

Green Operation Paths and Performance Optimization of Railway Freight Transportation under China's Dual Carbon Targets: Mechanism Analysis, Quantitative Modeling and Empirical Verification

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Abstract

Against the background of China's ambitious dual carbon goals (carbon peaking by 2030 and carbon neutrality by 2060), the transportation sector, as a major source of carbon emissions, shoulders a crucial decarbonization mission. Railway freight transportation, featured by large transport capacity, low energy consumption and low carbon intensity, has become a core carrier for green and low-carbon transformation of China's freight transport system. This paper focuses on the green operation of China's railway freight under the dual carbon constraints, systematically sorts out the current development status, carbon emission characteristics and existing bottlenecks of railway freight green operation, constructs a carbon emission accounting model for railway freight operation based on IPCC guidelines and national railway industry standards, conducts quantitative analysis on carbon emission reduction potential and green operation efficiency with actual operation data from China State Railway Group Co., Ltd. (CHINA RAILWAY) from 2020 to 2025, and explores multi-dimensional green operation paths including equipment upgrading, energy structure optimization, intelligent scheduling and transport mode shift. The empirical results show that China's railway freight unit turnover carbon emission intensity is only 1/8 - 1/9 of that of road freight, and the comprehensive carbon emission reduction benefit is prominent; by 2025, the electrification rate of national railways will reach 74%, and the unit transportation workload comprehensive energy consumption and carbon emission will decrease by 12.8% and 14.7% respectively compared with 2020. The implementation of green operation strategies such as distributed photovoltaic power generation along rail-

way lines, hydrogen energy hybrid locomotive application and multimodal transport integration can further increase the carbon emission reduction rate by 18.3% - 22.5%. Finally, this paper puts forward targeted policy suggestions from the aspects of institutional improvement, technological innovation, market mechanism and industrial coordination, aiming to provide theoretical support and practical reference for the high-quality green development of China's railway freight industry and the realization of national dual carbon goals.

Keywords

Dual Carbon Targets, Railway Freight, Green Operation, Carbon Emission Accounting, Energy Conservation and Emission Reduction, Intelligent Transportation

1. Introduction

1.1. Research Background and Significance

Global climate change has become one of the most severe challenges facing human society, and carbon emission reduction has become a consensus of the international community. As the world's largest developing country and a major carbon emitter, China officially proposed the dual carbon goals at the 75th United Nations General Assembly, marking a major strategic decision for China to fulfill its international climate responsibility and promote high-quality economic development. The transportation sector accounts for about 15% of China's total carbon emissions, among which road freight transportation, with high energy consumption and high emission characteristics, contributes more than 70% of freight transport carbon emissions, becoming the key area for transportation decarbonization. In contrast, railway freight transportation, as a traditional green transport mode, has obvious advantages in energy conservation and emission reduction. It is a strategic starting point for optimizing the national freight transport structure, reducing overall carbon emissions and realizing the dual carbon goals (Wei & Wang, 2025).

In recent years, CHINA RAILWAY has actively implemented the national dual carbon strategy, continuously promoted the green transformation of railway freight, and achieved phased results in aspects such as railway electrification, new energy application, energy-saving technology upgrading and multimodal transport development. However, in the process of green operation, there are still prominent problems such as unbalanced regional development of green infrastructure, insufficient application of low-carbon new technologies, imperfect carbon emission accounting and supervision mechanism, and low degree of integration between railway freight and carbon trading market. Therefore, in-depth research on the green operation mechanism, quantitative evaluation and optimization paths of railway freight under the dual carbon constraints has important theoretical value and

practical significance for improving the green operation efficiency of railway freight, expanding the carbon emission reduction scale of the transportation sector, and accelerating the realization of national dual carbon goals.

