Research on the establishment and operation mechanism of China's railway safety management system

Railway Sciences

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Abstract

Purpose – Against the backdrop of rising railway network density and operational complexity in China, the traditional reactive safety management paradigm fails to meet full-lifecycle safety control demands, and the current model suffers from poor institutional coherence, low coordination efficiency and inadequate control precision. This study explores the inherent logic and operational mechanism of railway safety management, constructs a well-structured safety management framework and dynamic operational model and provides theoretical and practical support for modernizing China's railway safety governance capacity to address safety challenges in high-density, high-speed and heavy-haul railway operations.

Design/methodology/approach – A systematic review and research integration approach is adopted. Theoretical advances and practical applications of railway safety management systems in the EU, the USA and Japan, as well as mature practices in China's civil aviation, power, petrochemical and coal mining industries, are systematically analyzed. Based on China's railway safety management practices and industrial characteristics, a "1 + 3+1" hierarchical three-dimensional core framework is constructed. Drawing on PDCA cycle theory, a SERA dynamic operational model is developed. Key digital technologies supporting the framework and model are identified via focused analysis of railway safety management digital transformation.

Findings – The findings indicate that integrating general international safety management concepts, foreign railway professional practices and domestic localization experiences is pivotal to constructing a railway safety management system tailored to the Chinese context. The "1+3+1" framework comprises legal-institutional and organizational responsibility systems as its strategic foundation, three core execution systems—prevention and control, emergency response and disposal, and assessment and improvement—as its operational pillars, and technological and cultural support systems as its enabling underpinning. This architecture enables full-element coverage, full-process integration and comprehensive coordination of railway safety management. The SERA dynamic functioning model achieves closed-loop iteration through the cycle of "Systematize and Support→Execute and Enforce→Respond and Recover→Assess and Advance". Integration of key digital technologies—including multi-source data fusion and intelligent risk alerting—enables efficient functioning of the framework and model. This integrated approach effectively addresses fragmentation and inadequate coordination in traditional railway safety management, thereby driving transformation from experience-driven to data-driven paradigms, from static control to dynamic optimization, and from passive response to proactive prevention.

Originality/value – First, this study transcends traditional fragmented safety management paradigms, constructing a railway safety management framework spanning the full lifecycle, all factors and full processes, thereby transforming railway safety management from scattered measures to systematic, goal-oriented endeavors. Second, it integrates general international safety management principles with Chinese railway contextual attributes, establishing the SERA dynamic functioning model with global interoperability and local adaptability, thereby achieving closed-loop connectivity from strategic design to operational implementation. Third, it comprehensively delineates key digital technologies for the digital transformation of China's railway safety management system, thereby providing technical solutions for precision and intelligentization in complex

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operational scenarios. Fourth, these findings enhance systematic rigor and methodological soundness in China's railway safety governance, while furnishing a replicable model for safety management of other complex transportation infrastructure – including highways and urban rail transit. This lays the foundation for a railway safety management paradigm that harmonizes Chinese characteristics with global interoperability, thereby contributing Chinese experience to global railway safety management.

Keywords China's railways, Safety management system, Management system framework, SERA model, Digitalization, Operation mechanism

Paper type Research article

1. Introduction

Railway safety constitutes a core dimension of national public safety and a strategic imperative for ensuring reliable railway operations and sustainable industry development (Liu *et al.*, 2025; Yan *et al.*, 2026). As China's railway network density increases and transportation operations grow increasingly complex, safety management requirements continue to escalate. The traditional reactive, post-incident management paradigm has proven inadequate for full-lifecycle safety control requirements (Wang and Liu, 2017; Ren *et al.*, 2018). Establishing a unified, standardized, and distinctively Chinese railway safety management system represents both an essential imperative for implementing the national transportation excellence strategy and a central pathway to addressing complex safety challenges in high-density, high-speed, and heavy-haul railway operations. However, amid multi-risk coupling environments and cross-stakeholder coordination demands (Chen, Zhao, Liu, Wang, & Guo, 2025; Fan *et al.*, 2022), the current railway safety management model exhibits notable deficiencies in institutional coherence, operational coordination efficiency, and control precision, necessitating a systematic and integrated safety management framework. This study conducts an in-depth analysis of the underlying logic and functioning mechanism of railway safety management, and systematically reviews theoretical advances and practical applications of railway and related industry safety management systems domestically and internationally. The objective is to construct a clearly structured and well-functioning railway safety management framework and dynamic functioning model, thereby providing theoretical support and practical approaches for the contemporary modernization of China's railway safety governance capacity. For the systematic review adopted in this study, relevant literature were collected from Web of Science, Scopus, and CNKI. The main search keywords were railway safety management, safety management system, risk early warning, emergency response, and system optimization. Peer-reviewed journal articles, authoritative industry reports, and standard documents closely related to the research theme were included, while duplicated publications, non-academic materials, and irrelevant studies were excluded. The collected literature were systematically sorted, summarized, and analyzed to extract core theories, practical experiences, and research deficiencies, which provides a solid methodological basis for framework construction and model design.

1.1 Literature review

The European Union (EU) has established a three-tiered control framework based on the Railway Safety Directive (EU Directive 2004/49/EC), implementing a unified safety certification system. Its Safety Management System (SMS) framework integrates the PDCA cycle, thereby achieving dynamic optimization (Ilczuk, Kycko, & Szmel, 2023). The United States adopts a hybrid model of federal regulations and industry self-regulation, establishing hierarchical governance systems for passenger System Safety Planning (SSP) and freight Risk Reduction Planning (RRP), with enhanced focus on core modules such as fatigue risk management (Li, Liu, Han, & Others, 2026; Fan *et al.*, 2021). Japan employs a hybrid regulatory-technological approach, grounded in the Railway Business Act, to develop a public-private collaborative framework, thereby fostering a "zero recurrence" safety culture and achieving continuous safety performance improvement through regular evaluations (Bugalia, Maemura, & Ozawa, 2021; Fan *et al.*, 2025).

