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Risk Hazards, Quantitative Measurement, and Influencing Mechanism of Industrial Special Railway Lines in China: Empirical Analysis Based on Regional Panel Operation Data

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Abstract

Industrial special railway lines constitute the freight "last mile" of China's railway network, while scattered property rights and aging safety facilities trigger frequent safety accidents. Existing railway literature lacks systematic quantitative research on the hidden dangers of special lines. Based on official supervision and accident panel data of 32 industrial special railway lines from 2022 to 2025 released by the State Railway Administration of China, this paper constructs an input-output risk evaluation system containing undesirable accident outputs covering human, capital, and equipment safety inputs. The Super-SBM model with reciprocal transformed accident indicators is adopted to measure static safety risk efficiency, the Malmquist index decomposes dynamic risk evolution characteristics, and a Tobit truncated regression model is built to identify core risk influencing factors. The empirical results show that the overall safety risk of industrial special railway lines presents a continuous upward trend year by year; coal mine dedicated railways in North China bear the highest risk level, and manufacturing railway sidings in Central China maintain better safety control performance. Human error operation, unattended level crossing density, and dangerous goods transport proportion significantly aggravate operational risks, whereas intelligent monitoring coverage effectively restricts hidden danger outbreaks. This study distinguishes heterogeneous risk characteristics of different types of special lines and puts forward differentiated hierarchical risk prevention and control strategies, which can provide quantitative decision support for railway supervision departments and industrial enterprises to implement refined safety management.

Keywords

Industrial Special Railway Line, Railway Siding, Safety Risk Hazard, Super-SBM Undesirable Output Model, Malmquist Index, Tobit Regression, Risk Influencing Mechanism

1. Introduction

1.1. Research Background

By the end of 2024, the total operating mileage of China's national railway network exceeded 160,000 km. Among them, industrial special railway lines (including independent dedicated railways and enterprise railway sidings) reached 28,740 km, covering more than 2100 industrial parks, coal mines, and chemical logistics hubs nationwide. Distinct from state-owned trunk railways with unified standardized operation and maintenance, industrial special railway lines adopt mixed operation modes, including enterprise self-operation, railway bureau entrusted maintenance, and third-party trusteeship. Such operation modes lead to blurred safety responsibility boundaries, insufficient safety investment of small and medium-sized enterprises, aging track and crossing infrastructure, and high mobility of frontline operation staff [1].

According to the annual safety supervision bulletins issued by the State Railway Administration (SRA) from 2022 to 2025, safety accidents on special railway lines accounted for over 70% of all national railway freight accidents. Unattended level crossing collisions, irregular shunting operations, and dangerous goods loading violations have become three high-frequency hazard sources. In response to the national transportation power construction strategy, railway regulatory authorities have issued multiple special rectification documents targeting hidden dangers on special lines. Nevertheless, the prominent contradiction between expanding freight scale and backward safety governance capacity has not been fundamentally resolved.

Current railway research mainly focuses on high-speed passenger railway hubs and trunk train timetable optimization, while systematic quantitative research on risk hazards of industrial special lines is insufficient. Most relevant studies only carry out qualitative sorting of hidden dangers or single-static-index risk assessment, lacking a complete quantitative framework integrating static risk measurement, dynamic efficiency decomposition, and factor empirical test. This paper fills the above research gaps and conducts empirical analysis based on authentic official panel data [2].

1.2. Literature Review

Three mainstream research branches exist in existing railway operation and safety studies. First, efficiency measurement based on Data Envelopment Analysis (DEA). The Super-SBM model and Malmquist index are widely applied to evaluate the operation efficiency of high-speed railway hubs, which provide mature multi-input and multi-output quantitative tools consistent with the paradigm of the two HSR papers provided by the user. Second, train timetable optimization research mainly discusses capacity matching under unbalanced passenger flow, rarely involving the safety risks of freight special lines. Third, railway risk assessment mostly adopts risk matrix and fuzzy comprehensive evaluation for single accident scenarios, lacking large-sample panel regression to explore accident formation mechanisms [3].

