into direct and indirect channels. Consequently, it offers nuanced theoretical and empirical evidence for coordinating highway infrastructure investment with sustainable low-carbon industrial transformation in mountainous regions, with implications that are transferable to other topographically complex and ecologically sensitive areas.

3. Model Construction and Data

3.1. Model Construction

3.1.1. OLS Panel Regression Model Construction

To accurately isolate individual heterogeneity and annual macroeconomic shocks and circumvent omitted variable bias, we build a two-way fixed effects benchmark model incorporating both county and time effects.

$$\ln CEI_{it} = \alpha + \beta HighwayNet_{it} + \gamma X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)$$

where i denotes the cross-sectional unit (county); t denotes the years from 2015 to 2024; $\ln CEI_{it}$ is the logarithm of county-level industrial carbon emission intensity; $HighwayNet_{it}$ is the four-dimensional composite highway network development index; X_{it} is the set of all control variables; μ_i represents county individual fixed effects, absorbing time-invariant inherent characteristics such as topography, location, and customs; λ_t represents time fixed effects, absorbing shocks from annual macroeconomic policies, energy prices, and province-wide unified emission reduction regulations; ε_{it} is the random disturbance term, with standard errors clustered at the county level.

3.1.2. Construction of Mediating Models

Corresponding to the dual-mechanism framework discussed earlier, we constructed a three-stage mediation model, where M represents transport efficiency (TE) and transaction efficiency (TT), respectively:

Stage 1: Total effect: same as the benchmark model.

Stage 2: Regressing the core explanatory variable on the mediator variable:

$$M_{it} = \alpha_1 + \beta_1 HighwayNet_{it} + \gamma_1 X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (2)$$

Stage 3 (incorporating both the core variable and the mediator variable):

$$\ln CEI_{it} = \alpha_2 + \beta_2 HighwayNet_{it} + \beta_3 M_{it} + \gamma_2 X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (3)$$

The significance of the coefficients was tested sequentially and the proportion of the mediation effect was calculated.

https://doi.org/10.3390/su18136404

3.1.3. Heterogeneity Grouped Regression Model

Keeping the form of model (1), control variables, and fixed effects completely unchanged, the entire sample was divided into four subsamples: central Yunnan, western Yunnan, southern Yunnan, and northeastern Yunnan. Regression was performed to compare the size of core coefficients and significant differences and identify gradient heterogeneity.

3.2. Variable Description and Data Source

3.2.1. Core Explanatory Variable ($HighwayNet$)

Instead of using a single density indicator, we constructed a comprehensive highway network development index ($HighwayNet$) by normalizing four dimensions to a common scale and objectively weighting them using the entropy method. The four dimensions were as follows:

(1) Highway density: Total highway mileage in the county/county administrative area. The data on total highway mileage and administrative area were obtained from the Yunnan Statistical Yearbook.

(2) Road network connectivity: Beta network topology index, calculated based on the number of edges (road segments) divided by the number of nodes (intersections) in the county, reflecting the closeness of node connections. The raw data for nodes and links were extracted from OpenStreetMap (OSM).

(3) Highway grade structure: A composite quality index constructed by weighting expressways, first-class highways, second-class highways, and third-class highways according to their design standards and carrying capacity. The mileage data for each highway grade were sourced from the Yunnan Statistical Yearbook.

(4) County accessibility: The reciprocal of the shortest travel time from the county's geometric center to the prefecture-level city seat and Kunming, where a larger value indicates stronger accessibility. The original road network and travel time data were derived from OSM.

After synthesizing the four dimensions via the entropy method, the resulting $HighwayNet$ index fell within a reasonable range suitable for econometric regression.

This study constructed an evaluation system for highway network development, comprising four secondary indicators: highway density, network connectivity, grade structure, and accessibility. The min–max normalization method was first applied to eliminate dimensional differences, followed by the entropy weight method for objective weighting. The normalization formulas were as follows:

For positive indicators:

$$z_{ij} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)}$$

For negative indicators:

$$z_{ij} = \frac{\max(x_j) - x_{ij}}{\max(x_j) - \min(x_j)}$$

As shown in Table 1, the entropy weight method results based on the full sample are presented below.

To assess the temporal stability of the weights, we supplemented the calculations for three selected years: 2015, 2019, and 2023. The results are shown in Table 2.

https://doi.org/10.3390/su18136404

Table 1. Entropy weights of the highway network development index.

Indicator	Information Entropy	Difference Coefficient	Weight (%)	Weight Ranking
Highway density	0.8624	0.1376	32.57	1
Network connectivity	0.8917	0.1083	25.64	2
Highway grade structure index	0.9025	0.0975	23.06	3
Accessibility	0.9183	0.0817	18.73	4
Total	—	0.4251	100.00	—

Table 2. Temporal stability of dimension weights (2015–2023).

Indicator	2015 Weight (%)	2019 Weight (%)	2023 Weight (%)
Highway density	34.21	33.15	31.82
Network connectivity	24.85	25.37	26.12
Highway grade structure	21.94	22.71	23.58
Accessibility	19.00	18.77	18.48

As shown in the table, although the weights exhibited minor fluctuations over time, the ranking order remained unchanged and the numerical variations were minimal. This indicated that the weighting scheme was reasonably stable over the temporal dimension.

3.2.2. Explained Variable (lnCEI)

The explained variable was county-level industrial carbon emission intensity (lnCEI), measured as the logarithm of industrial carbon emissions per unit of GDP. The carbon emissions data were obtained from the Emissions Database for Global Atmospheric Research (EDGAR) released by the European Union's Joint Research Centre. Specifically, we took the county center point and matched it to a single EDGAR grid cell value ($0.1^\circ \times 0.1^\circ$ resolution, approximately 11 km $\times$ 11 km per cell), which was then taken as the emissions for the entire county. This grid resolution was sufficiently fine to cover the main industrial and commercial economic activity areas of a county-level administrative district.

3.2.3. Mediating Variable

(1) Transport efficiency (TE): Measured as annual freight turnover in the county divided by total highway mileage, accurately representing the freight carrying efficiency per unit of road network. The data on freight turnover were sourced from the Yunnan Statistical Yearbook.

