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Optimization of Railway Bulk Cargo Transportation Organization under Green and Low-Carbon Concepts

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Abstract

Driven by the global carbon neutrality target and China's dual-carbon strategic deployment, the transportation industry has become a key field for energy conservation and emission reduction. As a low-carbon, high-capacity, and stable transportation mode, railway undertakes more than 70% of domestic bulk cargo transportation including coal, iron ore and grain. However, traditional railway bulk cargo transportation organization still suffers from unreasonable train marshalling, low wagon loading rate, high empty running ratio and unscientific operation scheduling, resulting in redundant energy consumption and excessive carbon emissions, which restricts the green upgrading of railway freight systems. This paper takes the actual operation scenarios of domestic railway bulk cargo transportation as the research object, constructs a complete railway freight carbon emission accounting model based on IPCC national greenhouse gas inventory guidelines and railway industry actual operation parameters, and establishes a multi-objective transportation organization optimization model aiming at minimum carbon emission, minimum transportation cost and maximum operation efficiency. A hybrid genetic algorithm integrating particle swarm optimization is adopted to solve the nonlinear constrained optimization problem. All statistical data spanning 2020-2025 are sourced from China State Railway Group freight big data platform covering five core bulk trunk lines; raw data adopts daily statistical granularity with total valid sample volume of 192,600 groups, abnormal data from temporary line overhaul and emergency suspension is eliminated via 3σ outlier screening during preprocessing. Based on the authentic statistical operation data of China State Railway Group from 2020 to 2025, empirical verification and scheme comparison are carried out. The research results show that the optimized organization scheme significantly improves the overall operation level of bulk railway freight. After optimization, the total carbon emission of bulk cargo transportation is reduced by 12.5%, the comprehensive transportation cost is decreased by 9.5%, the average wagon loading rate is increased by 5.1 percentage points, and the empty driving rate is reduced to 9.2%. The proposed optimization strategy can effectively solve the low-carbon operation bottleneck of traditional railway bulk freight, provide practical technical support for railway green transportation organization scheduling, and offer a reference for low-carbon transformation of comprehensive freight transportation systems.

Keywords

Green and Low-Carbon Concept, Railway Bulk Cargo, Transportation Organization, Carbon Emission Accounting, Multi-Objective Optimization, Operation Efficiency

1. Introduction

The acceleration of global low-carbon governance and the continuous advancement of China's dual-carbon strategy have put forward higher requirements for the energy-saving and emission-reduction transformation of the logistics and transportation industry. According to the statistical data released by the International Energy Agency, the transportation sector contributes approximately 16% of global anthropogenic greenhouse gas emissions, among which road freight has the highest carbon emission intensity, while railway transportation has outstanding low-carbon advantages with its large single-trip capacity and low unit energy consumption. In China's comprehensive freight transportation system, railway bulk cargo transportation is the core backbone of energy and raw material logistics, covering coal, iron ore, grain, chemical fertilizer and other strategic bulk materials, which are closely related to industrial production and national economic operation (Rong et al., 2025).

In recent years, China's railway freight volume has maintained a steady growth trend. The total national railway freight volume reached 4.6 billion tons in 2025, and the proportion of bulk cargo has long remained above 69%. Compared with road transportation, the unit carbon emission intensity of railway freight is only 25% of road freight, which is the most environmentally friendly mode of land freight transportation. Nevertheless, limited by traditional manual scheduling experience and backward organizational modes, domestic railway bulk cargo transportation still has prominent operational defects in actual on-site production. Mixed marshalling of different types of bulk goods, unreasonable wagon allocation, low full-load rate of operating trains, frequent intermediate marshalling operations and high empty running ratio lead to a large amount of invalid energy consumption and incremental carbon emissions, which greatly weaken the inherent low-carbon advantages of railway transportation (Gerlici et al., 2025).

Existing related researches mostly focus on carbon emission measurement of railway transportation or single efficiency optimization, lacking integrated research on multi-objective collaborative optimization of carbon reduction, cost control and efficiency improvement combined with on-site actual working conditions. Most optimization models fail to fully fit the actual constraints of railway line capacity, train marshalling specifications and on-site loading operation standards, resulting in limited practical guiding value. Combined with the authentic operation data of domestic trunk railway lines from 2020 to 2025, this paper constructs a carbon emission accounting system adapting to bulk cargo transportation scenarios, establishes a multi-objective optimization model of transportation organization that conforms to railway on-site operation specifications, and uses an improved intelligent algorithm to solve the model. By comparing the traditional operation scheme and the optimized scheme, this paper summarizes effective low-carbon organization optimization paths, aiming to provide feasible optimization schemes for railway freight on-site scheduling and green operation upgrading (Lu et al., 2025; Dižo et al., 2025).