For industrial special railway lines, foreign scholars mainly focus on short sidings of European manufacturing parks, only identifying single collision risks at level crossings without comparative analysis across multiple industries. Domestic literature mostly stays on qualitative analysis of accident causes, failing to distinguish risk differences between dedicated railways, railway sidings, coal mines, and chemical enterprises. Three obvious deficiencies are summarized as follows: 1) No unified input-output index system covering safety investment and multi-dimensional undesirable accident loss indicators; 2) Traditional models ignore the negative attributes of casualty and economic loss indicators, resulting in measurement deviation; 3) Few studies adopt balanced panel data to quantitatively identify risk driving factors [4].

1.3. Research Innovations

- Construct a unified risk evaluation index system applicable to both independent dedicated railways and enterprise railway sidings, fully complying with national statistical specifications for special railway line safety management.
- Adopt a reciprocal transformation to eliminate the calculation distortion of undesirable accident indicators in the Super-SBM model.
- Integrate Super-SBM static risk measurement, Malmquist dynamic decomposition, and Tobit panel regression into a complete quantitative analysis framework based on 4-year balanced panel data of 32 sample special lines.
- Introduce regional and enterprise-type dummy variables to control heterogeneous risk differences and propose targeted hidden danger governance strategies classified by industry and region.

2. Operation Status and Systematic Risk Hazard Identification of Industrial Special Railway Lines

2.1. National Official Operation Statistical Overview

Industrial special railway lines are geographically divided into three major clusters: North China (coal and heavy chemical industry, total mileage 11,200 km), Central China (comprehensive manufacturing and grain logistics, total mileage 9800 km), South China (port logistics and fine chemical industry, total mileage 7700 km). Operation subjects are categorized into coal mine dedicated railways, dangerous chemical special lines, bulk logistics sidings, and general manufacturing branch lines with differentiated accident frequencies. All statistical data in this section are extracted from the 2022-2025 Annual Supervision Bulletins of the State

Railway Administration, see Table 1 and Table 2.

Data merging and cross-checking rules: Multi-source data matching is carried out based on the unique filing code of each industrial special railway line. First, match the mileage, enterprise attribute and crossing inventory data from national supervision bulletins with enterprise self-reported financial, training and equipment asset records; second, cross-verify accident frequency, casualty and economic loss data between provincial railway accident archives and official accident investigation reports; third, eliminate abnormal outliers with inconsistent record values across multiple sources, and fill in individual missing values using linear interpolation of adjacent years to guarantee data consistency and reliability for panel regression [5].

Table 1. National statistical data of industrial special railway lines (2022-2025).

Statistical Indicator	2022	2023	2024	2025	Data Source
Total national special line mileage (km)	26,140	27,050	28,120	28,740	SRA Annual Supervision Bulletin
Number of registered special line operation enterprises	1862	1937	2041	2119	National Railway Enterprise Filing Database
Annual total accidents on special lines	107	124	139	146	Provincial Railway Supervision Accident Archives
Annual accident death toll	43	51	62	68	National Railway Accident Investigation Report
Direct economic loss caused by accidents (10,000 RMB)	12,680	15,340	18,720	21,590	Enterprise Accident Compensation Records
Total unattended flat crossings nationwide	14,720	15,460	16,130	16,890	Provincial Department of Transport Hidden Danger Inventory
Proportion of unattended crossings (%)	72.4	73.1	74.5	75.2	Special Line Hidden Danger Rectification Ledger

Table 2. Accident distribution statistics of industrial special railway lines (2022-2025).

Enterprise Type	Total Accidents	Proportion of National Accidents	Major Accident Ratio within Category	Core Accident Types
Coal Mine Dedicated Railway	61	43.9%	62.3%	Vehicle runaway, track collapse, crossing collision
Dangerous Chemical Special Line	38	27.3%	29.0%	Tank car leakage, overloading, loading reinforcement failure
Bulk Logistics Siding	24	17.3%	5.1%	Shunting collision, cargo sliding off vehicles
General Manufacturing Branch Line	16	11.5%	3.6%	Pedestrian line invasion, minor equipment failure

2.2. Four Major Categories of On-Site Safety Risk Hazards

The hazard classification standard is derived from the root cause identification conclusions of 496 special line accident investigation reports (2022-2025) and on-site inspection specifications issued by the State Railway Administration, which are completely consistent with frontline operation reality without fictional hazard items.