Domestic high-risk industries—including civil aviation, power, petrochemicals, and coal mining—have developed shared methodologies grounded in their distinctive risk profiles, encompassing risk control cycles, standardized implementation, technology-enabled innovation, and workforce engagement in safety governance. The civil aviation industry, benchmarking against the International Civil Aviation Organization (ICAO) Safety Management System (SMS), has established a collaborative functioning mechanism across four core modules, with dynamic risk management and rapid emergency response processes adaptable to railway emergency risk handling (Karanfil, 2025). The power industry's integrated system of proactive risk control, hazard investigation, and emergency support (Wang, Tang, Hong, Wang, & Chen, 2025), the petrochemical industry's HSE management system (Tian *et al.*, 2025), and the coal mining industry's team-based self-governance safety mechanism (Jamil *et al.*, 2025) all furnish practical references for local adaptation in railway safety management system development. Concurrently, national standards such as General Specifications for Enterprise Safety Production Standardization (AQ/T 9006–2010) and GB/T 43500–2023 Requirements for Safety Management Systems provide regulatory compliance foundations for the standardization and institutionalization of railway safety management systems.

Nevertheless, most existing studies remain fragmented and module-oriented, lacking a systematic, full-life-cycle, and China-adapted integrated framework for railway safety management. In addition, few studies have clarified the dynamic operation mechanism and digital implementation path, which motivates the research of this paper. Furthermore, existing research tends to be descriptive and application-oriented, with insufficient critical analysis of the contradictions between international safety management standards and China's railway operational characteristics. Most studies focus on individual components such as risk control or emergency disposal, but fail to establish a synergistic mechanism that integrates institutional guarantee, organizational responsibility, process implementation, technical support, and cultural guidance. Meanwhile, the connection between theoretical framework and practical landing is weak, and few studies systematically explain how to address the problems of poor coordination, low precision, and insufficient closed-loop iteration in traditional management. This study targets these gaps to construct a comprehensive system and dynamic operation model, thus making up for the deficiencies of existing research.

1.2 Motivation and contributions

The core challenge in contemporary railway safety management centers on integrating general international safety management concepts, foreign railway professional practices, and domestic localization experiences to construct a safety management system tailored to the distinctive characteristics of China's railways, while addressing deficiencies in coordination and precision. The core contributions of this study are threefold: First, it transcends traditional fragmented safety management paradigms, constructing a railway safety management framework with full-lifecycle, all-factor, and full-process coverage, thereby transforming safety management from fragmented measures to systematic, goal-oriented endeavors. Second, it integrates general international safety management principles with distinctive Chinese railway management requirements, establishing a dynamic functioning mechanism that is globally interoperable and locally adaptable, thereby ensuring operational consistency and traceability. Third, it articulates a practical implementation pathway for the railway safety management system, providing operational technical solutions for safety design, risk prevention and control, and continuous optimization in complex operational scenarios, thereby enhancing systematic rigor and methodological soundness in China's railway safety governance.

Compared with existing safety management systems (SMS), PDCA cycle, conventional risk control and emergency management approaches, the "1 + 3+1" framework and SERA model proposed in this study have distinct novelty and incremental value. Existing methods are often scattered, module-based, or process-single. In contrast, this study constructs a full-element, full-process, and full-lifecycle integrated system. The SERA model expands and optimizes the traditional PDCA cycle by combining China's railway regulatory characteristics, multi-stakeholder coordination, whole-chain responsibility, and digital enabling technologies. It realizes a closed-loop operation from top-level institutional design to on-site implementation, which effectively overcomes fragmentation and insufficient coordination in traditional management. This integrated design provides stronger systematicity, adaptability and operability for complex high-density, high-speed and heavy-haul railway operation scenarios.

2. Research on the safety management system framework of China's railways

Based on the practical requirements of railway safety management in China and sector-specific development characteristics (Wang, 2023), this study proposes a "1 + 3+1" hierarchical three-dimensional core framework. This framework adheres to the core logic of "institutional leadership, accountable implementation of responsibility and authority, preventive frontloading, emergency safeguard, enabling support, and closed-loop evaluation and rectification". These levels are intrinsically interconnected and operate synergistically to achieve comprehensive coverage, full-process control, and all-element coordination in railway safety management. The proposed framework is illustrated in Figure 1.

2.1 Legal-institutional framework and organizational responsibility system

Legal norms and organizational responsibility systems constitute the overarching design of the railway safety management framework, fulfilling the core functions of "establishing standards through regulation, constructing frameworks through organization, and ensuring implementation through strengthened accountability". These elements provide the legal foundation, organizational infrastructure, and accountability mechanisms for all safety management activities, ensuring that the system operates with "laws to abide by, regulations to comply with, and responsibilities clearly defined".