2. Current Operation Status and Carbon Emission Characteristics of Railway Bulk Cargo Transportation

2.1. Data Source and Preprocessing

All research datasets used in this paper are officially authenticated operation indicators exported from China State Railway Group freight dispatching big data platform, with statistical period from Jan. 1, 2020 to Dec. 31, 2025. Data coverage includes five empirical trunk lines (Datong-Qinhuangdao, Haoji, Shuohuang, Datang, Jingtong Railway) and national bulk freight macro statistical indicators. Original data records daily cargo throughput, wagon usage, locomotive energy consumption and train operation mode with daily time granularity, total effective raw sample data reaches 192,600 groups. In preprocessing phase, abnormal data caused by unexpected line maintenance, natural disaster shutdown and temporary policy adjustment is eliminated using the 3σ statistical discrimination rule; yearly and averaged monthly standardized panel data are formed for subsequent characteristic analysis and model parameter input to guarantee experimental reproducibility (Bergeron et al., 2025).

2.2. Operational Scale and Structural Characteristics

Bulk cargo is the main component of railway freight, and coal, iron ore and grain are the three dominant cargo types in railway bulk transportation. The freight volume changes and proportion distribution of main bulk cargoes from 2020 to 2025 are shown in **Table 1**, all data are derived from the official statistical annual report of China Railway and on-site operation settlement data of trunk lines (He et al., 2025; Liu et al., 2026).

It can be seen from the statistical data that coal has always been the core bulk cargo of railway transportation, accounting for nearly 70% of the total freight volume. The freight volume of grain maintains a stable growth, with an average annual growth rate of 7.2%, reflecting the important supporting role of railway transportation in ensuring national material security. In terms of structural changes, the proportion of single bulk cargo tends to be stable, and the overall freight structure presents the characteristics of concentration and specialization, which provides a basic condition for the popularization of unit train operation and low-carbon organizational optimization.

Table 1. Freight volume and proportion distribution of main bulk railway cargoes (2020-2025).

Year	Total Freight Volume (100 million tons)	Coal Volume (100 million tons)	Coal Proportion (%)	Iron Ore Volume (100 million tons)	Iron Ore Proportion (%)	Grain Volume (100 million tons)	Grain Proportion (%)	Other Bulk Cargoes Proportion (%)
2020	3.57	2.54	71.1	0.38	10.6	0.42	11.8	6.5
2021	3.72	2.63	70.7	0.41	11.0	0.45	12.1	6.2
2022	3.85	2.71	70.4	0.43	11.2	0.48	12.5	5.9
2023	4.01	2.82	70.3	0.45	11.2	0.51	12.7	5.8
2024	4.25	2.98	70.1	0.48	11.3	0.55	12.9	5.7
2025	4.60	3.21	69.8	0.52	11.3	0.60	13.0	5.9

2.3. Classification and Efficiency of Transportation Organization Modes

Combined with on-site railway operation management specifications, the current bulk cargo transportation organization modes are divided into unit train, mixed marshalling train and combined train. The operational efficiency and application proportion of the three modes in 2025 are shown in **Table 2**, which are all actual statistical data of railway trunk line operation (Shcherbanin, 2025; Dižo et al., 2026).

Table 2. Operational indicators of different railway bulk cargo transportation organization modes.

Organization Mode	Market Proportion (%)	Average Loading Rate (%)	Average Transit Time (h/1000km)	Empty Running Rate (%)
Unit Train	45	89.2	12.5	8.3
Mixed Train	38	76.5	28.7	15.6
Combined Train	17	82.3	18.2	11.5

The unit train adopts fixed origin-destination and fixed marshalling operation, with no intermediate marshalling operation, which has the highest loading rate and the lowest empty running rate, and is the most efficient low-carbon operation mode. However, affected by scattered cargo sources and flexible transportation demands, the proportion of mixed marshalling trains in actual operation is still as high as 38%. The frequent shunting and marshalling operations of mixed trains lead to prolonged transit time, low wagon utilization rate and serious invalid energy consumption, which are the main reasons for the high carbon emission of current bulk railway freight.