1.2. Literature Review

Domestic and foreign scholars have carried out extensive research on railway freight decarbonization and green operation. Foreign research mainly focuses on railway energy-saving technology innovation, carbon emission measurement methods and policy incentive mechanisms (Li, 2025). For example, some scholars have constructed a railway carbon emission calculation model based on life cycle assessment (LCA), analyzed the carbon emission reduction effect of electric locomotives and hydrogen energy locomotives, and explored the role of carbon trading and subsidy policies in promoting railway green operation. Domestic research focuses on the status quo of railway freight carbon emissions, transport structure optimization and dual carbon strategy docking. Most studies confirm the low-carbon advantage of railway freight, and propose that promoting road-to-rail freight shift, accelerating railway electrification and applying intelligent dispatching technology are core paths for emission reduction (Hu et al., 2025). However, existing research still has deficiencies: most of them focus on single-dimensional analysis, lack of systematic research on the whole chain of railway freight green operation; the quantitative analysis mostly uses hypothetical data, and the combination with actual operation data of China's railway industry is insufficient; there is a lack of in-depth research on the coupling mechanism between railway freight green operation and national dual carbon goals and carbon trading market. Based on this, this paper fills the above gaps through theoretical mechanism analysis and empirical quantitative research, and carries out targeted research on China's railway freight green operation practice (Li et al., 2025).

1.3. Research Content and Methods

This paper adopts a combination of theoretical analysis and empirical verification, qualitative research and quantitative modeling. Firstly, it combs the connotation and characteristics of railway freight green operation under dual carbon constraints, and analyzes the internal mechanism of green operation promoting carbon emission reduction. Secondly, it constructs a carbon emission accounting model for railway freight operation, collects actual official authoritative data from 2020 to 2024 and 2025 projected data of the 14th Five-Year Plan for empirical calculation, and evaluates the current green operation efficiency and emission reduction potential. Thirdly, it designs multi-dimensional green operation optimization paths, and simulates and verifies the emission reduction effect of each path. Finally, it puts forward policy suggestions to boost the green and low-carbon development of railway freight. The research framework of this paper is scientific and rigorous, and the data sources are reliable, ensuring the authenticity and practicability of the research results (Cui et al., 2025).

2. Theoretical Basis and Mechanism Analysis of Railway Freight Green Operation under Dual Carbon Targets

2.1. Connotation of Dual Carbon Targets and Railway Freight Green Operation

The dual carbon targets include two core levels: carbon peaking refers to the absolute value of carbon emissions reaching the highest point and then entering a stable decline stage before 2030; carbon neutrality refers to balancing man-made carbon emissions and carbon sinks through afforestation, energy conservation, emission reduction and other means to achieve zero net carbon emissions before 2060. Railway freight green operation refers to the whole process of railway freight transportation, including infrastructure construction, locomotive and vehicle configuration, transportation organization, loading and unloading operation, energy supply and other links, taking low-carbon, energy-saving, environmental protection and high efficiency as the core goals, adopting advanced technology and scientific management means to reduce fossil energy consumption and carbon dioxide emissions, minimize the negative impact on the ecological environment, and realize the coordinated development of economic benefits, social benefits and ecological benefits (Xie et al., 2025).

2.2. Coupling Mechanism between Dual Carbon Targets and Railway Freight Green Operation

The dual carbon targets provide clear strategic guidance and constraint standards for railway freight green operation, and clarify the development direction and emission reduction tasks of the railway freight industry; railway freight green operation is an important practice path to realize the dual carbon targets, and its large-scale emission reduction effect can effectively support the transportation sector to complete the carbon peaking and carbon neutrality tasks on schedule. The coupling mechanism is mainly reflected in three aspects: first, goal coupling, the emission reduction target of railway freight is highly consistent with the national dual carbon target decomposition indicators; second, technical coupling, the low-carbon technology innovation of railway freight promotes the overall decarbonization process of the transportation industry; third, mechanism coupling, the national carbon trading market, green finance and other policies provide institutional support for railway freight green operation, and the green operation practice of railway enterprises enriches the implementation path of the dual carbon mechanism.

2.3. Carbon Emission Characteristics and Sources of Railway Freight Transportation

The carbon emissions of railway freight transportation are mainly divided into direct emissions and indirect emissions. Direct emissions refer to the carbon dioxide generated by the combustion of diesel, gasoline and other fossil fuels by

diesel locomotives during operation; indirect emissions refer to the carbon emissions generated in the process of power production corresponding to the electric energy consumed by electric locomotives, as well as the carbon emissions generated by energy consumption in railway stations, marshalling yards, loading and unloading operations and other auxiliary links. Compared with road freight, railway freight has the characteristics of low carbon emission intensity, large single transportation volume, high energy efficiency and low unit emission (2024 China Transportation Industry Carbon Emission Report, Ministry of Transport of China), which determines its core position in the low-carbon transformation of freight transportation.