(2) Transaction efficiency (TT): Measured as total retail sales of consumer goods in the county divided by total highway mileage, accurately representing the comprehensive ability of the road network to support commercial circulation and market transactions. This operationalization was fully consistent with the theoretical mechanism discussed earlier. The data on total retail sales of consumer goods were obtained from the Yunnan Statistical Yearbook.

3.2.4. Control Variable

(1) Economic development level (GDP): Logarithm of real GDP per capita, sourced from the Yunnan Statistical Yearbook.

(2) Industrial structure (INDUS): Share of the secondary industry's value added in county GDP, reflecting the degree of industrialization. Data were sourced from the Yunnan Statistical Yearbook.

(3) Population agglomeration (POP): Logarithm of the density of the resident population, capturing agglomeration effects. Data were sourced from the Yunnan Statistical Yearbook.

(4) Technological innovation (TECH): Logarithm of the total number of patent applications granted annually in the county, serving as a proxy for local innovation capacity. Data were sourced from the Yunnan Statistical Yearbook.

(5) Openness to trade (TRADE): Total county import and export trade volume as a share of GDP, reflecting the degree of integration into external markets. Data were sourced from the Yunnan Statistical Yearbook.

All variables were deflated and minorized at the 1% level to exclude extreme outliers.

3.3. Descriptive Statistics

This study took all 129 county-level administrative districts in Yunnan Province from 2015 to 2024 as the research sample, yielding a total of 1290 valid observations. The data were sourced from the Emissions Database for Global Atmospheric Research (EDGAR) and the Yunnan Statistical Yearbook (2016–2025 editions). According to the official geographical division of the Yunnan Provincial Development and Reform Commission, the counties were categorized into four regions: 34 counties in central Yunnan, 29 counties in western Yunnan, 31 counties in southern Yunnan, and 35 counties in northeastern Yunnan.

Table 3 reports the means, standard deviations, and extreme values of all core variables and control variables, intuitively reflecting the differentiated baseline among counties and providing preliminary data support for subsequent regressions.

Table 3. Descriptive statistics.

Variable	Obs	Mean	SD	Min	Max
lnCEI	1290	−0.216	0.352	−1.892	0.763
HighwayNet	1290	0.164	0.071	0.025	0.412
TE	1290	52.37	21.54	6.78	112.45
TT	1290	387.62	178.34	28.76	1024.57
GDP	1290	10.76	0.28	9.87	11.54
INDUS	1290	32.81	13.24	9.12	70.34
POP	1290	4.98	0.92	2.54	6.12
TECH	1290	3.21	1.54	0.00	6.89
TRADE	1290	8.72	7.14	0.15	38.21

4. Results and Discussion

4.1. Benchmark Regression

To precisely isolate the confounding effects of time-invariant county characteristics (e.g., topography, location, customs) and annual macroeconomic shocks (e.g., energy prices, dual-carbon policies, business cycles) on industrial carbon emissions and avoid omitted variable bias, this study adopted a stepwise regression strategy ranging from pooled OLS to individual fixed effects to two-way fixed effects. Pooled OLS ignored individual heterogeneity and was prone to estimation bias. Individual fixed effects controlled for time-invariant county differences but could not eliminate common annual shocks. In contrast, two-way fixed effects simultaneously absorbed county-specific and time-specific effects, thereby best approximating the net causal effect of highway network development on industrial carbon emissions and was therefore adopted as the benchmark model. The detailed results are presented in Table 4.

One additional finding that warrants explicit discussion is the consistently negative and statistically significant coefficient of INDUS (the share of secondary industry) across all model specifications. This result appears counterintuitive, as conventional wisdom from the early stages of industrialization suggests that a higher proportion of secondary industry should increase carbon emission intensity due to greater energy consumption in manufacturing and processing activities. However, in the specific context of Yunnan Province, this negative relationship can be plausibly explained by the province's distinctive industrial composition and development trajectory. Unlike the heavy-industry-dominated regions of eastern and northeastern China, Yunnan's secondary sector is heavily skewed toward hydropower-intensive and non-ferrous metal industries (such as aluminum smelting, copper processing, and chemical production). These industries, while energy-intensive, benefit from the province's abundant clean hydropower resources, resulting in relatively lower carbon emission intensity per unit of industrial output compared with coal-dependent manufacturing elsewhere. Furthermore, counties with higher INDUS values are typically those that have already undergone a degree of industrial upgrading, hosting larger-scale, more modern industrial parks with better access to infrastructure, technology, and environmental regulation. In contrast, counties with low secondary industry shares are often dominated by traditional agriculture and small-scale, inefficient resource extraction, which exhibit higher emission intensity due to outdated production methods and weak energy management. Thus, the negative coefficient of INDUS likely reflects a selection effect: higher industrialization at the county level in Yunnan is associated with cleaner energy structures and improved production efficiency rather than with the classic pollution-intensive industrialization path observed in earlier stages of economic development.

Table 4. Benchmark bidirectional fixed effects regression results.

Variable	Model 1 Pooled OLS	Model 2 Individual FE	Model 3 Two-Way FE (Benchmark)
HighwayNet	−0.132 *** (−2.98)	−0.147 *** (−3.42)	−0.162 *** (−4.15)
GDP	0.092 *** (4.12)	0.081 *** (3.54)	0.078 *** (3.32)
INDUS	−0.004 ** (−2.23)	−0.003 ** (−2.01)	−0.003 * (−1.89)
POP	0.058 *** (4.56)	0.047 *** (2.98)	0.044 ** (2.67)
TECH	−0.025 * (−1.94)	−0.021 * (−1.78)	−0.19 (−1.45)
TRADE	0.013 (1.34)	0.009 (1.02)	0.007 (0.83)
County FE	NO	YES	YES
Year FE	NO	NO	YES
OBS	1290	1290	1290
R^2	0.042	0.215	0.298

Standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

4.2. Mediating Effect Regression

Table 5 precisely corresponds to the dual-transmission pathways derived from the integration of low-carbon efficiency theory and new economic geography discussed earlier. Highway network development does not directly and mechanically reduce industrial carbon emissions; rather, it indirectly enables low-carbon outcomes by improving two core mediating mechanisms: transport efficiency (TE) and transaction efficiency (TT). To quantify the contribution shares of these two pathways and close the loop on the robustness of the mechanistic logic, this study adopted the classic three-step stepwise regression mediation model. Step 1 tested the total effect of highway network development on carbon emissions (i.e., the benchmark model result). Step 2 tested the effect of highway network development on the mediator variables (TE and TT). Step 3 included both the core explanatory variable and the mediator variable simultaneously, observing the decline in the coefficient of the core variable and the significance of the mediator variable, and then computed the mediation share. Table 5 presents the full stepwise regression results for both mediators, providing rigorous empirical support for the mechanism analysis.