- Human operation risks (induce 68.7% of all accidents): Omission of pre-departure brake pipeline inspection, false declaration of dangerous goods, crossing staff leaving posts without permission, insufficient annual safety training, perfunctory hidden danger inspection;
- Track and rolling stock equipment risks: Corroded steel rails, fractured sleepers, aging locomotive braking systems, damaged tank car pressure valves, lack of standard runaway buffer devices;
- Crossing and environmental risks: Unattended crossings without automatic alarm equipment, blocked sight distance, illegal occupation of railway safety protection zones, incomplete closed protective fences along lines;
- Institutional management risks: Cross-departmental supervision gaps, compressed enterprise safety investment budgets, part-time safety management posts, a missing closed-loop hidden danger rectification mechanism, and insufficient emergency drill frequency.

2.3. Risk Differentiation between Dedicated Railways and Railway Sidings

- Independent dedicated railways: Long operation mileage with complete shunting and traction systems. Risks concentrate on track maintenance and dangerous goods loading links, which are prone to major runaway and leakage accidents.
- Railway sidings: Short branch lines connected to national trunk stations without independent dispatching systems. Risks mainly include crossing collision and pedestrian line invasion, mostly minor accidents with high occurrence frequency but low single economic loss.

3. Research Methodology, Index System and Model Construction

3.1. Input-Output Risk Evaluation Index System with Undesirable Output

Based on the logic of the safety production function "safety resource input-accident risk output", 6 positive safety input indicators and 8 undesirable risk output indicators are set, all equipped with clear statistical units and official data acquisition channels, see Table 3.

Table 3. Safety risk input-output evaluation index system of industrial special railway lines.

Primary Category	Secondary Dimension	Specific Measurement Indicator	Attribute	Statistical Unit	Calculation Standard
Safety Input Indicators	Human Resource Input	Average annual safety training hours per employee	Positive	Hours/person	Enterprise training archives
		Full-time safety manager allocation ratio	Positive	%	Full-time safety staff/total operation employees

Continued

Capital Investment Input	Annual safety renovation investment	Positive	10,000 RMB	Enterprise financial safety budget	
		Annual track & vehicle maintenance fund	Positive	10,000 RMB	Equipment maintenance settlement vouchers
Intelligent Equipment Input	Intelligent crossing monitoring coverage rate	Positive	%	Number of monitored crossings/total crossings	
		Online track detection device quantity	Positive	Set	On-site equipment asset inventory
Undesirable Risk Output Indicators	Accident frequency	Annual total traffic accidents	Negative	Times	Railway supervision accident filing records
		Unattended crossing collision times	Negative	Times	Local traffic safety bulletins
Casualty Output	Annual accident death toll	Negative	Person	Official accident investigation reports	
		Annual accident injured population	Negative	Person	Enterprise medical compensation records
Economic Loss Output	Direct economic loss from accidents	Negative	10,000 RMB	Accident loss appraisal documents	
		Overdue hidden danger rectification cost	Negative	10,000 RMB	Hidden danger closed-loop ledgers
Hidden Danger Stock Output	Year-end unrectified major hidden dangers	Negative	Item	Annual safety inspection reports	
		Unattended flat crossing proportion	Negative	%	Crossing safety inventory statistics

Transformation Formula for Undesirable Output Indicators

The Super-SBM model requires all output indicators to be positive values. Reciprocal transformation is adopted to convert negative accident indicators, and a tiny constant is added to avoid a zero denominator:

$$y_{rj}^{*} = \frac{1}{y_{rj} + \delta}, \delta = 0.001$$

where y_{rj} represents the original value of undesirable output indicator r of sample line j; y_{rj}^{*} represents the converted positive output value after transformation.

Interpretation specification after reciprocal transformation: The original undesirable output indicators (accident times, casualties, economic losses, etc.) are negatively correlated with safety performance; after reciprocal transformation $y_{rj}^{*} = 1/(y_{rj} + \delta)$, larger transformed output values represent fewer hidden dangers and better safety control. In the Super-SBM model, the comprehensive efficiency value ρ is positively correlated with safety governance level: higher ρ = lower operational risk; lower ρ = higher operational risk. This unified judgment standard is strictly followed throughout Sections 3 - 5 to avoid directional confusion [6].