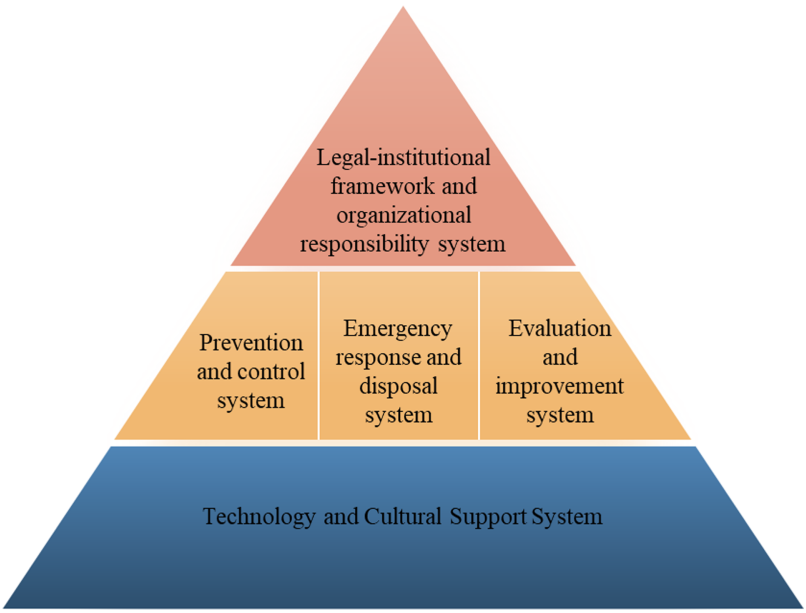

Figure 1. Framework diagram of China's railway safety management system. Source: Author's own work

(1) Hierarchical normative system: This involves establishing a three-level interconnected standardization framework of "national legislation – industry standards – enterprise rules", with the Work Safety Law of the People's Republic of China serving as the fundamental legal basis, the Railway Safety Management Regulations and other administrative statutes as specific requirements, railway technical standards and safety management norms formulated by the National Railway Administration as unified industry benchmarks, and the technical directives of China State Railway Group and its subsidiaries as the internal implementation foundation. This ensures seamless linkage across macro-level legislation, meso-level standardization, and micro-level operational rules. Additionally, a three-tier emergency response planning system comprising "master plans, specialized plans, and on-site response protocols" is established, encompassing both routine operations and emergency contingencies.

(2) Collaborative organizational structure: This involves establishing a two-tier collaborative structure of "industry supervisory bodies – enterprise management organizations". At the industry supervision level, a vertical oversight network led by the National Railway Administration and implemented by seven Regional Railway Supervision Bureaus is established, enabling coordinated hierarchical supervision and collaborative oversight mechanisms with local governments. At the enterprise management level, a five-tier vertical management system comprising China State Railway Group – Railway Bureau Group Companies – stations – workshops – teams is established, with dedicated safety management teams at each tier. The safety responsibilities and accountabilities of each organizational level are clearly defined, achieving a management pattern of "top-level governance, middle-level coordination, and grass-roots implementation".

(3) Full-chain responsibility cascade system: This involves clearly defining the full-chain responsibility boundaries of "external collaborative responsibility – internal hierarchical responsibility". Externally, this encompasses the industry supervision responsibility of the National Railway Administration, the primary safety responsibility of China State Railway Group, the local jurisdiction responsibility of regional governments, and the collaborative responsibility of relevant stakeholders. Internally, the system implements "dual responsibility for single positions and liability for dereliction of duty", thereby establishing a comprehensive responsibility transmission mechanism extending from enterprise leadership to frontline personnel. Safety responsibilities are allocated to each position and operational link, with a responsibility pursuit mechanism established to form a closed-loop process of "responsibility definition – responsibility fulfillment – responsibility pursuit", ensuring that responsibility transmission occurs without attenuation and implementation has no blind spots.

2.2 Three core execution systems

The prevention and control system, the emergency response system, and the assessment and improvement system constitute the core operational pillars of the railway safety management framework. These align with the ex-ante – in-event – ex-post continuum of safety management, forming three lines of defense for railway safety and enabling full-lifecycle management from proactive risk control through emergency response to continuous system optimization.

(1) Prevention and control system: This system serves as the "frontline" of safety risk prevention and control, with its core objective being the establishment of a dual-prevention mechanism encompassing hierarchical risk control and hidden danger

detection and rectification, thereby achieving proactive control and dynamic management of safety risks. Risks are identified and assessed across all processes and elements, classified into four tiers (major, significant, general, and low), and subject to differentiated control measures. A closed-loop management process of "detection–registration–rectification–closure–re-inspection" is established for hidden dangers to ensure continuous remediation. Additionally, three supporting subsystems are established: (1) equipment quality assurance, realizing full-lifecycle quality management from design to decommissioning; (2) personnel competency assurance, covering recruitment, training, skill assessment, and performance-based incentives to enable fine-grained management of human-factor risks; and (3) environmental safety assurance, focusing on trackside protection zone management, linear environmental governance, and disaster monitoring and early-warning systems, thereby comprehensively addressing safety risks. For risk classification, a complete implementation logic is followed: risk identification → risk assessment → classification into four levels (major, significant, general, and low) → hierarchical control → dynamic early warning. For hidden danger management, a closed-loop implementation process is adopted: hidden danger detection → registration and filing → rectification and treatment → review and verification → closure and cancellation. Such a clear process enhances the operability and standardization of safety management.

(2) Emergency response and disposal system: This system establishes an emergency response framework characterized by "comprehensive contingency planning, robust command structures, abundant resource reserves, and professional rescue teams", ensuring rapid response, efficient disposal, and minimized personnel casualties and asset damage. A three-tier emergency planning system comprising "master contingency plans, specialized contingency plans, and on-site disposal protocols" is established, accompanied by a dynamic updating and regular drilling mechanism. A centralized emergency command platform is constructed to integrate multi-source information, enabling real-time dissemination, unified resource allocation, and streamlined command delivery to frontline units. The spatial distribution of emergency rescue bases is optimized, professional rescue teams are organized, and emergency resource reserves and public-private coordination mechanisms are established, forming a national railway emergency support network that enhances comprehensive disposal capabilities. Additionally, capacities for addressing emerging risks—including natural disasters and public security incidents—are systematically strengthened.