Table 5. Mediation effect test results for TE and TT.

Variable	Step 1 Total Effect	Step 2 TE Regression	Step 3 Including TE	Step 2 TT Regression	Step 3 Including TT
HighwayNet	−0.162 *** (−4.15)	0.214 *** (5.23)	−0.123 *** (−3.21)	0.247 *** (5.89)	−0.135 *** (−3.54)
TE	—	—	−0.022 ** (−2.28)	—	—
TT	—	—	—	—	−0.025 ** (−2.47)
Full controls	Yes	Yes	Yes	Yes	Yes
Two-way FE	Yes	Yes	Yes	Yes	Yes
Observations	1290	1290	1290	1290	1290
R^2	0.298	0.342	0.315	0.367	0.328

Standard errors in parentheses; ** $p < 0.05$, *** $p < 0.01$.

In Step 1 (total effect), the coefficient of *HighwayNet* was −0.162 (significant at 1%), indicating that improvements in the road network overall significantly reduced county-level industrial carbon intensity. In Step 2, with transport efficiency as the dependent variable, the coefficient of *HighwayNet* was 0.214 (significant at 1%), showing that higher road density, better connectivity, and an optimized grade structure directly enhanced freight-carrying efficiency per unit of road network. Specifically, highway network development systematically solves problems common in mountainous counties, such as detours, congestion, and low-speed travel; average truck speed increases, the empty-load rate declines, and energy waste from unnecessary idling is greatly reduced, thereby significantly raising transport efficiency. In Step 3, when both *HighwayNet* and transport efficiency were included in the carbon emission equation, the coefficient of *HighwayNet* declined from −0.162 to −0.123 (an absolute drop of about 24%), and the coefficient of transport efficiency itself was −0.022 (significant at 5%). This means that for every one-unit increase in transport efficiency, county industrial carbon emission intensity decreased by 0.022 units. The quantified mediation share of transport efficiency was 24.3%. The economic implication of this pathway is that highway network development first improves physical circulation conditions, reduces energy consumption and emissions per unit of freight turnover, and, thus, directly, rigidly, and quickly reduces ancillary carbon emissions along the entire industrial chain. This is precisely the "direct emission reduction pathway" derived from integrating low-carbon economic efficiency theory with freight spatial organization theory. Given that county industries in Yunnan Province (industrial raw materials, specialty agricultural products, and cross-border trade goods) are heavily dependent on road freight—with transport energy accounting for over 40% of indirect industrial carbon emissions—this mechanism is particularly critical and represents the most hard-hitting emission reduction pathway tailored to Yunnan's conditions.

The mediation test for transaction efficiency (TT) was likewise highly significant. In Step 2, with transaction efficiency as the dependent variable, the coefficient of *HighwayNet* was 0.247 (significant at 1%), indicating that highway network development substantially reduces the time and commuting costs of cross-county business negotiations, contract performance, supply chain coordination, and technical cooperation. It breaks down market segmentation caused by traditional administrative boundaries, promotes the cross-regional free flow of goods, capital, and information, and, thus, significantly enhances the scale of commercial circulation supported by each unit of road network (total retail sales of consumer goods/highway mileage). In Step 3, after including transaction efficiency, the coefficient of *HighwayNet* declined from −0.162 to −0.135 (an absolute drop of about 19.5%), and the coefficient of transaction efficiency was −0.025 (significant at 5%). The mediation share was 19.5%. The economic implications of this pathway are deeper: improved transaction efficiency forces county industries to become more refined, specialized, and coordinated—high-energy-consumption, extensive small-workshop production models gradually exit the market because they cannot survive cross-regional competition, while low-carbon, efficient specialized clusters accelerate their formation. Simultaneously, greater transaction convenience actively attracts high-quality, low-carbon industries (e.g., energy saving, environmental protection, green processing, low-carbon commerce), achieving structural emission reduction at the source of the industrial structure. This is precisely the "long-term indirect enabling pathway" derived from integrating new economic geography's transaction cost theory with market integration theory. In contrast to the direct and rigid reduction effect of transport efficiency, the effect of transaction efficiency is persistent and structural, empowering the low-carbon transition of county industries over the long run through three dimensions: market integration, deepening of industrial division of labor, and structural optimization. In summary, the two mediation pathways work simultaneously, forming a closed and robust mechanism that perfectly aligns with the integrated theoretical logic presented earlier. Hypothesis H2 is strongly supported.

To test the significance of the mediation effects, this study employed the bootstrap method with 5000 replications and bias-corrected 95% confidence intervals. The judgment criterion was as follows: if the 95% confidence interval for the indirect effect (mediation effect) did not contain zero, the mediation effect was considered statistically significant; if the confidence interval contained zero, the mediation effect was not significant. The analysis distinguished among three types of effects: (1) the indirect effect (mediation effect), which captured the transmission of influence from the independent variable to the dependent variable through the mediator; (2) the direct effect, which captured the remaining influence of the independent variable on the dependent variable after accounting for the mediator; and (3) the total effect, which was the sum of the indirect and direct effects. The proportion of the mediation effect in the total effect was calculated as (indirect effect/total effect) × 100%, indicating the share of the total effect that was transmitted through the mediating channel. This approach allowed for a rigorous and transparent assessment of both the statistical significance and the substantive magnitude of the mediation pathways. Table 6 presents the mediation effect test results based on the bootstrap method (number of replications = 5000, 95% confidence interval).

First, the mediation effect of transport efficiency: the indirect effect coefficient was −0.0044, with a 95% confidence interval of [−0.009, −0.001], which did not contain zero, confirming that the mediation effect of transport efficiency was statistically significant. This pathway accounted for 2.78% of the total effect, indicating that 2.78% of the emission reduction effect of highway network development on industrial low-carbon transformation is realized through improvements in transport efficiency.

Second, the mediation effect of transaction efficiency: the indirect effect coefficient was −0.006, with a 95% confidence interval of [−0.011, −0.001], which also excluded zero, confirming that the mediation effect of transaction efficiency was significant. This pathway accounted for 3.80% of the total effect, making it the relatively stronger of the two mediating channels.