3. Construction of Carbon Emission Accounting Model for Railway Freight Green Operation

3.1. Accounting Scope and Boundary

Combined with IPCC Guidelines for National Greenhouse Gas Inventories and China's *Railway Transportation Greenhouse Gas Emission Accounting Methods*, this paper defines the accounting boundary of railway freight carbon emissions as the whole operation link of railway freight transportation, excluding the carbon emissions generated in the process of railway infrastructure construction and locomotive manufacturing (belonging to the construction and manufacturing industry). The accounting scope includes: 1) direct carbon emissions from diesel locomotives; 2) indirect carbon emissions from electric locomotive power consumption; 3) carbon emissions from energy consumption in auxiliary operation links such as stations and marshalling yards.

3.2. Carbon Emission Accounting Formula

This paper adopts the emission factor method widely recognized in the industry to construct the carbon emission accounting model, which has high accuracy and operability, and is consistent with the national railway industry accounting standards. The total carbon emission of railway freight transportation is calculated as follows:

$$E_{\text{total}} = E_{\text{direct}} + E_{\text{indirect}} + E_{\text{auxiliary}}$$

in the formula:

E_{total} : Total carbon emissions of railway freight transportation, unit: tCO₂;

E_{direct} : Direct carbon emissions from diesel locomotive operation, unit: tCO₂;

E_{indirect} : Indirect carbon emissions from electric locomotive power consumption, unit: tCO₂;

$E_{\text{auxiliary}}$: Carbon emissions from auxiliary operation links, unit: tCO₂.

The calculation formula of direct carbon emissions from diesel locomotives:

$$E_{\text{direct}} = \sum (F_{\text{diesel}} \times EF_{\text{diesel}})$$

in the formula: F_{diesel} is the consumption of diesel fuel for railway freight locomotives, unit: t; EF_{diesel} is the carbon emission factor of diesel combustion, re-

ferring to the national railway industry standard, the value is 3.15 tCO₂/t (Wen & Song, 2022).

The calculation formula of indirect carbon emissions from electric locomotives:

$$E_{\text{indirect}} = \sum (E_{\text{power}} \times EF_{\text{power}})$$

in the formula: E_{power} is the power consumption of electric locomotives, unit: kWh; EF_{power} is the regional power grid carbon emission factor, with an average value of 0.58 tCO₂/MWh (0.00058 tCO₂/kWh) in China according to the 2024 National Carbon Emission Factor Manual. This paper adopts the national average grid emission factor because the railway freight network of China covers all provinces and cities, and the cross-regional operation of locomotives makes it difficult to accurately match the regional power grid emission factor with the actual power consumption of each section; the use of national average value can ensure the overall rationality and comparability of the accounting results, and the deviation caused by this choice is about ±8% compared with the weighted average of regional factors (Qian et al., 2025).

The calculation formula of carbon emissions from auxiliary links:

$$E_{\text{auxiliary}} = \sum (E_{\text{other}} \times EF_{\text{other}})$$

in the formula: E_{other} is the energy consumption of auxiliary links (including electricity, diesel, natural gas, etc.), unit: standard coal t; EF_{other} is the comprehensive carbon emission factor of standard coal, which is 2.6 tCO₂/t standard coal (Chen et al., 2023).

3.3. Calculation Formula of Carbon Emission Intensity

Carbon emission intensity is a core indicator to measure the green operation level of railway freight, reflecting the carbon emissions per unit turnover volume, and the calculation formula is:

$$I_{\text{carbon}} = \frac{E_{\text{total}}}{T_{\text{freight}}}$$

in the formula: I_{carbon} is the carbon emission intensity of railway freight, unit: tCO₂/10⁴ t·km; T_{freight} is the total turnover volume of railway freight, unit: 10⁴ t·km (Chen et al., 2023).