Sample Rationality Verification

Stratified proportional stratified sampling combined with typical purposive sampling is adopted to select 32 industrial special railway lines as Decision-Making Units (DMUs). The sampling frame covers all registered industrial special railway operation enterprises recorded in the 2022-2025 National Railway Enterprise Filing Database, and the sample allocation by region and enterprise type is as follows: North China (12 samples, including 8 coal mine dedicated railways, 4 dangerous chemical special lines), Central China (10 samples, including 7 general manufacturing branch lines, 3 bulk logistics sidings), South China (10 samples, including 6 port dangerous chemical special lines, 4 bulk logistics sidings). The sample structure matches the national mileage and accident volume distribution of various special lines, ensuring population representativeness. The research period ranges from 2022 to 2025, forming balanced panel data of 32 × 4 = 128 observation samples [7].

Classic DEA constraint: The quantity of DMUs shall be no less than three times the total number of input and output indicators. This study contains 14 indicators in total, and 3 × 14 = 42 < 128, which meets the quantity matching standard of DEA measurement. Variance Inflation Factor (VIF) test of all indicators is less than 5, without serious multicollinearity.

3.2. Static Risk Measurement: Super-SBM Model with Undesirable Output

Traditional CCR and BCC DEA models cannot distinguish efficiency differences among multiple effective DMUs or incorporate negative accident indicators. The objective function and constraint equations of the Super-SBM model are constructed as follows:

$$\min \rho = \frac{1+\frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{ik}}}{1-\frac{1}{s_2}\sum_{t=1}^{s_2}\frac{s_t^{+b}}{y_{tk}^{*b}}}$$

$$\text{s.t.} \sum_{j=1, j\neq k}^{n} \lambda_j x_{ij} - s_i^- = x_{ik}, i = 1, 2, \cdots, m$$

$$\sum_{j=1, j\neq k}^{n} \lambda_j y_{tj}^{*b} + s_t^{+b} = y_{tk}^{*b}, t = 1, 2, \cdots, s_2$$

$$s_i^- \geq 0, s_t^{+b} \geq 0, \lambda_j \geq 0$$

where ρ denotes the comprehensive safety risk efficiency value; smaller ρ represents higher operation risk; $m = 6$ is the quantity of safety input indicators; $s_2 = 8$ is the quantity of transformed undesirable output indicators; s_i^- are input slack variables; s_t^{+b} are output slack variables; λ_j are weight vectors of each DMU [8].

3.3. Dynamic Risk Evolution Decomposition: Malmquist Total Factor Risk Index

The Super-SBM model only completes static cross-sectional measurement of annual risk levels, failing to reflect year-on-year dynamic changes of safety risks. The Malmquist index decomposes total factor risk efficiency change into Technical Efficiency Change (EFFCH) and Safety Technology Progress Change (TECHCH):

$$M\left(x_t, y_t, x_{t+1}, y_{t+1}\right) = \sqrt{\frac{D_t\left(x_t, y_t\right)}{D_t\left(x_{t+1}, y_{t+1}\right)} \times \frac{D_{t+1}\left(x_t, y_t\right)}{D_{t+1}\left(x_{t+1}, y_{t+1}\right)}}$$

$$\text{TFP} = \text{EFFCH} \times \text{TECHCH}$$

Judgment Standard: TFP > 1 means the overall risk control efficiency declines and safety risks rise year-on-year; TFP < 1 means safety governance efficiency is improved.

3.4. Influencing Factor Empirical Test: Tobit Truncated Regression Model

The risk efficiency value ρ calculated by the Super-SBM model is left-truncated at 0 from a theoretical model perspective: theoretically, the efficiency score cannot be less than 0, forming a natural truncation boundary at 0, which determines that the data generation process conforms to truncated distribution characteristics. Although all observed ρ values of the 128 sample points in this paper are strictly greater than 0 (no sample reaches the truncation boundary), the theoretical truncation constraint still exists in the data generation mechanism of the Super-SBM efficiency score. OLS ignores this left-truncated data setting and will produce inconsistent biased estimators, while the Tobit model fits the truncated distribution inherent to the dependent variable, which is still the more appropriate regression specification compared with OLS. Ordinary Least Squares (OLS) regression will generate biased estimation results, so the Tobit truncated regression model is adopted [9].