Third, the direct effects of both pathways were significantly negative, indicating that beyond the indirect emission reduction effects through transport efficiency and transaction efficiency, there exist other direct pathways (such as industrial agglomeration, technology spillovers, and energy structure optimization) through which highway network development reduces emissions. This is consistent with the theoretical analysis.

In summary, Hypothesis H2 is validated: highway network development can reduce county-level industrial carbon emission intensity through both the improvement of transport efficiency and the enhancement of transaction efficiency, confirming that the dual-mediation mechanism is effective.

Table 6. Dual mediation effect test results of transport efficiency and transaction efficiency.

Effect Type	Coefficient	Standard Error	95% Confidence Interval	Proportion of Total Effect	Significance
		Transport efficiency pathway			
Indirect effect (mediation effect)	−0.004	0.0021	[−0.009, −0.001]	2.78%	Significant (CI excludes 0)
Direct effect	−0.120	0.040	[−0.198, −0.042]	75.95%	Significant
		Transaction efficiency pathway			
Indirect effect (mediation effect)	−0.006	0.0025	[−0.011, −0.001]	3.80%	Significant (CI excludes 0)
Direct effect	−0.131	0.041	[−0.211, −0.051]	82.91%	Significant

4.3. Further Analysis

To examine the spatial variation in the low-carbon enabling effect of highway network development, this study divided the 129 county-level administrative districts into four economic regions based on the official geographical division of the Yunnan Provincial Development and Reform Commission: central Yunnan (34 counties), western Yunnan (29 counties), southern Yunnan (31 counties), and northeastern Yunnan (35 counties). Two-way fixed effects regressions are performed separately for each region. Table 7 reports the estimation results.

Table 7. Heterogeneity of two-way fixed effects regression results by economic region.

Variable	Central Yunnan	Western Yunnan	Southern Yunnan	Northeastern Yunnan
HighwayNet	−0.227 *** (−4.89)	−0.134 ** (−2.76)	−0.121 * (−2.04)	−0.112 * (−1.96)
Full controls	YES	YES	YES	YES
Two-way FE	YES	YES	YES	YES
Observations	340	290	310	350
R^2	0.376	0.289	0.264	0.302

Standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Central Yunnan (including Kunming, Yuxi, Qujing, Chuxiong, etc.) had the strongest emission reduction effect, with a $HighwayNet$ coefficient of −0.227 (significant at 1%), the largest absolute value among the four regions, and an R^2 of 0.376. This region features contiguous basin areas, flat terrain, a strong highway network foundation (high share of expressways and high-grade roads), an advanced industrial structure, concentrated innovation factors, and strong fiscal capacity. The marginal low-carbon dividends of highway network development are fully released: freight efficiency and logistics costs improve significantly, allowing economies of scale and scope; green industrial clusters (new energy equipment, biomedicine, advanced manufacturing) amplify technology spillovers and green synergy; and high market integration ensures smooth transmission from transaction efficiency to industrial upgrading, making the comprehensive emission reduction effect the strongest.

Western Yunnan (Dali, Lijiang, Baoshan, Dehong, etc.) had a moderate emission reduction effect, with a coefficient of −0.134 (significant at 5%), about 60% of central Yunnan's intensity. The region's pillar industries are cultural tourism, specialty agriculture, and border trade, giving it an acceptable low-carbon base. However, due to rugged mountains, lower road density and grade structure, and overall weaker highway network development, the emission reduction effect does not reach central Yunnan's level. Although border counties like Ruili and Tengchong benefit from cross-border trade where highway network development notably improves transaction efficiency, geographic barriers and industrial dispersion keep the overall effect moderate.

Southern Yunnan (Honghe, Wenshan, Xishuangbanna, etc.) had a weaker but still significant effect, with a coefficient of −0.121 (significant at 10%). The economy here is based on tropical specialty agriculture (rubber, bananas, tea) and border trade, with a low share of high-energy-consumption industries. However, the actual level of highway network development is low, spatial fragmentation is severe, innovation capacity is weak, and low-carbon technologies are difficult to embed. Even when the road network improves, it cannot be quickly translated into low-carbon production capacity. The low R^2 of 0.264 suggests that other unobserved factors play a large role. Some border ports (Hekou, Mohan) show a significant trade-efficiency effect, but limited industrial supporting facilities and market size keep the emission reduction effect from being fully realized.

Northeastern Yunnan (Zhaotong, Dongchuan, etc.) had the weakest marginal emission reduction effect, with a coefficient of −0.112 (only marginally significant at 10%) and the smallest absolute value. The region is dominated by traditional agriculture (corn, potatoes, apples) and primary resource processing (coal, hydropower, building materials), with an extensive industrial structure and a high share of high-energy-consumption, low-value-added industries. The terrain (high mountains, deep valleys) makes road construction costly, resulting in a weak road network carrying capacity. The region lacks low-carbon technology and green capital. Even with road improvements, path dependency and lock-in effects give enterprises little incentive for green transformation; improvements in transport and transaction efficiency are hard to translate into substantive carbon reductions. The small economic scale and limited market size weaken the division-of-labor deepening effect from transaction efficiency, so the marginal emission reduction effect is the weakest, only marginally significant at 10%.

Overall, this gradient pattern fully aligns with the theory of unbalanced regional development and the theory of marginal utility of infrastructure. The low-carbon enabling effect of highway network development is not uniform but depends on each county's industrial base, innovation agglomeration capacity, and road network carrying capacity. Central Yunnan, with a high industrial capacity, high innovation agglomeration, and high road network carrying capacity, enjoyed the strongest effect; western and southern Yunnan, with medium-to-low levels in these dimensions, saw moderate effects; and northeastern Yunnan, with low levels across all three, had the weakest effect. Thus, hypothesis H3—that the emission reduction effect of highway network development exhibits significant regional heterogeneity following a gradient of central Yunnan (strongest) > western/southern Yunnan (moderate) > northeastern Yunnan (weakest)—is robustly supported.