(3) Evaluation and improvement system: This system establishes a closed-loop optimization mechanism of "monitoring–evaluation–rectification–enhancement", enabling timely identification of operational deficiencies and driving continuous improvement of the safety management framework. A multi-tier safety oversight mechanism comprising "industry regulatory inspection, internal enterprise auditing, and third-party assessment" is established to enable comprehensive monitoring of operational effectiveness. Additionally, a KPI-based safety performance assessment system is developed, integrating outcome metrics with process indicators to enable integrated quantitative and qualitative evaluation. Assessment results are linked to performance appraisal, compensation, and career advancement, establishing incentive and disincentive mechanisms. Accident investigations are conducted in strict accordance with the "four non-let-go" principle(no let-go until root causes are identified, responsible parties are held accountable, corrective measures are implemented, and lessons are disseminated), thoroughly identifying root causes and establishing lessons-learned dissemination mechanisms. These insights are translated

into actionable improvements, including system standard revisions and control measure optimizations, thereby achieving continuous enhancement through investigation-driven and lesson-based improvement.

2.3 Technology and cultural support system

The technical and cultural support system serves as a critical underpinning and enabling mechanism for the railway safety management framework. It provides solid technical support and cultural guarantee for the efficient operation of the whole framework.

(1) Technical support system: This system adheres to the "Technology for Safety" strategy, developing a comprehensive, intelligent technical support infrastructure that promotes the integration of modern information technology with railway safety management. It develops and deploys intelligent monitoring equipment for rolling stock, infrastructure, and signaling systems, enabling real-time monitoring of asset conditions and operational environments. It leverages big data, artificial intelligence, and machine learning to construct intelligent risk analytics and predictive models, establishing a risk monitoring and early-warning system grounded in an integrated risk data repository, thereby enabling accurate risk identification and proactive alerting. It establishes a unified digital and intelligent safety management platform, integrating multidimensional operational data encompassing safety monitoring, hazard detection, risk mitigation, and emergency response. This achieves data interoperability, advanced analytics, and visualization, thereby enhancing the digitalization and intelligent capabilities of safety management.

(2) Safety culture system: This system cultivates a professional safety ethos of "reverence for life, compliance with regulations, and commitment to responsibility", establishing a comprehensive cultural framework encompassing communication, exemplary leadership, and lessons-learned programs, thereby internalizing institutional requirements as employee behaviors. It utilizes diverse channels—including notice boards, internal publications, and digital media platforms—to broadly disseminate safety legislation, regulations, and best practices, fostering a pervasive safety culture. It identifies and promotes safety excellence exemplars, demonstrating leadership and inspiring employees to pursue safety excellence. It conducts regular lessons-learned programs through accident case video sessions, visits to safety education centers, and case study analysis, thereby enhancing safety consciousness and accountability across the workforce.

3. Research on the dynamic operation mechanism of China'S railway safety management based on the SERA model

Drawing on PDCA cycle theory and China's railway safety management framework (Jia *et al.*, 2020), we formulated the SERA model—comprising "Systematize and Support," "Execute and Enforce," "Respond and Recover," and "Assess and Advance"—as illustrated in Figure 2. This model enables organic integration across architectural tiers, coordinated interaction among management elements, and closed-loop iteration of process stages, thereby ensuring the system's adaptive alignment with evolving railway safety demands.

3.1 Phase S: systematize & support

The Systematize and Support (S) stage encompasses the legal-institutional and organizational responsibility systems and the technological and cultural support system within the "1 + 3+1" framework. It serves as the logical starting point and foundational underpinning of the entire safety management framework. Its core objective is to establish the normative foundation and