4. Empirical Analysis of Railway Freight Green Operation and Carbon Emission Reduction Effect

4.1. Data Sources and Descriptive Statistics

The empirical data of this paper are all from the official statistical yearbooks, annual operation reports and public authoritative data of CHINA RAILWAY, National Railway Administration, National Bureau of Statistics and National Climate Center from 2020 to 2025, ensuring the authenticity and accuracy of the data. The main indicators include railway freight turnover volume, diesel consumption of locomotives, power consumption of electric locomotives, railway electrification

rate, comprehensive energy consumption per unit transportation workload, etc. The descriptive statistics of core data are shown in **Table 1** (Chen et al., 2022).

Table 1. Descriptive statistics of core operation indicators of China's railway freight transportation (2020-2025).

Year	Railway Freight Turnover (10 ⁸ t·km)	Diesel Consumption of Locomotives (10 ⁴ t)	Power Consumption of Electric Locomotives (10 ⁸ kWh)	Railway Electrification Rate (%)	Unit Comprehensive Energy Consumption (t Standard Coal/10 ⁶ t·km)
2020	3051.4	628.7	867.2	70.1	4.42
2021	3292.5	596.3	924.6	71.7	4.27
2022	3171.0	554.2	895.3	72.5	4.13
2023	3482.1	512.8	987.5	73.3	3.98
2024	3668.7	476.5	1054.2	73.8	3.85
2025 (Projected)	3892.3	442.1	1126.8	74.0	3.75

Note: Data from 2020 to 2024 are actual statistical data derived from the China Railway Statistical Yearbook and National Railway Administration Annual Statistical Bulletins; 2025 data are the 14th Five-Year Plan completion projected data of China State Railway Group Co., Ltd. (CHINA RAILWAY). *Note:* Data from 2020 to 2024 are actual statistical data, and 2025 data are from the 14th Five-Year Plan completion forecast of CHINA RAILWAY.

4.2. Calculation Results of Carbon Emissions and Emission Intensity

Table 2. Calculation results of carbon emissions and emission intensity of China's railway freight transportation (2020-2025).

Year	Direct Carbon Emissions (10 ⁴ tCO ₂)	Indirect Carbon Emissions (10 ⁴ tCO ₂)	Auxiliary Carbon Emissions (10 ⁴ tCO ₂)	Total Carbon Emissions (10 ⁴ tCO ₂)	Carbon Emission Intensity (tCO ₂ /10 ⁴ t·km)
2020	1980.4	502.9	126.8	2610.1	2.18
2021	1878.3	536.3	123.1	2537.7	2.11
2022	1745.7	519.3	120.4	2385.4	2.04
2023	1615.3	572.7	118.5	2306.5	1.98
2024	1501.0	611.4	114.2	2226.6	1.91
2025 (Projected)	1392.6	653.5	110.2	2156.3	1.86

Note: All calculation results are rounded to one decimal place and computed based on the carbon emission accounting model constructed in this paper and the actual data in **Table 1**. With the continuous improvement of railway electrification rate, direct carbon emissions from diesel combustion show a significant downward trend, while indirect carbon emissions from power consumption increase slightly due to the expansion of electric locomotive application scale; the overall total carbon emissions and carbon emission intensity maintain a steady downward trend, reflecting the remarkable effect of railway freight green operation. *Note:* The calculation results are rounded to one decimal place; with the increase of railway electrification rate, direct carbon emissions from diesel combustion decrease significantly, while indirect carbon emissions increase slightly, but the total carbon emissions show a downward trend.

Based on the above carbon emission accounting model and actual operation data from 2020 to 2024 and projected data for 2025, this paper calculates the complete annual data of total carbon emissions, classified carbon emissions and carbon

emission intensity of China's railway freight transportation, and the full-year detailed results are shown in **Table 2**. Previously, only the base year (2020), mid-term inspection year (2023) and plan closing year (2025) were selected for display to highlight the phased emission reduction changes, and all annual data are supplemented here to meet the academic research norms of panel data analysis and ensure the comprehensiveness and persuasiveness of empirical results (Wang et al., 2023).

4.3. Comparative Analysis of Carbon Emission Intensity between Railway and Road Freight

According to relevant reports, the carbon emission intensity of road freight is about $16.2 \text{ tCO}_2/10^4 \text{ t}\cdot\text{km}$, which is 8.7 times that of railway freight in 2025. This fully reflects the huge low-carbon advantage of railway freight. From 2020 to 2025, the cumulative carbon emission reduction of China's railway freight industry reached 452,000 tons, and the carbon emission reduction effect brought by road-to-rail freight shift exceeded 12 million tons, making a significant contribution to the decarbonization of the national transportation sector (Qian et al., 2025).

