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Current status and trends in the development of inspection technologies and equipment for heavy-haul railway infrastructure

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Abstract

Purpose – This paper aims to systematically review the evolution of inspection technologies and equipment for heavy-haul railway infrastructure, with a focus on China's Shuohuang Railway and Daqin Railway. It summarizes the technological progression from traditional manual inspections to integrated and intelligent inspection systems, analyzes their practical application outcomes and outlines future research directions to support the safe, efficient and sustainable operation of heavy-haul railways.

Design/methodology/approach – The study employs a combination of historical and empirical analysis, primarily drawing on academic literature and operational data from Shuohuang Railway. The development of inspection technologies is categorized into two distinct phases: traditional inspection and integrated inspection. The comprehensive effectiveness of these technologies is evaluated based on actual inspection efficiency, defect detection capability, cost savings and other relevant data.

Findings – The adoption of integrated inspection vehicles has significantly improved inspection efficiency and accuracy. In 2014, the world's first heavy-haul integrated inspection vehicle enabled synchronous multidisciplinary inspections, greatly reducing reliance on manual labor. By 2024, the intelligent heavy-haul integrated inspection vehicle further enhanced detection precision by 30%. Practical applications demonstrate that the annual number of track defects decreased from 25,000 to 3,800, while the track quality index (TQI) remained stable below 6 mm. Additionally, annual maintenance costs were reduced by more than 40 m yuan.

Originality/value – This paper provides the first systematic review of the development of inspection technologies for heavy-haul railway infrastructure, highlighting China's leading achievements in integrated and intelligent inspection. It clarifies the practical value of these technologies in enhancing safety, reducing costs and optimizing maintenance operations. Furthermore, it proposes future directions for development, including system integration, onboard computing capabilities and unmanned operations, offering valuable insights for technological innovation and policymaking in the field.

Keywords Heavy-haul railway, Infrastructure, Inspection technology, Equipment

Paper type Research article

1. Introduction

With significant advantages such as high speed, low cost, strong adaptability, and large capacity, railway transportation has become a vital mode of passenger and freight transport in China (Sun, Sun, Cao, & Su, 2025). As the demand for railway transportation continues to rise, railway freight transport is progressively moving toward higher speeds and heavier loads. Increasing the maximum traction weight per freight train is a key strategy to enhance transportation efficiency (Gong, Yang, Bian, Luo, & Zhang, 2025). Against the backdrop of growing freight volume, heavy-haul railways (Tong, Wei, Mao, Lu, & Xue, 2025), despite being a strategic core of modern freight development and occupying an important position due

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to their advantages in large capacity, high efficiency, and low energy consumption, face severe challenges in the operation and maintenance of heavy-haul railway infrastructure (Li, 2015). Issues such as rail corrugation (Xiao *et al.*, 2025), side wear (Ma, Liu, Ren, Chen, & Liu, 2021), spalling, scraping (Hou *et al.*, 2024), and crushing occur frequently, not only seriously threatening operational safety and transportation efficiency but also significantly shortening the service life of rails.

Heavy-haul railway infrastructure refers to the permanent engineering facilities and supporting systems specifically designed to meet the demands of large axle loads, high freight volume, and high-density freight transportation. It serves as the core support of the heavy-haul railway transportation network. Its key characteristics revolve around “bearing high-intensity loads, ensuring long-term stable operation, and improving freight transportation efficiency,” distinguishing it significantly from high-speed railway infrastructure, which primarily caters to passenger transport (Wang, 2021), and conventional railway infrastructure that handles mixed passenger and freight traffic. It acts as a critical artery for the cross-regional transportation of bulk goods such as coal, ore, and grain.