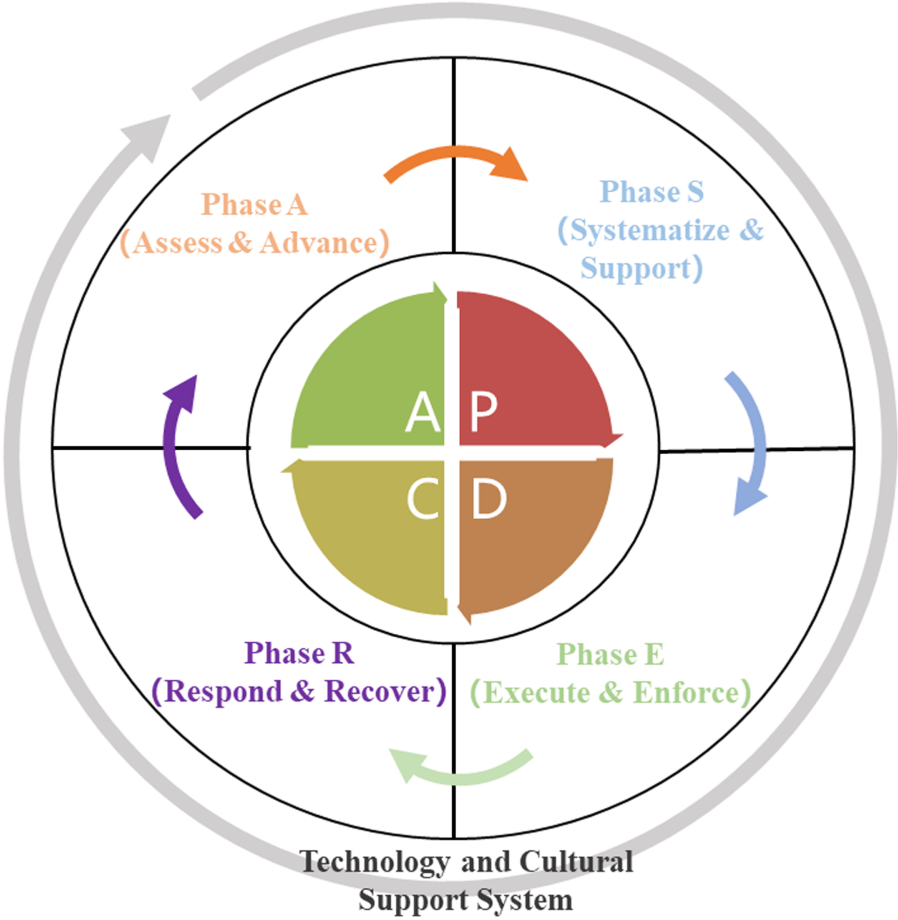

Figure 2. The SERA model diagram of China's railway safety management system. Source: Author's own work

organizational infrastructure for safety management, embedding technical and cultural enablement throughout all subsequent processes, thereby providing the legal basis, organizational platform, and enabling capacity for all subsequent safety management operations.

The core tasks of this stage encompass two pillars: First, system architecture. This involves establishing a normative system ("national legislation–industry norms–enterprise regulations"), a framework spanning standard-setting and enterprise implementation, and a comprehensive accountability system ("full-chain, full-coverage"), thereby forming a top-level framework that clarifies operational rules and authority boundaries while strengthening executive commitment. Second, process-integrated support. Technological and cultural enablers are embedded throughout system operations. Technological enablement is realized through digital platforms enabling system management and data-driven accountability tracing, while cultural support is delivered through value dissemination and cultural cultivation, strengthening employee recognition of and compliance with the framework, thereby ensuring its implementability and sustainability. Concurrently, resources are mobilized, capabilities enhanced, and safety awareness elevated, providing comprehensive enablement for system operations.

3.2 Phase E: execute & enforce

The Execute and Enforce (E) stage encompasses the prevention and control system within the "1 + 3+1" framework. It constitutes the core operational function and frontline of risk prevention and control in railway safety management. Its core objective is to translate the institutional framework established in the S stage into routine safety management operations. Through comprehensive, all-factor, and full-process control measures, it establishes a risk defense system to achieve "ex-ante prevention and in-process control", thereby preventing incidents at their source.

At this stage, the dual-prevention mechanism serves as the core, establishing a three-dimensional prevention and control framework encompassing "hierarchical risk control, dynamic hazard remediation, and integrated factor-based safeguards". Regular risk identification and hierarchical control enable dynamic risk management across all operational domains and throughout the railway transportation lifecycle. Closed-loop hazard detection and remediation ensure timely elimination of potential safety risks. Systemic assurance for equipment, personnel, and environmental conditions consolidates the safety management foundation. Concurrently, the technological support system enables intelligent risk monitoring and precise early warning, while the safety culture system standardizes workforce operational behavior, enabling fine-grained control of human-factor risks and ensuring effective implementation of prevention and control measures. Furthermore, safety management of partners, contractors, and suppliers is strengthened, change management protocols are enforced, and full-process operational control is achieved.

3.3 Phase R: respond & recover

The Respond and Recover (R) stage encompasses the emergency response and disposal system within the "1 + 3+1" framework. It serves as the final line of defense and ultimate safeguard against emergencies. Its core objective is to ensure rapid response, scientific handling, and efficient rescue when emergencies exceed preventive capacity, thereby minimizing personnel casualties and asset damage while restoring normal railway operations expeditiously.

At this stage, operations are guided by the principle of "integrating routine and emergency preparedness, ensuring rapid response and efficient disposal". The emergency response system, command platform, and rescue capabilities constitute the core of a full-lifecycle, closed-loop emergency management system. Upon emergency detection, the corresponding response plan is activated according to incident severity, leveraging the emergency command platform to enable real-time information dissemination, unified resource allocation, and remote command coordination. Professional rescue teams are integrated with civilian response resources to conduct personnel recovery and infrastructure restoration. Following incident containment, rapid restoration—including infrastructure rehabilitation, service resumption, and stakeholder management—is executed, alongside a comprehensive post-incident review to distill lessons learned and optimize response protocols and support systems. Technical and cultural support serve critical functions at this stage. Digital and intelligent technologies enhance emergency command and resource allocation efficiency, while safety culture fosters collaborative response consciousness and collective accountability.

3.4 Phase A: assess & advance

The Assess and Advance (A) stage encompasses the assessment and improvement system within the "1 + 3+1" framework, serving as the catalyst for continuous optimization and iterative advancement of railway safety management. Its core objective is to pinpoint systemic weaknesses through multi-faceted evaluation, translate assessment outcomes into actionable improvements, and achieve assessment-driven improvement and improvement-driven excellence.

At this stage, the core functions encompass safety supervision and inspection, safety assessment and evaluation, and accident investigation and lessons learned. A closed-loop optimization mechanism of “monitoring–evaluation–improvement–enhancement” is established. Multi-dimensional safety supervision and inspection enable comprehensive assessment of operational effectiveness, alongside internal audits and management reviews. Scientific safety performance assessment systematically evaluates management effectiveness, establishing incentive and disincentive mechanisms. Thorough accident investigation and lessons-learned programs analyze root causes, refining standards and control measures to ensure continuous improvement. Concurrently, the technological support system enables data-driven assessment and analysis. Big data analytics uncover underlying patterns and trends in safety data, providing a scientific basis for system refinement. The safety culture system fosters an atmosphere of “honest reporting and continuous learning”, encouraging workforce participation in optimization and ensuring sustainable implementation of improvements.