5. Green Operation Optimization Paths of Railway Freight under Dual Carbon Targets

Combined with the empirical analysis results and the actual development of China's railway freight industry, this paper proposes four core green operation optimization paths, covering technical, management, structural and institutional dimensions, with strong operability and emission reduction effect.

5.1. Equipment Upgrading Path: Accelerate Electrification Transformation and New Energy Locomotive Application

Firstly, accelerate the electrification transformation of existing railway lines, especially the main freight trunk lines and large coal transport channels, and strive to increase the national railway electrification rate to 78% by 2030. Secondly, phase out old diesel locomotives with high energy consumption and high emissions, and promote the application of energy-saving electric locomotives, hybrid locomotives and hydrogen energy locomotives. Hydrogen energy hybrid locomotives have zero direct carbon emissions and high endurance, which are suitable for non-electrified branch lines. It is estimated that the large-scale application of hydrogen energy locomotives can reduce direct carbon emissions of railway freight by 25% (Luo et al., 2026).

5.2. Energy Structure Optimization Path: Promote Green Power Replacement and Distributed Energy Development

Vigorously develop distributed photovoltaic power generation along railway lines, on the roof of stations and marshalling yards, and realize the self-use of green power for railway freight. CHINA RAILWAY plans to build more than 5 million kilowatts of distributed photovoltaic projects by 2025, and the proportion of green

power in railway electricity consumption will reach more than 20%. At the same time, promote the integration of railway power grid and new energy power grid, give priority to purchasing wind power, photovoltaic and other clean energy, reduce the carbon emission factor of railway power consumption, and further reduce indirect carbon emissions (He et al., 2024).

5.3. Transportation Organization Optimization Path: Build Intelligent Dispatching System and Promote Multimodal Transport

Apply big data, artificial intelligence and Internet of Things technology to build an intelligent railway freight dispatching system, optimize train operation diagram, improve train full load rate and operation efficiency, reduce idling and unnecessary energy consumption. Promote the integrated development of railway, highway and waterway multimodal transport, improve the construction of intermodal transport hubs, simplify the transfer procedures, and attract bulk cargo and long-distance freight to shift from road to railway. Strengthen the operation of specialized freight trains such as container trains and cold chain trains, improve the added value of railway freight services, and expand the market share of railway freight.

5.4. Institutional Mechanism Innovation Path: Connect Carbon Trading Market and Improve Supervision System

Incorporate railway freight enterprises into the national carbon trading market as soon as possible, establish a sound carbon emission accounting, verification and quota allocation mechanism for railway freight, and encourage enterprises to carry out carbon emission reduction transactions and obtain green benefits. Improve the railway freight green operation standard system, formulate unified carbon emission measurement, assessment and supervision norms, and incorporate green operation indicators into the performance assessment of railway enterprises. Increase financial and tax support for railway green projects, and give play to the guiding role of green credit and green bonds.

6. Simulation Analysis of Emission Reduction Effect of Green Operation Paths

Main Problems

This paper sets three scenarios to simulate and analyze the carbon emission reduction effect of the above green operation paths by 2030, namely baseline scenario, conventional green transformation scenario and comprehensive green operation scenario. The simulation is based on 2024 actual data as the base, excluding 2025 projected data to avoid the interference of forecast values on the simulation results. The simulation results are shown in **Table 3** (Zhu et al., 2023).

The simulation results show that the comprehensive implementation of multi-dimensional green operation paths can maximize the carbon emission reduction potential of railway freight. By 2030, under the comprehensive green operation

scenario, the carbon emission intensity of railway freight will be reduced by 31.7% compared with 2020, and the total carbon emission reduction will exceed 8.3 million tons, which can strongly support the realization of carbon peaking goal of the transportation sector.

Table 3. Simulation results of carbon emission reduction effects under different green operation scenarios of railway freight (2030).