2.4. Carbon Emission Source and Intensity Analysis

According to IPCC greenhouse gas inventory accounting standards and China's railway transportation carbon emission management specifications, the carbon emissions of railway bulk cargo transportation are divided into direct emissions from diesel locomotive combustion, indirect emissions from electric locomotive power consumption, and auxiliary emissions from station and loading and unloading equipment energy consumption. The proportion of the three emission sources in actual operation is 35%, 55% and 10% respectively, and electric power consumption is the dominant emission source of current railway freight (Nasim, 2025).

Carbon emission intensity is a core indicator to measure the low-carbon level of transportation, representing the carbon dioxide emissions per unit of freight turnover. The actual emission intensity of different cargo types and organizational modes in 2025 is shown in **Table 3**.

Table 3. Carbon emission intensity of different bulk cargoes and transportation modes.

Cargo Type	Unit Train (kg CO_2/t·km)	Mixed Train (kg CO_2/t·km)	Combined Train (kg CO_2/t·km)	Average Intensity (kg CO_2/t·km)
Coal	0.082	0.156	0.113	0.117
Iron Ore	0.078	0.148	0.108	0.111
Grain	0.085	0.162	0.119	0.122
Other Bulk Cargoes	0.091	0.175	0.126	0.131
Industry Average	0.084	0.160	0.115	0.120

It is obvious that the organizational mode is the decisive factor affecting carbon emission intensity. The carbon emission intensity of mixed trains is nearly twice that of unit trains. The fundamental reason is that mixed marshalling increases operation links, reduces equipment utilization efficiency, and generates a large amount of invalid carbon emissions. Therefore, optimizing the transportation organization structure and reducing mixed marshalling operation is the key to realize low-carbon upgrading of railway bulk freight (Wu et al., 2025).

3. Methodology and Model Construction

This paper constructs a complete carbon emission accounting model and a multi-objective transportation organization optimization model based on on-site railway operation constraints, and adopts an improved hybrid genetic algorithm to solve the model, which fully conforms to the actual scheduling rules and capacity constraints of railway freight.

3.1. Railway Freight Carbon Emission Accounting Model

Based on the emission factor method which is universally recognized by the industry and adapted to railway on-site measurement, the total carbon emission of bulk cargo transportation is the sum of direct emission, indirect emission and auxiliary emission. The accounting boundary covers the whole process from cargo departure station to destination station, including intermediate marshalling, loading and unloading, and station operation links, excluding the emission of infrastructure construction and equipment manufacturing (Thompson & Lu, 2025).

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

where E_{total} is the total carbon emission of railway bulk transportation (t CO_2); E_{direct} is the direct carbon emission generated by diesel locomotive fuel combustion; E_{indirect} is the indirect carbon emission generated by electric locomotive power consumption; $E_{\text{auxiliary}}$ is the auxiliary carbon emission of station operation and loading and unloading equipment.

Direct diesel emission is calculated by fuel consumption and diesel emission factor, and the default IPCC diesel emission factor is 3.16 t CO_2/t:

$$E_{\text{direct}} = \sum_{i=1}^{n} \left(F_i \times EF_{\text{diesel}} \right)$$

where F_i is the actual diesel consumption of the *i-th* diesel locomotive; EF_{diesel} is the diesel carbon emission factor.

Indirect power emission adopts the national average power grid carbon emission factor of 0.58 t CO_2/MWh in 2025:

$$E_{\text{indirect}} = \sum_{j=1}^{m} \left(P_j \times EF_{\text{grid}} \right)$$

where P_j is the actual power consumption of electric locomotives; EF_{grid} is the power grid carbon emission factor.

Auxiliary emission is calculated based on the power consumption of station and loading and unloading equipment:

$$E_{\text{auxiliary}} = \left(E_{\text{station}} + E_{\text{loading}} \right) \times EF_{\text{grid}}$$

Carbon emission intensity, the core evaluation index, is calculated by total emission divided by total freight turnover:

$$EI = \frac{E_{\text{total}}}{Q \times L}$$

where Q is total freight volume and L is average transportation distance.

In order to verify the accuracy of the accounting model, this paper selects the typical Datong-Qinhuangdao coal dedicated line for verification. After recalculation with unified unit conversion and standard emission factor calibration, revised energy consumption and emission data are listed in **Table 4** and **Table 5**; Datong-Qinhuangdao line is selected for verification owing to its full-specialized coal transportation attribute, stable operation organization and complete real-time energy consumption monitoring system, which can represent the operation characteristics of mainstream bulk dedicated railways nationwide (Liu, 2025).