3.5 The closed-loop functioning logic of the SERA model

The SERA model is not merely a linear sequence of four stages, but rather a dynamic, cyclical functioning system grounded in systems theory and closed-loop management principles. Its core logic takes data as the link to realize the integration and iteration of the four stages. Concurrently, technical and cultural enablers permeate the entire cycle, providing sustained enablement for the model’s functioning.

Operationally, regulatory, organizational, and accountability data generated in the S stage provide a binding foundation for risk identification and hazard detection in the E stage. Dynamic risk data, hazard remediation records, and equipment operational data collected in the E stage provide precise guidance for emergency alerting and response in the R stage. When risk thresholds are exceeded, emergency response protocols are activated. Data on emergency response, resource utilization, and response effectiveness in the R stage inform performance evaluation and incident analysis in the A stage. Improvement plans and system revision recommendations generated in the A stage are fed back into the S stage, driving iterative refinement of the normative framework, organizational infrastructure, and accountability systems, thereby establishing the closed-loop functioning cycle “S→E→R→A→S”.

Throughout the functioning cycle, technological enablement leverages digital and intelligent technologies to optimize and refine management processes across all stages, thereby enhancing operational precision and efficiency. In parallel, cultural support instills core values across the workforce, internalizing systemic constraints as behavioral norms, thereby strengthening intrinsic motivation for system functioning. These dual enablers collectively ensure efficient, continuous, and stable functioning of the SERA model, driving the fundamental transformation of railway safety management from experience-driven to data-driven paradigms, from static compliance to dynamic optimization, from passive response to proactive prevention, while aligning with international best practices in railway safety management.

4. Key technologies for digitalization of China’S railway safety management system

Digital transformation constitutes the central pathway for enhancing the effectiveness of China’s railway safety management system. It also provides the technological foundation for the efficient functioning of the “1 + 3+1” framework and the SERA model. Leveraging next-generation information technologies—including big data, artificial intelligence, the Internet of Things, and 5G communication—the approach centers on data integration, intelligent monitoring, risk alerting, emergency command, and assessment optimization, establishing a digital and intelligent safety management infrastructure spanning the full lifecycle and all operational dimensions. This furnishes precise, efficient, and intelligent capabilities for railway safety management, while advancing quantified risk control and dynamic management, thereby aligning with international best practices.

4.1 Multi-source data fusion and standardization technology

Data constitutes the cornerstone of digital transformation. Railway safety management spans multiple disciplines and operational scenarios, including infrastructure maintenance, signaling systems, electrification, rolling stock, and traffic control. This domain is characterized by heterogeneous data types, disparate formats, and distributed sources. Standardization and fusion technologies can break information silos and build a unified data system for quantitative risk control.

(1) Data standardization technology: This involves developing unified data classification standards, coding standards, and interface protocols for railway safety management. It clearly defines the collection scope, format specifications, and quality standards for data categories, encompassing equipment status, risk surveillance, operational performance, and emergency response data. Standardized processes are established for data cleansing, de-identification, and transformation, encompassing deduplication and anomaly correction, thereby ensuring data accuracy, completeness, and consistency, and establishing the foundation for data sharing and advanced analytics.

(2) Multi-source data fusion technology: This involves adopting a distributed data storage architecture to establish a unified safety big data center across the railway network, integrating heterogeneous data sources, including wayside monitoring equipment, onboard sensing systems, dispatching and command platforms, and emergency management systems. Data fusion algorithms are employed to enable seamless integration of structured and unstructured data, thereby establishing a holistic safety data perspective, supporting cross-disciplinary and multi-scenario analytics, and enabling quantified risk analysis.

(3) Data security assurance technology: This involves establishing a multi-tiered data security protection framework, employing encrypted transmission, access control, data anonymization, and related measures to ensure data security across the entire lifecycle from collection through transmission and storage to utilization. A data security auditing mechanism is established to monitor data access activities in real time, enabling prompt detection and prevention of security risks including data leakage and tampering, thereby ensuring compliant utilization of data resources.

4.2 Full-element intelligent monitoring and perception technology

Intelligent monitoring and perception are essential for enabling proactive risk prevention and control. Deployment of advanced sensing equipment and monitoring systems enables real-time status perception of critical elements, including railway infrastructure, equipment, personnel, and environmental conditions, thereby furnishing precise data for risk identification and hazard detection in the Execute and Enforce (E) stage of the SERA model.

(1) Line and infrastructure monitoring technology: This involves deploying fiber-optic sensing, inertial measurement units, high-definition imaging, and related technologies at critical infrastructure, including track, bridges, and tunnels, enabling real-time monitoring of track geometry, subgrade settlement, bridge structural integrity, and tunnel lining deformation. Image recognition and LiDAR technologies are applied to automatically detect potential hazards, including foreign object intrusion, fastener

loosening, and tunnel lining cracks, thereby enhancing monitoring precision and efficacy.

(2) Equipment full-lifecycle monitoring technology: This involves installing vibration and temperature sensors, along with electrical parameter monitors, on critical assets, including rolling stock, signaling systems, and traction power systems, to collect real-time operational data. Fault diagnosis algorithms are applied to operational data to enable early detection and alerting of incipient faults, supporting a precision maintenance paradigm of condition-based maintenance prioritized over scheduled maintenance, thereby extending operational lifespan and mitigating equipment-failure-induced safety risks.