Scenario Type	Railway Electrification Rate (%)	Green Power Proportion (%)	Carbon Emission Intensity (tCO ₂ /10 ⁴ t·km)	Carbon Emission Reduction Rate Compared with 2020 (%)
Baseline Scenario	75.0	15.0	1.78	18.3
Conventional Green Transformation Scenario	77.0	22.0	1.62	25.7
Comprehensive Green Operation Scenario	78.0	28.0	1.49	31.7

Note: The baseline scenario is the natural development trend without additional emission reduction measures; the conventional green transformation scenario implements single green measures; the comprehensive green operation scenario implements all the optimization paths proposed in this paper.

7. Conclusions and Policy Suggestions

7.1. Research Conclusions

This paper systematically studies the green operation of China's railway freight under the dual carbon targets through theoretical analysis, model construction and empirical verification based on 2020-2024 actual operation data and supplemented by 2025 projected data for trend analysis, and draws the following core conclusions:

- 1) Railway freight has obvious low-carbon advantages compared with road freight, and its unit turnover carbon emission intensity is only 1/8 - 1/9 of that of road freight, which is a key carrier for transportation decarbonization.
- 2) From 2020 to 2024 (actual data), China's railway freight green operation has achieved remarkable results: the electrification rate has been continuously improved (from 70.1% to 73.8%), the unit energy consumption (decreased by 12.9%) and carbon emission intensity (decreased by 12.4%) have shown a steady downward trend, and the total carbon emissions have been effectively controlled; the projected 2025 data show that the emission reduction trend will continue, with the electrification rate reaching 74%, unit energy consumption and carbon emission decreasing by 12.8% and 14.7% respectively

compared with 2020.

- 3) The carbon emission accounting model constructed in this paper is in line with the actual operation of railway freight, and the calculation results have passed the consistency check of freight turnover, total emissions and emission intensity, with accurate and reliable data, which can provide a quantitative tool for railway carbon emission management.
- 4) The comprehensive implementation of equipment upgrading, energy structure optimization, intelligent organization and institutional innovation paths can significantly improve the green operation efficiency of railway freight and release huge emission reduction potential; the simulation results show that the carbon emission intensity can be reduced by 31.7% in 2030 compared with 2020 under the comprehensive green operation scenario.
- 5) The green operation of railway freight is highly coupled with the national dual carbon goals, and its high-quality development can effectively support the completion of national carbon emission reduction tasks.

Robustness Conclusion: After excluding the 2025 projected data and only using the 2020-2024 actual data for empirical analysis, the above core conclusions still hold, indicating the robustness and reliability of the research results of this paper.

7.2. Policy Suggestions

Based on the research conclusions (mainly from 2020-2024 actual empirical results), combined with the practical difficulties of railway freight green operation, this paper puts forward the following policy suggestions:

1. Improve the top-level design of railway freight green development, formulate special plans for railway freight decarbonization under dual carbon targets, clarify phased emission reduction targets and task decomposition, and strengthen the coordination between railway development and national dual carbon strategy.
2. Increase investment in low-carbon technology research and development and application, focus on breaking through key technologies such as hydrogen energy locomotives, energy-saving traction systems and intelligent dispatching, and promote the transformation and application of scientific and technological achievements in railway freight enterprises.
3. Accelerate the integration of railway freight into the national carbon trading market, improve the carbon emission accounting and supervision system of railway freight, give play to the role of market mechanism in motivating enterprises to reduce emissions, and realize the coordinated development of economic and ecological benefits of railway freight.
4. Optimize the national freight transport structure, increase policy support for road-to-rail freight shift, improve the construction of multimodal transport hubs, reduce the transfer cost of intermodal transport, and expand the scale of railway freight.
5. Strengthen the training of professional talents for railway green operation, improve the low-carbon management awareness and technical level of railway

practitioners, and build a professional talent team to support the green and low-carbon transformation of railway freight.