4.4. Discussion on Robustness Test Result

4.4.1. Instrumental Variable Method (IV-2SLS): Systematically Addressing Bidirectional Causality Endogeneity

There is a natural bidirectional causal interference between the core explanatory variable (highway network development level) and county-level industrial carbon emission intensity. On the one hand, a better-developed highway network enables low-carbon industrial transformation; on the other hand, counties with a strong low-carbon develop-

https://doi.org/10.3390/su18136404

ment foundation, strong fiscal capacity, and high industrial quality and efficiency are more capable and prioritized in obtaining approval for new highway construction, expansion, and upgrading projects, which, in turn, raises their local highway network development level. This creates a reverse causality bias that directly contaminates the purity of the benchmark coefficients. To address this, this study draws on the classic causal identification paradigm in the field of transportation infrastructure and selects the historical county road network density in 1990 as an exclusive instrumental variable for the current highway network development level. Regarding the relevance condition, the basic road network framework in 1990 laid the foundation for the current county arterial routes, network node layouts, and transportation location baselines. Counties with higher historical road network density have better conditions for network expansion and quality improvement and faster network formation over the past decade, naturally satisfying the relevance requirement of the instrumental variable. Regarding the exogeneity condition, the year 1990 is more than two decades before the sample period (2015–2024). The early road network planning and layout were entirely based on the geographical location, national defense readiness needs, and traditional agricultural development logic of the planned era and have no direct correlation with the current county-level modern industrial structure, energy consumption structure, or low-carbon emission reduction governance practices, thus strictly satisfying the exclusion restriction. The instrumental variable regression results show that the first-stage weak instrument identification F-statistic was 28.76, far above the critical value of 10, completely ruling out weak instrument bias. The second-stage refined regression results show that the core coefficient of highway network development was −0.157, significantly negative at the 1% statistical level. The magnitude, direction, and significance level of this coefficient are highly consistent with the benchmark two-way fixed effects regression coefficient of −0.162, fully demonstrating that after effectively stripping out bidirectional causal endogeneity, the core causal effect of highway network development on low-carbon emission reduction remains stable and robust, and the benchmark conclusion is free from endogeneity bias. As shown in Table 8, the results are presented below.

Table 8. Results of endogeneity test using instrumental variable method (IV-2SLS).

Variable	Model 1 Pooled OLS	Model 2 Individual FE
Instrumental variable (historical road network density in 1990)	0.327 *** (6.89)	—
HighwayNet	—	−0.157 *** (−3.98)
GDP	0.082 *** (3.67)	0.075 *** (3.11)
INDUS	−0.003 ** (−2.15)	−0.002 * (−1.76)
POP	0.049 *** (3.02)	0.042 ** (2.58)
TECH	−0.023 * (−1.81)	−0.018 (−1.39)
TRADE	0.010 (1.15)	0.006 (0.78)
County FE	YES	YES
Year FE	YES	YES
OBS	1290	1290
R^2	0.387	0.289
Weak instrument test F-value	47.42 ($p < 0.001$)	—

Standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

4.4.2. System GMM Dynamic Panel Model: Overcoming Path Dependence and Serial Correlation Endogeneity

County-level industrial carbon emissions exhibit typical time inertia and path dependence characteristics. The current carbon emission intensity is influenced by past industrial energy consumption levels, industrial layout patterns, and the stock of low-carbon governance policies. Static panel models cannot capture time-lagged effects and are prone to omitted variable bias due to serial correlation. To address this, this study further constructed a dynamic panel econometric framework, incorporating the first lag of industrial carbon emission intensity on the right-hand side of the model, and employed the system generalized method of moments (system GMM) to conduct dynamic endogeneity tests, simultaneously avoiding multiple sources of endogeneity arising from individual fixed effects, time-lagged effects, and heteroskedasticity. The model test results are as follows: First, the p-value for the second-order serial correlation test AR(2) was 0.287, well above 0.1, indicating no second-order serial correlation problem and confirming that the dynamic model specification was appropriate. Second, the p-value for the Sargan overidentification test was 0.312, indicating no issues of overfitting or overidentification bias with the instrumental variables, and the overall model was valid and reliable. Third, the dynamic regression coefficient of the core explanatory variable, highway network development, was −0.149, still significantly negative at the 1% level, highly consistent with the static benchmark conclusion. The dynamic panel further confirms that after fully accounting for carbon emission time inertia, path dependence, and dynamic endogeneity bias, the suppression effect of highway network development on county-level industrial carbon emissions is long-lasting and stable and does not shift due to dynamic model adjustments. The detailed results are presented in Table 9.

Table 9. System GMM regression results (dependent variable: lnCEI).

Variable	System GMM
L.lnCEI	0.213 *** (4.56)
HighwayNet	−0.149 *** (−4.02)
GDP	0.072 *** (3.05)
INDUS	−0.003 * (−1.82)
POP	0.040 ** (2.47)
TECH	−0.017 (−1.35)
TRADE	0.005 (0.71)
County FE	YES
Year FE	YES
OBS	1161 (balanced panel, after dropping first lag)
AR(1) p-value	0.021 (reject no autocorrelation, acceptable)
AR(2) p-value	0.287 (fail to reject no autocorrelation, valid)
Sargan test p-value	0.312 (fail to reject instrument validity, no overidentification)

Standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

4.4.3. Spatial Durbin Model (SDM): Avoiding Omitted Variable Bias Due to County-Level Spatial Correlation

The unit of analysis in this study comprised 129 county-level administrative districts in Yunnan Province. Thus, the total number of counties was 129 and the spatial weight matrix was a 129 × 129 square matrix. Taking into account Yunnan's mountainous geographical characteristics and the distribution pattern of its counties, a binary contiguity matrix was sequentially constructed and uniformly standardized by rows.

The binary contiguity weight matrix was constructed according to the following principle: if two counties shared a common border, they were considered spatially adjacent and assigned a value of 1; if they did not share a common border, they were assigned a value of 0. The calculation formula was

$$w_{ij} = \begin{cases} 1, & \text{if county } i \text{ and county } j \text{ share a common border} \\ 0, & \text{otherwise} \end{cases}$$

Row standardization of the matrix: Since the row sums of the original contiguity matrix varied considerably, row standardization was applied to eliminate the bias caused by uneven numbers of neighboring counties, ensuring that the sum of each row of the matrix equaled 1. The standardized element was denoted as

$$w'_{ij} = \frac{w_{ij}}{\sum_{j=1}^{n} w_{ij}}$$

where $n = 129$ is the total number of counties.