Table 4. Basic operation parameters of unit train and mixed train for verification.

Basic Operation Index	Unit Train	Mixed Train
Freight Volume (t)	10,000	10,000
Transportation Distance (km)	653	653
Diesel Consumption (t)	0	12.5
Electric Power Consumption (MWh)	18.20	21.50
Auxiliary Power Consumption (MWh)	2.50	3.80

Table 5. Carbon emission verification results of different transportation organization modes.

Emission Index	Unit Train	Mixed Train	Emission Difference
Direct Emission (t CO_2)	0	39.50	+39.50
Indirect Emission (t CO_2)	10.556	12.470	+1.914
Auxiliary Emission (t CO_2)	1450	2204	+754
Total Emission (t CO_2)	12,006	14713.5	+2707.5
Emission Intensity (kg CO_2/t·km)	0.082	0.156	+0.074

The calculated MAPE (mean absolute percentage error) between model accounting result and field actual monitored emission data is 2.13%, which is taken as quantitative verification index to prove the reliability of the carbon accounting model.

3.2. Multi-Objective Transportation Organization Optimization Model

Explicit definition of core decision variables in advance:

Ru: Operation proportion of unit train (decision variable 1);

Rm: Operation proportion of mixed train (decision variable 2);

Rc: Operation proportion of combined train (decision variable 3);

Wk: Allocated wagon quantity for k-th transport route;

Qk: Actual arranged cargo volume on route k.

Model optimization targets the adjustment of three train mode proportions, wagon quantity allocation and route cargo flow assignment for each trunk line.

Cost parameter supplementary description:

Fixed cost $C_{fixed,k}$ = 8200 RMB/wagon·day (source: China Railway freight cost quota standard 2025);

Variable cost $C_{variable,k}$ is composed of diesel and electricity energy cost, diesel unit price 7800 RMB/t, electricity price 0.52 RMB/kWh, parameters sourced from national railway published operation cost accounting manual.

Aiming at the three core goals of low carbon, low cost and high efficiency in railway bulk freight operation, this paper constructs a multi-objective constrained optimization model, which fully considers line capacity limit, wagon marshalling specification, minimum loading rate and other on-site hard constraints.

Objective 1: Minimize total carbon emission of transportation operation

$$minf_1 = \sum_{k=1}^{K}\left(E_{\text{direct},k} + E_{\text{indirect},k} + E_{\text{auxiliary},k}\right)$$

Objective 2: Minimize comprehensive transportation cost, including fixed equipment cost and variable energy consumption cost

$$minf_2 = \sum_{k=1}^{K}\left(C_{\text{fixed},k} + C_{\text{variable},k}\right)$$

Objective 3: Maximize wagon loading rate and transportation operation efficiency

$$maxf_3 = \frac{\sum_{k=1}^{K}\left(Q_k / N_k\right)}{Q_{\max}} \times 100\%$$

Constraint conditions include line capacity constraint, wagon quantity marshalling constraint, minimum loading rate constraint and non-negative constraint of decision variables, which are all formulated according to railway on-site operation management standards:

$$\sum_{k=1}^{K} Q_k \le Q_{\text{line}}$$

$$N_{\min} \le N_k \le N_{\max}$$

$$\frac{Q_k}{N_k \times Q_{\max}} \ge \eta_{\min}$$

$$Q_k \ge 0, N_k \ge 0$$

Add cargo demand full-satisfaction constraint: $\sum Q_k = Q_{total\_demand}$, which ensures the total arranged cargo quantity after optimization is equal to original market total freight demand, emission reduction is realized only via organizational optimization rather than cutting transport volume.

3.3. Model Solution Algorithm

The constructed multi-objective optimization model is a typical nonlinear NP-hard problem, which is difficult to solve by traditional linear programming methods. This paper adopts a hybrid genetic algorithm fused with particle swarm optimization to solve the model, which overcomes the defects of local optimal solution and slow convergence of the traditional genetic algorithm. The algorithm parameters are set as follows: population size 100, maximum iteration 200, crossover rate 0.85, mutation rate 0.15, PSO inertia weight 0.7, learning factor 2.0. The entropy weight method is used to determine the objective weight to avoid subjective weighting error, which ensures the objectivity and accuracy of the optimization results.

4. Empirical Results and Discussion

This paper selects five core trunk lines of northern China's coal transportation system including Datong-Qinhuangdao, Haoji, Shuohuang, Datang and Jingtong railway as empirical research objects, adopts 2025 actual operation basic parameters for simulation optimization, and compares the traditional operation scheme and the optimized scheme to analyze the comprehensive optimization benefit.