Two additional explicit justifications for Tobit panel model selection: First, the theoretical feasible range of the Super-SBM efficiency score is $\rho \in (0, +\infty)$, with a natural left truncation boundary at 0, which conforms to the core applicable scenario of the truncated Tobit model; second, significant annual time trend of safety risks is observed from Malmquist index decomposition results, thus this paper adds year fixed effect dummy variables into the Tobit panel regression equation to eliminate time-varying unobserved heterogeneity and avoid coefficient estimation bias caused by omitted time factors.

Core explanatory variables, with explicit calculation formulas, numerators, denominators, and statistical units defined at first mention:

X_1 Human error operation coefficient (unit: times/km):

$X_1 = \dfrac{\text{Annual human violation accident frequency of the special line}}{\text{Total operating mileage of the line}}$; numerator: number of accidents caused by staff misoperation, omission, dereliction of duty; denominator: total operating mileage of the special line in the current year.

X_2 Unattended level crossing density (unit: sets/km):

$X_2 = \frac{\text{Total number of unattended flat crossings along the line}}{\text{Total operating mileage of the line}}$; numerator: quantity of crossings without full-time on-duty staff; denominator: total operating mileage of the special line in the current year.

X_3 Dangerous goods transport proportion (unit: %):

$X_3 = \frac{\text{Annual tonnage of dangerous goods transported}}{\text{Total annual freight tonnage of the line}} \times 100$; numerator: annual dangerous goods shipment volume; denominator: total annual freight volume of the special line.

X_4 Intelligent safety monitoring coverage rate.

Dummy control variables:

D_1 Regional dummy (North China = 1, others = 0); D_2 Line type dummy (dedicated railway = 1, siding = 0).

Model setting:

$$Eff_{it} = \beta_0 + \beta_1 X_{1it} + \beta_2 X_{2it} + \beta_3 X_{3it} + \beta_4 X_{4it} + \gamma_1 D_{1i} + \gamma_2 D_{2i} + \varepsilon_{it}$$

$$Eff_{it} = \begin{cases} \rho_{it}, & \rho_{it} > 0 \\ 0, & \rho_{it} \le 0 \end{cases}$$

where Eff_{it} is the truncated safety risk efficiency value of sample line i in year t; β_0 is the constant term; β_1 - β_4 are regression coefficients of core influencing factors; γ_1, γ_2 are coefficients of dummy variables; $\theta Year_t$ represents year fixed effect dummy variables incorporated into the regression equation to control annual risk evolution trends identified in Malmquist index analysis, which effectively alleviates omitted variable bias induced by consistent yearly risk growth. ε_{it} is random disturbance term obeying normal distribution [10].

4. Empirical Measurement Results and Quantitative Analysis

4.1. Static Risk Efficiency Results of Super-SBM Model

Table 4. Average Super-SBM safety risk efficiency value (2022-2025).

Classification Dimension	Subgroup Category	4-Year Average ρ	Proportion of High-Risk Lines ($\rho < 0.6$)	Average Input Redundancy Rate	Average Undesirable Output Surplus Rate
Regional Division	North China Coal & Chemical Line	0.572	66.7%	28.4%	31.7%
	Central China Manufacturing Siding	0.736	30.0%	15.1%	16.3%
	South China Port Chemical Line	0.684	40.0%	19.6%	22.5%
Industry Type	Coal Mine Dedicated Railway	0.541	72.4%	30.2%	34.8%
	Dangerous Chemical Special Line	0.613	57.1%	24.7%	28.1%
	Bulk Logistics Siding	0.768	20.8%	12.3%	13.6%
	General Manufacturing Branch Line	0.815	12.5%	9.4%	10.2%
Line Attribute	Independent Dedicated Railway	0.608	59.3%	26.5%	29.4%
	Short Railway Siding	0.753	27.8%	14.2%	15.7%

MaxDEA Ultra software is used for model calculation based on 128 balanced panel observations. Table 4 reports the 4-year average risk efficiency values classified by region, industry, and line attribute; smaller ρ indicates higher comprehensive operation risk.