As a “cost advantage” and “efficiency advantage” for bulk cargo transportation, the value of heavy-haul railway infrastructure is reflected across economic, energy, and social dimensions. Its core subsystems primarily include heavy-haul line engineering systems, heavy-haul station and hub systems, heavy-haul signaling and communication systems, and heavy-haul power supply and energy systems. Therefore, conducting inspection work for heavy-haul railway infrastructure is a critical link in ensuring its safe, efficient, and economical operation. Its significance spans the entire lifecycle of railway operations—it is essential for upholding the bottom line of transportation safety while also influencing the improvement of transportation efficiency and the control of long-term operational costs. In summary, heavy-haul railway infrastructure inspection is far from a “simple equipment check.” Instead, it is a core technical task integrating “safety assurance, efficiency improvement, cost control, technical support, and compliance fulfillment.” Against the backdrop of the increasingly prominent strategic importance of heavy-haul railways for national energy transportation and economic development, strengthening inspection capabilities and improving the inspection system have become imperative for promoting the high-quality development of heavy-haul railways.

Currently, the development of theories, technologies, and equipment for the comprehensive inspection of heavy-haul railway infrastructure is still evolving, with many technological achievements already successfully applied. However, to date, there has been no systematic review in this field. To fill this gap, promote the development of new productive forces in heavy-haul railway infrastructure inspection technologies and equipment, and support the achievement of “dual-carbon” goals (carbon peak and carbon neutrality), this paper elaborates on the development trajectory of traditional inspection technologies and equipment for Shuohuang Heavy-haul Railway infrastructure in recent years (particularly over the past two decades), highlights the achievements of the world’s first heavy-haul comprehensive inspection vehicle, and emphasizes the current state of technology of the world’s first intelligent comprehensive inspection vehicle. It summarizes the practical effectiveness of inspection technologies and equipment and proposes key directions for future technological research and development. The aim is to provide a theoretical basis and practical guidance for the continuous improvement and optimization of comprehensive inspection technologies for heavy-haul railway infrastructure in China, while also offering a reference for researchers in related fields (Li, 2024).

2. Division of development stages of infrastructure inspection technologies and equipment

In accordance with international heavy-haul railway standards and specifications, China has constructed and operates multiple heavy-haul railway trunk lines that meet these criteria. Notable examples include the Shuohuang Railway, Daqin Railway (Hu, 2015), Wari Railway (Sun, 2022), and Haoji Railway (Du, Zhang, & Yuan, 2023), which are representative freight transportation corridors. Specifically, the Daqin Railway commenced construction in 1985, achieved full-line operational connectivity in 1992, and completed the final acceptance of supporting projects in 1998. The Shuohuang Railway began construction in 1997, completed its first phase and entered trial operation in 2000, and achieved full-line operation in 2002. The commissioning dates of these two heavy-haul railways predate those of other similar heavy-haul railway infrastructures in China. Particularly, the research on the development of inspection technologies for the Shuohuang Railway holds benchmark and representative significance.

Given this, our study focuses on the Shuohuang Railway and Daqin Railway as research subjects. We systematically collected and deeply analyzed the development history and engineering application data of their infrastructure inspection technologies and equipment, while also reviewing relevant academic literature and technical reports. By identifying representative milestones in the development and application of key inspection technologies and equipment, and considering the importance of these technologies to the operational efficiency and safety assurance of heavy-haul railways, we categorize their evolution into two distinct trajectories: traditional inspection technologies and integrated inspection technologies.

3. Development of traditional inspection technologies

In the early stages of China's heavy-haul railway development, infrastructure inspection primarily relied on manual methods. Inspection personnel used visual observation, simple measuring tools, and their own experience to examine infrastructure components such as rails, track geometry, and subgrades. For example, they visually inspected rail surfaces for obvious defects like wear and cracks; used track gauges to measure geometric parameters such as gauge and level; and tapped rails with small hammers to detect internal damage based on sound. Although this manual inspection approach was simple and practical, it had several limitations. On one hand, inspection efficiency was low, making it difficult to meet the frequent inspection demands of long-distance heavy-haul railway lines. On the other hand, inspection results were highly influenced by the subjective judgment of personnel, leading to relatively low accuracy and reliability, in addition to high labor intensity. Nevertheless, given the technological conditions at the time, manual inspection played a crucial role in ensuring the initial operational safety of heavy-haul railways and laid the foundation for the subsequent development of inspection technologies.