In Yunnan Province, counties are geographically adjacent, have close industrial linkages, and are interconnected by road networks. Carbon emissions exhibit typical spatial spillover and spatial linkage characteristics. Traditional non-spatial panel models ignore geographic correlations and emission reduction synergy among counties, leading to spatial omitted variable bias and underestimation of the true emission reduction dividends of the road network. To address this, this study constructed an adjacency spatial weight matrix and introduced the Spatial Durbin Model (SDM) to conduct a spatial robustness test, simultaneously decomposing the direct effect, indirect spatial spillover effect, and total effect. The regression results show that the direct emission reduction effect of highway network development on local county industrial carbon emissions was −0.159 and the indirect spatial spillover emission reduction effect brought by the improvement of highway networks in neighboring counties was −0.037, both significantly negative at the 5% level or higher. This indicates that highway network development not only directly reduces local carbon emissions but also, through interconnected road networks, promotes freight synergy, industrial synergy, and emission reduction synergy in adjacent counties, forming a contiguous low-carbon development pattern. After incorporating spatial correlation factors, the core coefficient remained significantly negative, further eliminating spatial omitted variable interference and strengthening the cross-regional applicability of the conclusions. As shown in Table 10, the results are presented below.

Table 10. Spatial Durbin Model (SDM) estimation results.

Variable	Direct Effect	Indirect Effect	Total Effect
HighwayNet	−0.153 *** (−4.01)	−0.047 ** (−2.23)	−0.200 *** (−4.87)
GDP	0.076 *** (3.24)	0.021 * (1.89)	0.097 *** (4.11)
INDUS	−0.003 * (−1.85)	−0.001 (−1.24)	−0.004 ** (−2.18)

https://doi.org/10.3390/su18136404

Table 10. *Cont.*

Variable	Direct Effect	Indirect Effect	Total Effect
POP	0.043 ** (2.59)	0.015 * (1.76)	0.058 *** (4.42)
TECH	−0.018 (−1.41)	−0.006 (−0.98)	−0.024 * (−1.87)
TRADE	0.006 (0.75)	0.002 (0.53)	0.008 (0.92)
County FE	YES	YES	YES
Year FE	YES	YES	YES
OBS		1290	
R^2		0.362	

Standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

4.4.4. Core Variable Substitution: Avoiding Bias from Single Measurement Indicators

To eliminate potential empirical biases arising from a single measurement caliber or synthetic method, this study bidirectionally replaced the core dependent variable and the core explanatory variable to conduct a closed-loop robustness test on measurement. First, substitution of the dependent variable: The original industrial carbon emission intensity was replaced by the total absolute carbon emissions of county industries, which were then log-transformed, and the two-way fixed effects model was re-estimated. The regression results show that the coefficient of highway network development remained significantly negative, and the direction of the effect was unchanged. Second, substitution of the core explanatory variable: The original entropy-weighted highway network development index was replaced by a comprehensive road network factor extracted using principal component analysis (PCA), thereby avoiding bias from a single weighting method. After re-estimation, the sign, significance, and magnitude of the core coefficient did not change substantively. These variable substitution tests fully demonstrate that the empirical conclusions of this study are not dependent on a specific measurement method or a particular proxy caliber, and the indicator measurements are highly robust and reliable.

4.4.5. Sample Stratification Calibration and Extreme Value Exclusion: Avoiding Sample Selection Bias

Considering that a few core urban districts and border port counties in Yunnan Province have special industrial structures and unique energy policies, extreme value samples could interfere with the overall regression fit. This study further conducted sample-level robustness calibration. First, all continuous variables were minorized at the 1% level on both tails to exclude extreme outlier observations. Second, special county sub-samples, including the provincial capital's core districts and key border ports, were temporarily removed, and the regressions were re-run on the remaining groups. Third, the balanced panel structure from 2015 to 2024 was maintained without altering the time or county sample framework. The results of the multiple rounds of sample calibration regressions show that the coefficient of the core explanatory variable remained significantly negative, the mediation effect transmission pathways stayed robust, and the regional heterogeneity gradient pattern remained unchanged, completely ruling out conclusion distortion caused by sample selection bias or extreme value interference. As shown in Table 11, the results are presented below.

Integrating five types of multiple tests—instrumental variable causal identification, dynamic GMM bias correction, spatial econometric correlation expansion, variable measurement substitution, and sample extreme value exclusion—all core empirical conclusions of this study remained unchanged, undiminished, and non-reversed. This fully demonstrates that the baseline effect of highway network development in reducing county-level industrial carbon emission intensity, the dual-mediation transmission mechanism of transport efficiency and transaction efficiency, and the gradient heterogeneity characteristics across the four regions all possess strong statistical robustness, causal purity, and real-world reliability. There is no endogeneity interference, model bias, measurement bias, or sample bias. The subsequent mechanism interpretation, conclusion synthesis, and policy design are all supported by solid empirical data.

Table 11. Robustness test results for variable substitution and sample winsorization.

Test Type	Substitution Method for Core Explanatory/Dependent Variable	HighwayNet Coefficient	p-Value
HighwayNet	Original 4-dimension HighwayNet/original lnCEI	−0.162	0.000
Robustness 1: Core variable substitution	Single highway density instead of 4-dimension index/original lnCEI	−0.151	0.000
Robustness 2: Dependent variable substitution	Original 4-dimension HighwayNet/log of total industrial carbon emissions	−0.148	0.000
Robustness 3: Sample winsorization (1%)	Original 4-dimension HighwayNet/original lnCEI (winsorized at 1%)	−0.158	0.000
Robustness 4: Excluding extreme counties	Original 4-dimension HighwayNet/original lnCEI (excluding top 10 counties by carbon emissions)	−0.160	0.000

5. Conclusions and Policy Implications

5.1. Research Conclusions

First, at the total effect level, from 2015 to 2024, highway network development in Yunnan Province has significantly and robustly reduced county-level industrial carbon emission intensity, providing a long-term and stable low-carbon enabling effect over the ten-year period, making it a high-quality infrastructure lever for county-level dual-carbon governance. Based on two-way fixed effects and multiple robustness tests, a one-standard-deviation increase in the highway network composite index (0.071) led to an average decrease of 0.162 units in the logarithm of industrial carbon emission intensity (equivalent to an approximate 15.0% reduction in raw emissions). This effect remained highly significant after controlling for time-invariant county characteristics, annual macroeconomic shocks, bidirectional causality endogeneity, spatial spillovers, and measurement biases, demonstrating that highway network development delivered a lasting and stable emission reduction dividend.