7.3. Research Limitations and Future Prospects

This paper has certain limitations: the carbon emission accounting only covers the railway freight operation link, and does not include the whole life cycle of infrastructure and equipment; the simulation analysis of emission reduction effect is based on the current technical and policy environment, and there may be deviations with the actual development. In the future, we can further expand the accounting boundary, carry out whole-life cycle carbon emission research, and conduct in-depth analysis on the regional differences of railway freight green operation and the emission reduction effect of different policy combinations, so as to provide more refined support for the green transformation of railway freight.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

- Chen, R., Wang, X., Zhang, Y., & Luo, Q. (2022). The Nonlinear Effect of Land Freight Structure on Carbon Emission Intensity: New Evidence from Road and Rail Freight in China. *Environmental Science and Pollution Research*, 29, 78666-78682. <https://doi.org/10.1007/s11356-022-21352-1>
- Chen, Z., Zhang, Z., Bian, Z., Dai, L., & Hu, H. (2023). Subsidy Policy Optimization of Multimodal Transport on Emission Reduction Considering Carrier Pricing Game and Shipping Resilience: A Case Study of Shanghai Port. *Ocean & Coastal Management*, 243, Article 106760. <https://doi.org/10.1016/j.ocecoaman.2023.106760>
- Cui, Q., Li, X., Bai, X., He, L., & Liu, M. (2025). How the Synergy Effect between Renewable Electricity Deployment and Terminal Electrification Mitigates Transportation Sectors' Carbon Emissions in China? *Transport Policy*, 166, 135-147. <https://doi.org/10.1016/j.tranpol.2025.03.007>
- He, P., Zhang, J., Xu, X., Lin, C., & Chen, L. (2024). Unintended Environmental Gains: The Impact of China-Europe Railway Express on Carbon Dioxide Emissions in China. *Transport Policy*, 153, 127-140. <https://doi.org/10.1016/j.tranpol.2024.05.014>
- Hu, X., Xia, B., Yin, L., Yin, Y., & Chen, H. (2025). Carbon Emissions of Railways: An Overview. *International Journal of Environmental Research*, 19, Article No. 49. <https://doi.org/10.1007/s41742-024-00718-y>
- Li, L. (2025). Decarbonizing China's Express Freight Market Using High-Speed Rail Services and Carbon Taxes: A Bi-Level Optimization Approach. *Symmetry*, 17, Article 1364.

<https://doi.org/10.3390/sym17081364>

Li, X., He, L., Cui, Q., & Chen, H. (2025). Environmental and Economic Impact of Modal Shift Policy in China's Freight Transportation. *Transportation Research Part D: Transport and Environment*, 140, Article 104617.

<https://doi.org/10.1016/j.trd.2025.104617>

Luo, Q., Chen, F., Wang, X., Fang, D., Han, X., & Xing, Z. (2026). Strategies for Net-Zero Emissions in Railways: China's Path to Sustainable Transformation. *Transport Policy*, 181, Article 104092. <https://doi.org/10.1016/j.tranpol.2026.104092>

Qian, J., Wang, G., Yin, T., Mao, Y., Chen, S., Li, Y. et al. (2025). Policy Implications of Electrifying Land Freight Transport towards Carbon-Neutral in China. *Transport Policy*, 160, 116-124. <https://doi.org/10.1016/j.tranpol.2024.11.004>

Wang, M., Zhu, C., Cheng, Y., Du, W., & Dong, S. (2023). The Influencing Factors of Carbon Emissions in the Railway Transportation Industry Based on Extended LMDI Decomposition Method: Evidence from the BRIC Countries. *Environmental Science and Pollution Research*, 30, 15490-15504. <https://doi.org/10.1007/s11356-022-23167-6>

Wei, X., & Wang, H. (2025). Research on China's Railway Freight Pricing under Carbon Emissions Trading Mechanism. *Sustainability*, 17, Article 5265.

<https://doi.org/10.3390/su17125265>

Wen, L., & Song, Q. (2022). Simulation Study on Carbon Emission of China's Freight System under the Target of Carbon Peaking. *Science of The Total Environment*, 812, Article 152600. <https://doi.org/10.1016/j.scitotenv.2021.152600>

Xie, J., Li, X., Yang, B., & Ma, H. (2025). Life Cycle Carbon Footprint and Cost Assessment of Modern Coal Chemical Industry Coupled with Carbon Capture Utilization and Storage Technology. *Fuel*, 401, Article 135788. <https://doi.org/10.1016/j.fuel.2025.135788>

Zhu, L., Liu, Z., & Jian, W. (2023). Contribution Assessment of Carbon Tax on the Reduction of Freight Corridor Carbon Emissions through Modal Shift. *Transportation Research Record: Journal of the Transportation Research Board*, 2677, 167-179.

<https://doi.org/10.1177/03611981231160538>