(3) Personnel and operational behavior monitoring technology: This involves utilizing video surveillance, smart wearable devices, and body-worn cameras to conduct real-time monitoring of operational behavior, work processes, and environmental conditions of frontline personnel. Behavior recognition algorithms are employed to automatically detect unsafe behaviors, including procedural violations and fatigue-induced impairment, enabling prompt alerting and intervention. Smart wearable devices collect physiological indicators to monitor personnel health status in real time, thereby preventing human-factor-induced incidents and enabling fine-grained management of human-factor risks.

(4) Environmental and External Risk Monitoring Technology: This involves establishing a meteorological and geological disaster monitoring network spanning the railway network, deploying rain gauges, anemometers, and geological sensors to monitor natural disaster risks—including heavy rainfall, snowfall, severe convective weather, mudslides, and landslides—in real time. Video surveillance and infrared detection technologies are employed to monitor external safety risks, including unauthorized structures, light floating objects, and third-party construction damage along the railway corridor, thereby enabling early warning and precise mitigation of external risks.

4.3 Risk intelligence early warning and prediction technology

Intelligent risk alerting and forecasting is central to advancing predictive safety management. By integrating multi-source monitoring data with big data analytics and artificial intelligence, the system enables precise risk identification, tiered assessment, and trend prediction, supporting hierarchical risk control in the Execute and Enforce (E) stage of the SERA model.

(1) Intelligent risk identification technology: This involves constructing a railway safety risk knowledge base, integrating historical accident data, hazard detection records, equipment failure data, and related sources, and establishing a risk identification rule base. Machine learning and deep learning algorithms are employed to analyze real-time monitoring data, automatically detecting potential risks across infrastructure, equipment, personnel, and environmental dimensions, thereby enabling automated and intelligent risk identification.

(2) Risk tiered assessment technology: This involves constructing a quantitative risk assessment model based on probability of occurrence and consequence severity indicators. The Analytic Hierarchy Process (AHP) and risk matrix methods are employed to classify identified risks, delineating boundaries among major, significant, general, and low risk tiers. Risk assessment indicators and weights are dynamically adjusted based on scenario-specific characteristics, thereby enhancing scientific rigor and targeted precision of risk tiered assessment, and enabling quantified risk control.

(3) Risk trend prediction technology: This involves employing time series analysis and neural network algorithms, leveraging historical and real-time monitoring data, to forecast safety risk trajectories and evolutionary patterns. For major risks, dedicated prediction models are established to project potential consequences, thereby furnishing a scientific basis for tiered risk control strategies.

4.4 Intelligent emergency response technology

Intelligent emergency response is central to enhancing incident response effectiveness. This involves establishing an intelligent emergency command platform, integrating emergency response assets, and optimizing response workflows, thereby furnishing technical enablement for response and recovery operations in the Respond and Recover (R) stage of the SERA model.

(1) Emergency command visualization technology: This involves constructing a railway safety emergency command visualization platform based on Geographic Information System (GIS) and three-dimensional modeling technologies, integrating railway network distribution, asset deployment, emergency resources, and real-time monitoring data, thereby enabling holistic situational visualization. Real-time connectivity between the emergency command center and incident sites is established through video conferencing and satellite communication technologies, thereby furnishing technical enablement for remote command and distributed collaboration.

(2) Intelligent emergency resource dispatch technology: This involves establishing an emergency resource database for digital management of response teams, specialized equipment, emergency supplies, and related assets, enabling real-time monitoring of resource distribution and operational status. Intelligent dispatch algorithms are applied to automatically plan resource transportation routes based on incident type, location, and scale, enabling optimal allocation and expedited dispatch of emergency resources, thereby enhancing emergency response support efficiency.

(3) Intelligent emergency decision support technology: This involves establishing an emergency response knowledge base, integrating response protocols, technical remedies, and case studies for various emergency scenarios. Leveraging real-time incident data and artificial intelligence algorithms, the system automatically matches similar cases and generates tailored response strategies, thereby furnishing intelligent support for command decision-making, and enhancing scientific rigor and responsiveness of emergency response.

4.5 Safety management assessment and optimization technology

Evaluation and optimization technologies are central to the iterative refinement of the safety management system. Data-driven evaluation and analysis furnish technical support for performance assessment and continuous improvement of the SERA model in the Assess and Advance (A) stage, thereby enabling dynamic optimization of the safety management system.

(1) Safety performance quantified assessment technology: This involves developing a multidimensional safety performance assessment indicator framework, encompassing incident occurrence rate, hazard remediation rate, risk control adherence rate, and asset integrity rate. Big data analytics are employed to conduct quantitative assessment of safety performance indicators, thereby objectively reflecting safety management effectiveness. Data visualization technologies present assessment results intuitively, thereby furnishing management with actionable insights into safety management status.

(2) Accident and hazard root cause analysis technology: Data mining and association analysis techniques are applied to conduct in-depth analysis of incident and hazard data, uncovering underlying managerial gaps, technical def0069ciencies, and institutional weaknesses. Complemented by methods such as Five Whys and Fault Tree Analysis (FTA), a comprehensive review of incidents and hazards is conducted, thereby furnishing a scientific basis for developing improvement measures, and aligning with the international best practice of "learning from incidents".

(3) System dynamic optimization technology: This involves generating recommendations for revising normative standards, optimizing management processes, and enhancing technical measures, based on safety performance assessment results and root cause analysis findings, employing system optimization algorithms. A tracking and verification mechanism is established to monitor real-time implementation progress and effectiveness of corrective actions, thereby forming a closed-loop optimization process of "assessment–analysis–improvement–verification", promoting iterative refinement of the railway safety management system, and fulfilling the improvement objectives of the PDCA cycle.