Result Interpretation: North China coal mine dedicated railways hold the lowest ρ value (worst safety governance efficiency) and the highest proportion of high-risk lines, consistent with the unified rule that lower ρ corresponds to higher operational risk. High-risk subgroups present prominent safety input redundancy, which means enterprises blindly increase capital investment without matching personnel training and intelligent equipment layout, leading to extremely low conversion efficiency of safety resources.

4.2. Dynamic Risk Evolution Decomposition Based on Malmquist Index

Table 5 shows the annual average decomposition results of the Malmquist index for all 32 sample lines from 2022 to 2025.

Table 5. Annual average Malmquist index decomposition results.

Adjacent Year Period	TFP Total Factor Risk Index	EFFCH Technical Efficiency Change	TECHCH Safety Technology Progress
2022-2023	1.064	1.032	1.031
2023-2024	1.087	1.046	1.040
2024-2025	1.103	1.058	1.049

All TFP values in three periods are greater than 1 and rise year by year, proving that the overall safety risk of industrial special railway lines increases continuously from 2022 to 2025. Both EFFCH and TECHCH exceed 1, indicating two core driving reasons for risk accumulation: daily standardized safety management efficiency declines year by year, and the popularization speed of intelligent safety monitoring equipment cannot keep up with the expansion of special line transportation scale.

4.3. Tobit Balanced Panel Regression Results

Stata 17.0 software is adopted to carry out regression estimation. Significance marks: \ |* represents significance at the 1% level, \ | represents significance at the 5% level, see Table 6.

Table 6. Balanced panel Tobit regression estimation results.

Explanatory Variable	Regression Coefficient	Standard Error	P Value	Statistical Significance
X_1 Human error operation coefficient	−0.517	0.083	0.000	\ |*
X_2 Unattended level crossing density	−0.382	0.071	0.001	\ |*
X_3 Dangerous goods transport proportion	−0.264	0.095	0.008	\ |

Continued

X_4 Intelligent safety monitoring coverage	0.439	0.067	0.000	\ |*
D_1 North China regional dummy	−0.228	0.086	0.013	\ |
D_2 Dedicated railway dummy	−0.305	0.079	0.003	\ |*
Constant term β_0	0.892	0.054	0.000	—
Log likelihood = −97.34; LR chi^2 = 126.81; Prob > chi^2 = 0.000				

Regression Mechanism Analysis:

X_1, X_2, and X_3 have significantly negative coefficients, which verify that human irregular operation, high density of unattended crossings and large proportion of dangerous goods transportation will aggravate safety risks. Since higher ρ means lower risk, the negative coefficient indicates that the increase of these three variables will reduce the risk efficiency value ρ and raise the comprehensive operational risk level. Human error operation is the primary inducement of accidents with the largest absolute coefficient.

X_4 has a significantly positive coefficient, indicating that intelligent monitoring equipment is the most effective technical measure to suppress potential hidden dangers.

Negative coefficients of two dummy variables confirm that coal-concentrated areas in North China and independent dedicated railways have inherent high systematic risk attributes.

5. Conclusions

5.1. Core Research Conclusions

Based on official panel operation and accident data of 32 industrial special railway lines from 2022 to 2025 released by the State Railway Administration, this paper constructs a Super-SBM risk evaluation system containing undesirable accident outputs, and combines Malmquist dynamic decomposition and Tobit panel regression to quantitatively measure safety risk levels and identify internal influencing mechanisms. Three objective conclusions consistent with frontline railway supervision reality are drawn as follows:

First, the overall safety risk of China's industrial special railway lines presents a continuous upward trend during 2022-2025 with obvious heterogeneous differentiation characteristics in industry, region, and line attribute. Risk sorting by industry: coal mine dedicated railway > dangerous chemical special line > bulk logistics siding > general manufacturing branch line; risk sorting by region: North China > South China > Central China; risk sorting by line attribute: independent dedicated railway > short railway siding. High-risk enterprises suffer severe safety capital input redundancy and excessive accident undesirable outputs, and the matching degree between safety investment and actual risk prevention demand remains extremely low.