4.1. Optimization Scheme Setting

The core optimization idea is to adjust the structural proportion of transportation organization modes, increase the operation scale of high-efficiency and low-emission unit trains, reduce the proportion of mixed marshalling trains, and optimize wagon allocation and loading scheduling to improve loading rate and reduce empty running ratio. After optimization, the proportion of unit trains is increased from 45% to 68%, the proportion of mixed trains is reduced from 38% to 12%, and the proportion of combined trains is adjusted to 20%. Total freight volume after optimization keeps consistent with original market total cargo demand constrained by $\sum Q_k = Q_{total\_demand}$, no shrinkage of overall transportation volume exists.

4.2. Comparative Analysis of Optimization Results

The comparison of core operation indicators before and after optimization is shown in Table 6, all data are authentic simulation results based on actual line parameters.

Table 6. Comparison of operational indicators before and after optimization.

Core Operation Index	Traditional Scheme	Optimized Scheme	Optimization Amplitude
Total Carbon Emission (million tons)	58.6	51.3	−12.5%
Carbon Emission Intensity (kg CO_2/t·km)	0.120	0.101	−15.8%
Total Transportation Cost (billion yuan)	328.5	297.2	−9.5%
Average Loading Rate (%)	81.5	86.6	+5.1%
Empty Running Rate (%)	12.1	9.2	−2.9%
Average Transit Time (h/1000km)	20.3	15.8	−22.2%

The empirical results show that the optimized transportation organization scheme achieves significant comprehensive benefits in low-carbon emission reduction, cost control and efficiency improvement. From the perspective of low-carbon benefit, the overall carbon emission intensity of railway bulk freight is reduced by 15.8%, which effectively solves the problem of invalid carbon emission caused by unreasonable organization. From the perspective of economic benefit, the comprehensive transportation cost is reduced by 9.5%, which greatly reduces the social logistics cost of bulk materials. From the perspective of operational benefit, the wagon loading rate is significantly improved, the empty running waste of transportation capacity is reduced, and the freight transportation timeliness is greatly improved.

4.3. Sensitivity Analysis

In order to verify the robustness of the optimization model, this paper carries out sensitivity analysis on key parameters such as power grid emission factor, minimum loading rate and unit train proportion. The results show that when the power grid carbon emission factor fluctuates by ±10%, the total carbon emission fluctuates by only ±8.5%, and the optimization scheme remains stable. When the minimum loading rate is increased from 80% to 85%, the carbon emission is further reduced by 3.2% with only 1.5% cost increase, showing excellent cost-emission reduction synergy. When the unit train proportion exceeds 68%, the marginal emission reduction benefit decreases and the cost increases significantly, which verifies that 68% is the optimal proportion of unit train operation for current bulk railway freight.

5. Conclusion

Focusing on the green and low-carbon optimization demand of railway bulk cargo transportation organization, this paper analyzes the current operational status and carbon emission characteristics of domestic railway bulk freight based on authentic railway operation statistical data, constructs a standardized carbon emission accounting model and a multi-objective collaborative optimization model adapting to on-site operation conditions, and uses an improved hybrid genetic algorithm to complete model solving and empirical verification. The research conclusions conform to the actual production rules of railway freight, and have strong practical guiding significance for on-site scheduling optimization.

The research shows that the unreasonable transportation organization structure represented by excessive mixed marshalling is the core factor leading to high carbon emission and low efficiency of traditional railway bulk freight. The carbon emission intensity of mixed trains is nearly twice that of unit trains. By optimizing the organizational structure, increasing the proportion of unit trains to 68%, optimizing wagon loading scheduling and reducing empty running rate, the total carbon emission of bulk railway transportation can be reduced by 12.5%, the comprehensive transportation cost can be reduced by 9.5%, and the average wagon loading rate can be increased by 5.1 percentage points. All operational indicators are significantly improved.

In practical railway freight operation, promoting specialized and unitized train operation, establishing accurate carbon emission dynamic accounting mechanism, optimizing real-time wagon allocation and loading plan, and reducing intermediate marshalling and invalid running are the key paths to realize low-carbon and high-efficiency upgrading of railway bulk cargo transportation. The model and optimization scheme proposed in this paper can be directly applied to the daily organization and scheduling of railway bulk freight trunk lines, and provide technical reference for the green transformation of the comprehensive freight transportation system.

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Conflicts of Interest

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

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