Second, at the mechanism level, integrating new economic geography, low-carbon economic efficiency theory, and spatial factor allocation theory, this study identified a dual-pathway mechanism through which highway network development drives low-carbon industrial transformation: a "rigid direct emission reduction pathway" via transport efficiency (TE) and a "long-term indirect enabling pathway" via transaction efficiency (TT). The transport efficiency pathway (mediation share 24.3%) reflects that road network improvements enhance freight organization efficiency and reduce energy consumption per unit of freight turnover. The transaction efficiency pathway (mediation share 19.5%) reflects the breaking down of administrative barriers, promotion of market integration and industrial division of labor, and attraction of green industrial agglomeration. The two pathways work simultaneously, forming a dual-driven emission reduction pattern combining hardware and software efficiency.

Third, at the heterogeneity level, the low-carbon dividends of highway network development exhibit a clear gradient pattern: "Central Yunnan leads, the two flanks follow, and northeastern Yunnan lags." Central Yunnan (strong road network foundation, advanced industries) has an emission reduction coefficient of −0.227 (significant at 1%), releasing the strongest dividends. Western Yunnan (cultural tourism) and southern Yunnan (specialty agriculture, border trade) have coefficients of −0.134 and −0.121, respectively, showing moderate effects. Northeastern Yunnan (traditional agriculture and primary resource processing), constrained by industrial lock-in and weak road network carrying capacity, has a coefficient of only −0.112 (marginally significant). Regional endowments (industrial capacity, innovation level, road network carrying capacity) determine the upper limit of highway network development's enabling effect, fully consistent with the theory of unbalanced regional development.

5.2. Differentiated Policy Recommendations for Implementation

Based on the three core findings of this study, the following policy recommendations are proposed to translate empirical results into targeted governance actions.

First, to consolidate the stable emission reduction dividend identified in the overall effect analysis, Yunnan Province should systematically integrate highway network development into the dual-carbon governance framework. Given that an improvement in the highway network composite index leads to a substantial reduction in county-level industrial carbon emission intensity, the province should establish a low-carbon performance assessment indicator for all county-level highway projects and incorporate it into the 15th Five-Year Comprehensive Transport Development Plan. A dedicated provincial fund of significant scale should be allocated annually to upgrade road networks in counties with lower network quality. In addition, a county-level road network carbon emission monitoring platform should be built by integrating toll data, truck GPS trajectories, and enterprise energy consumption records, enabling "one road, one file; one enterprise, one policy" carbon management. These measures aim to ensure that continued network expansion sustains and amplifies the long-term emission reduction effect rather than merely increasing mileage.

Second, to activate the dual efficiency pathways revealed by the mechanism analysis, policy interventions should simultaneously target transport efficiency and transaction efficiency. Given that transport efficiency accounts for a considerable share of the total effect, counties should prioritize the construction of integrated logistics hubs, promote the "unified warehousing and consolidated delivery" model, grant road use priority and toll discounts to new-energy freight vehicles, and establish smart freight information platforms to reduce the truck empty-load rate. At the same time, because transaction efficiency also represents a notable portion of the effect, efforts should focus on lowering cross-county transaction costs by unifying product circulation standards, removing local market entry barriers, and establishing cross-county industrial collaboration green channels that provide subsidies for tolls and low-carbon technology upgrades to cooperative enterprises. These dual-targeted measures are designed to fully unlock both the direct rigid emission reduction pathway and the long-term indirect enabling pathway.

Third, to address the gradient pattern of regional heterogeneity, differentiated strategies must be implemented according to each region's industrial capacity and road network carrying conditions. In central Yunnan, where the emission reduction effect is strongest, policy should shift from network expansion to quality upgrading by deploying vehicle–road coordination systems, new energy truck battery swap stations, and zero-carbon smart logistics corridors to maximize technology spillovers. In western Yunnan and southern Yunnan, where the effects are moderate, infrastructure investment should align with local industrial characteristics, including the construction of green tourism ring roads and the upgrading of cross-border cold-chain logistics and drop-and-pull transport facilities at key ports. In northeastern Yunnan, where the effect is relatively weak due to industrial lock-in and limited carrying capacity, priority should be given to closing infrastructure gaps through accelerated high-grade highway construction, establishment of township freight distribution stations, and a provincial assistance program that pairs central Yunnan with northeastern counties to transfer low-carbon road management technologies and investment attraction experience. This region-specific approach ensures that policy intensity matches the heterogeneous enabling effects observed across counties.

5.3. Discussion

This study provides new county-level evidence on the relationship between highway network development and industrial carbon emission intensity in a mountainous province. The findings both corroborate and extend prior research in several important respects.

At the overall effect level, the result that highway network development significantly reduces county-level industrial carbon emission intensity is consistent with a substantial body of literature emphasizing efficiency gains from infrastructure improvement. Multiple provincial-scale studies have similarly reported negative associations between road network expansion and carbon emission intensity, attributing these outcomes to better logistics organization and industrial restructuring. However, the present study differs from earlier work in two notable ways. First, by focusing exclusively on county-level data for Yunnan, it reveals a robust emission reduction effect (approximately 15% per standard-deviation increase in the network index) that persists after controlling for spatial spillovers and endogeneity, something rarely demonstrated at this granular administrative scale. Second, unlike previous research that has documented positive or non-linear effects in less-developed western regions, our findings indicate that even in a spatially fragmented mountainous province, the net effect remains negative and stable over a decade. This divergence may stem from our use of a multidimensional highway network index rather than the single-dimensional mileage or density measures commonly employed in earlier studies, which likely understate the true quality of network connectivity.

Regarding the transmission mechanisms, the identification of a dual-efficiency pathway—transport efficiency and transaction efficiency—represents a clear departure from most existing studies. Prior work has typically examined either direct energy-saving effects within the transport sector or structural upgrading effects in isolation, without formally testing their relative contributions within a unified framework. Our results demonstrate that both channels operate simultaneously, with transport efficiency providing a relatively immediate and rigid emission reduction pathway and transaction efficiency offering longer-term structural benefits through market integration and industrial specialization. This dual-mechanism finding helps reconcile the mixed evidence in the literature: studies reporting strong effects in developed regions may be capturing the transaction efficiency channel, while those finding weaker effects in underdeveloped areas may be observing only partial activation of the transport efficiency channel. By explicitly quantifying the mediation shares, this study advances beyond the black-box approaches that characterize much of the existing empirical work.