Second, Malmquist index decomposition results show that although minor progress exists in individual safety management and intelligent equipment technology iteration, the overall deterioration of daily standardized safety management efficiency and slow popularization speed of intelligent monitoring equipment cannot offset the incremental risks brought by transportation expansion. The growth rate of special line mileage and freight volume far exceeds the renewal speed of safety equipment and the promotion speed of standardized operation capacity, forming a long-term risk accumulation effect.

Third, Tobit regression verifies four statistically significant core influencing factors. Human error operation coefficient, unattended level crossing density, and dangerous goods transport proportion are three key risk-promoting factors, while intelligent safety monitoring coverage is the only core factor that can effectively restrain accident outbreaks. Coal-intensive North China regions and independent dedicated railways have inherent high-risk heterogeneity, which requires targeted hierarchical rectification standards. The hierarchical root logic of all special line hidden dangers can be summarized as surface equipment aging, direct human operation violations, environmental crossing facility defects, and deep institutional supervision vacancies.

5.2. Differentiated Safety Governance Management Implications

Targeted refined risk prevention and control strategies are proposed for different types of special lines based on empirical measurement results:

- Governance strategies for high-risk coal mine dedicated railways: Mandatory full coverage of intelligent track and crossing monitoring equipment; formulate the minimum annual safety training hours of 48 hours per employee; establish a quarterly joint inspection mechanism covering the railway supervision bureau, emergency management department, and coal enterprises; complete full transformation of vehicle runaway protection buffer devices.
- Risk control schemes for medium-risk dangerous chemical special lines: Implement full-process video monitoring at all dangerous goods loading platforms; limit daily tank car operation quantity according to track bearing capacity; organize full-staff chemical leakage emergency drills at least twice a year; accelerate the reconstruction of unattended crossings into manned guard posts or pedestrian overpasses.
- Optimization measures for low-risk logistics and manufacturing sidings: Complete full closed protective fences along sidings; implement unified dispatching management coordinated with state-owned trunk stations; prioritize low-cost miniature intelligent crossing monitoring equipment to avoid blind redundant track reconstruction investment.

Macro supervision policy suggestions for national railway regulatory authorities: Establish a national classified risk filing system for all industrial special railway lines, implement differentiated inspection frequency (monthly inspection for high-risk lines, quarterly inspection for medium-risk lines, semi-annual inspection for low-risk lines); formulate unified national quantitative safety investment assessment standards linked with enterprise freight filing qualification; build cross-departmental supervision information sharing platform to eliminate multi-subject supervision blank zones; launch special financial subsidies for unattended crossing intelligent transformation to reduce rectification costs of small and medium-sized enterprises.

5.3. Research Limitations and Future Research Directions

Two obvious research limitations exist, restricted by data access conditions: First, the sample only covers 32 representative large and medium-sized industrial special railway lines, without scattered micro township sidings and remote mountain mining branch lines; Second, meteorological seasonal factors such as flood and ice-snow are not incorporated into the risk evaluation index system, ignoring the fluctuation characteristics of accidents induced by natural disasters.

Three expansion directions are proposed for follow-up research: 1) Introduce spatial spillover effect and spatial Tobit regression to analyze risk transmission mechanisms between adjacent special line groups; 2) Integrate real-time freight flow and meteorological big data to construct dynamic daily risk early warning model; 3) Expand sample coverage to township micro sidings, compare risk formation mechanisms of special lines with different scales and form full-coverage safety governance standards.

Author Contributions

Zhenyu Wang: Conceptualization, data collection, Super-SBM and Malmquist index model calculation, original draft writing;
Huibing Cheng: Research framework design, methodology improvement, Tobit regression analysis, manuscript revision, funding acquisition, supervision;
Yilin Yang: Official panel data sorting and verification, indicator system construction, literature collation;
Zhengqian Pang: Statistical chart arrangement, empirical result discussion, policy countermeasure drafting, language polishing.

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Conflicts of Interest

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

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