5. Conclusion

This study focuses on the insufficient adaptability of traditional safety management models facing the rapid development of China's railways. A "1 + 3+1" safety management framework and a closed-loop SERA dynamic operation model are constructed, which integrate international advanced experience and Chinese railway characteristics. The main conclusions are as follows:

(1) Theoretical contributions

- This study breaks through the fragmented management mode of traditional railway safety, and constructs a full-element, full-process and full-cycle safety management framework, which realizes the transformation from scattered control to systematic governance.(2) Based on the PDCA cycle theory, the SERA dynamic operation model is proposed, which forms a complete closed loop from top-level design to operation implementation, and improves the theoretical rigor of railway safety governance.(3) The key digital technologies supporting the system are clarified, which provides a theoretical reference for the intelligent and digital transformation of railway safety management.

(2) Practical applications

- The "1 + 3+1" framework can be directly integrated with the current safety management practice of China's railways, and has strong engineering applicability.(2) The SERA model realizes the closed-loop iteration of safety management, which helps to improve the coordination efficiency and risk prevention ability of railway safety.(3) The digital technical system provides practical solutions for intelligent monitoring, risk early warning, emergency command and performance evaluation, and supports the transformation from experience-based management to data-driven management.

In the future, with the continuous development of new-generation information technologies such as big data and artificial intelligence, the framework and model will be further optimized and upgraded to promote the modernization of railway safety governance capacity.

Reference

Bugalia, N., Maemura, Y., & Ozawa, K. (2021). Characteristics of enhanced safety coordination between high-speed rail operators and manufacturers. *Safety Science*, *145*, 107995. doi: 10.1016/j.ress.2021.107995.

Chen, J., Zhao, L., Liu, J., Wang, G., & Guo, Z. (2025). Investigating the coupling relationships of railway safety risks using the N-K model and complex network theory. *PLoS One*, *20*(9), e0332948. doi: 10.1371/journal.pone.0332948.

Fan, D., Zhang, A., Feng, Q., Cai, B., Liu, Y., & Ren, Y. (2021). Group maintenance optimization of subsea Xmas trees with stochastic dependency. *Reliability Engineering and System Safety*, *209*, 107450. doi: 10.1016/j.ress.2021.107450.

Fan, D., Sun, B., Dui, H., Zhong, J., Wang, Z., Ren, Y., & Wang, Z. (2022). A modified connectivity link addition strategy to improve the resilience of multiplex networks against attacks. *Reliability Engineering and System Safety*, *221*, 108294. doi: 10.1016/j.ress.2021.108294.

Fan, D., Liu, M., Shao, Y., Yang, L., Liu, Y., Zhang, Y., . . . Wang, Z. (2025). Domain-specific large language model for maintenance decision-making on wind farms by labeled-data-supervised fine-tuning. *Engineering*, *60*, 343–361. doi: 10.1016/j.eng.2025.12.019.

Ilczuk, P., Kycko, M., & Szmel, D. (2023). Dynamic safety management model for rail traffic control. *Journal of Civil Engineering and Transport*, *5*(4), 53–63. doi: 10.24136/tren.2023.016.

Jamil, Z., Nordin, S., Miraj, M., Alqahtani, M., Shaik, R. A., Akhter, S., & Nizam Isha, A. S. (2025). Sustainable safety practices and hazard management in the oil and gas industry: An HSE perspective. *Frontiers in Public Health*, *13*, 1234567. doi: 10.3389/fpubh.2025.1611106.

Karanfil, S. M. (2025). Evaluating the reporting and safety culture of an airline according to Patankar and Sabin's safety culture pyramid. *International Journal of Aviation, Aeronautics, and Aerospace*, *12*(1), 27.

Jia, Y. M., Nie, L., Wang, H. X., *et al.* (2020). Research on the framework of China railway operation safety management system (CRSMS). *Chinese Railway*, 01, 43–47.

Li, Q., Liu, J., & Han, J., & Others (2026). Analysis on characteristics of foreign railway safety management systems and suggestions for optimization of China's railway safety management system. *Chinese Railway*, 01, 134–141.

Liu, P., Fang, X., Chen, J., Zhang, J., Zhang, K., & Wang, M. (2025). Reliability allocation of railway system based on fault tree. *Railway Sciences*, *4*(4), 550–562. doi: 10.1108/rs-06-2025-0020.

Ren, Y., Fan, D., Wang, Z., Yang, D., Feng, Q., Sun, B., & Liu, L. (2018). System dynamic behavior modeling based on extended GO methodology. *IEEE Access*, *6*, 22513–22523. doi: 10.1109/access.2018.2816165.

Tian, S., Wang, R., Li, H., Chen, L., Kuang, Y., & Mao, J. (2025). Predictive analysis of miners' group unsafe behavior based on group dynamics and institutional environment. *Scientific Reports*, *15* (1), 12345. doi: 10.1038/s41598-025-89860-x.

Wang, Y. G., & Liu, J. H. (2017). Comparative analysis of railway safety management systems between China and foreign countries. *Railway Quality Control*, *45*(6), 1–6, 18.

Wang, B. G. (2023). Construction and implementation path of modern railway safety guarantee system. *Chinese Railway*, *10*, 1–6.

Wang, C., Tang, M., Hong, G., Wang, D., & Chen, Z. (2025). Dynamic integrated approach to safety risk management in substation maintenance and testing integration operations. *Reliability Engineering and System Safety*, *261*, 109798. doi: 10.1016/j.ress.2025.111061.

Yan, S., Fan, D., Li, B., Ji, Z., Zhang, Y., & Ren, Y. (2026). Coordinative optimization strategy for group track maintenance planning and train scheduling of railways. *Reliability Engineering and System Safety*, *271*, 112272. doi: 10.1016/j.ress.2026.112272.

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