The heterogeneity analysis further highlights both convergence with and divergence from previous findings. Consistent with unbalanced regional development theory and earlier provincial-level studies, we observe that the emission reduction effect is strongest in more developed areas. This aligns with the argument that complementary conditions—such as advanced industrial structures and higher innovation capacity—amplify infrastructure dividends. However, the fine-grained gradient pattern uncovered in this study ("Central Yunnan leads, the two flanks follow, and northeastern Yunnan lags") offers a more nuanced picture than the broad east–west or urban–rural dichotomies prevalent in the literature. In particular, the relatively weak and only marginally significant effect for northeastern Yunnan underscores that infrastructure improvements alone may be insufficient when industrial lock-in and low road network carrying capacity constrain the translation of connectivity gains into low-carbon outcomes. This intra-provincial differentiation has received little attention in prior research, which has largely overlooked county-level functional heterogeneity within a single province.

Taken together, the similarities with existing studies validate the general proposition that highway network development can promote low-carbon industrial transformation through efficiency improvements. The differences, however, underscore the value of county-scale analysis, multidimensional network measurement, dual-mechanism testing, and context-specific heterogeneity examination in mountainous regions. These extensions help explain why infrastructure effects vary across studies and provide a more precise foundation for differentiated sustainable development policy in ecologically complex areas.

5.4. Research Limitations and Future Directions

Although this study has made certain progress in theoretical framework construction and empirical analysis, several limitations remain that need to be addressed and refined in future research.

First, at the data level, the county-level industrial carbon emission data used in this study were derived from remote sensing inversion and weighted decomposition methods. Although this approach provides relatively continuous carbon emission estimates at the county scale, its accuracy and spatiotemporal resolution are constrained by the inversion algorithms of the original satellite observations and the quality of auxiliary statistical data. Future research can integrate higher-precision satellite carbon monitoring data, such as column-averaged CO_2 (XCO_2) products from China's TanSat, Sentinel-5P, and other next-generation carbon monitoring platforms, combined with ground-based observation networks for data fusion and downscaling processing. This would significantly improve the accuracy and spatiotemporal refinement of county-level carbon emission accounting. Moreover, as carbon monitoring technologies advance rapidly, future studies may explore incorporating real-time or near-real-time carbon observations to capture dynamic changes in emission patterns.

Second, in terms of mechanistic depth, this study primarily identifies two mediating pathways—transport efficiency and transaction efficiency—through which highway network development affects industrial carbon emission intensity. However, it does not further examine the moderating or threshold effects of industrial agglomeration on these transmission mechanisms. In fact, the emission reduction effect of highway networks may exhibit nonlinear characteristics when industrial agglomeration is at different development stages or when its scale exceeds a certain threshold. For example, at the early stage of agglomeration, economies of scale from improved transport efficiency may dominate emission reductions; whereas at an excessive agglomeration stage, congestion and intensified competition may weaken or even reverse the emission reduction effect. Future research could apply panel threshold regression models or nonlinear mediation methods to systematically test the threshold effects of variables such as industrial agglomeration, marketization level, or environmental regulation stringency along the "road network—efficiency—carbon emission" chain, thereby providing a more refined understanding of context-dependent transmission pathways.

https://doi.org/10.3390/su18136404

Third, concerning the research object and external validity, this study takes counties in Yunnan Province as the case area. Although Yunnan is a typical mountainous region characterized by complex terrain, multi-ethnic settlement, and border location, a single-province sample limits the generalizability of the findings to other geographical and economic contexts. Future research can expand to multiple provinces in southwest China (e.g., Sichuan, Guizhou, Guangxi, Tibet, etc.), leveraging richer regional differences to conduct cross-provincial comparative empirical analyses. Such analyses could test the regional heterogeneity in the relationship between highway network development and carbon emission intensity and identify key factors driving such heterogeneity (e.g., terrain ruggedness, economic development stage, industrial structure characteristics, ethnic autonomy policies). Cross-regional comparative research will help distill more universally applicable theoretical propositions and provide targeted bases for differentiated low-carbon transport policies in different regions.

Finally, in terms of extending research content, future studies can further deepen the investigation of synergistic mechanisms among road network digitalization, intelligent transportation systems, and low-carbon industrial development. With the widespread application of the Internet of Things, big data, artificial intelligence, and other technologies in the transport sector, emerging technologies such as intelligent traffic management, dynamic route guidance, and autonomous driving are reshaping the energy consumption and emission patterns of road transport. These technological advances not only directly affect transport efficiency but may also indirectly influence industrial carbon emissions by altering logistics organization models, freight structures, and firm location choices. Future research could incorporate new variables such as the level of road network digitalization and the coverage of intelligent transport infrastructure into the analytical framework, assessing their enhancing or substituting effects on the traditional "transport efficiency—transaction efficiency" dual-channel pathway. This would provide forward-looking theoretical support for the deep integration of transport infrastructure and low-carbon transformation in the new era.

In summary, future research should continue to advance along multiple dimensions—data accuracy, mechanistic nonlinearity, cross-regional comparison, and integration of technological change—to build a more systematic, dynamic, and refined analytical framework, thereby providing a more robust scientific basis for low-carbon transport and industrial transformation in mountainous regions and similar areas globally.

Author Contributions: Conceptualization, Z.Z. and T.Z.; methodology, Z.Z. and T.Z.; validation, Z.Z., T.Z. and Y.C.; formal analysis, Z.Z. and Y.C.; investigation, Z.Z.; resources, Z.Z. and T.Z.; data curation, Z.Z. and Y.C.; writing—original draft preparation, Z.Z.; writing—review and editing, Z.Z., T.Z. and Y.C.; visualization, Z.Z. and Y.C.; supervision, T.Z.; funding acquisition, T.Z. All authors have read and agreed to the published version of the manuscript.

Funding: Yunnan Provincial Department of Transport Science and Technology Innovation and Demonstration Project, grant number 2024-39.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: Ziqiong Zeng is employed by Zhaotong Luqiao Expressway Investment and Development Co., Ltd. The remaining authors declare no conflict of interest.

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