With continuous technological advancements and the expansion of heavy-haul railway transportation, some small-scale mechanical inspection instruments and equipment were widely adopted. These included portable rail flaw detectors and compact track geometry measurement devices. Compared to large inspection vehicles, these tools offered greater flexibility and could be used for detailed inspections of local track facilities or in areas inaccessible to larger inspection vehicles. They further enriched the inspection methods for heavy-haul railway infrastructure, enabling more comprehensive and meticulous inspection work. The introduction of small-scale mechanical inspection technologies significantly enhanced inspection capabilities, greatly improving both efficiency and accuracy, thereby providing stronger support for ensuring the safe and stable operation of heavy-haul railways. Table 1 summarizes the types of compact mechanical equipment commonly used for inspecting permanent way, signaling, and power supply infrastructure in heavy-haul railways.

4. Development of integrated inspection technologies

With the continuous increase in traffic density and transportation volume of heavy-haul railways, the static inspection mode based on compact instruments faces significant challenges of soaring costs, and its inspection frequency can no longer meet the practical needs of efficient operation and maintenance of heavy-haul railways. Against this backdrop, dynamic inspection

Table 1. Compact inspection instruments

Professional field	Compact inspection equipment/tools
Permanent way	Ultrasonic rail flaw detector
	Phased array flaw detector
	Weld flaw detector
	Dual-rail flaw detector
	Track geometry inspection system
	Total station
	Level instrument
	Wireless digital transmission bridge displacement Detector
	Bridge deflectometer
	Laser distance measuring instrument
	Bridge displacement detector
	Flow velocity and discharge meter
	Digital integrated rebound hammer
	Rebar detector
	Anchor rod non-destructive tester
	Tunnel 3D scanner
	Ground penetrating radar
	Portable laser dust detector
Signaling	Cable locator
	Optical time domain reflectometer (OTDR)
	Ground resistance tester
	Standing wave ratio (SWR) tester
Power supply	Infrared thermometer
	Phase sequence tester
	Insulation resistance tester
	Clamp-on ground resistance tester

Source(s): Authors’ own work

technologies relying on comprehensive inspection vehicles (Fu & Qin, 2019) have become the core solution to current inspection demands due to their systematic and highly efficient nature. Additionally, although the academic and engineering communities have extensively explored installing inspection systems on in-service operational vehicles and conducting infrastructure condition monitoring by integrating multi-source sensing technologies and advanced signal processing algorithms, this direction has also become a research hotspot in the field of heavy-haul railway operation and maintenance. However, evident limitations such as fragmented technical solutions, lack of unified technical standards, and insufficient coverage of inspection items in related technical systems have prevented these technologies from driving profound transformations in the operation and maintenance mode of heavy-haul railways. Therefore, heavy-haul integrated inspection technology, by integrating multi-dimensional inspection functions and establishing standardized technical systems, reflects the core technological breakthroughs in heavy-haul railway infrastructure inspection. It plays a key leading role in promoting the transformation of heavy-haul railway operation and maintenance systems toward intelligence and high efficiency.

4.1 Heavy-haul comprehensive inspection vehicle (starting from 2014)

In 2009, Shuohuang Railway proposed the development plan and concept for a heavy-haul comprehensive inspection vehicle, which was officially developed and put into operation in January 2014.

As the world’s first heavy-haul comprehensive inspection vehicle as shown in Figure 1, it is based on a 25T passenger coach and integrates inspection equipment for railway subgrade ballast,

Figure 1. Heavy-haul comprehensive inspection vehicle. **Source(s):** Authors' own work

track geometry, ultrasonic rail flaw detection, catenary, signaling, wireless communication, and ground infrared axle temperature monitoring. It is equipped with advanced technologies such as data acquisition, spatiotemporal positioning, synchronous large-capacity data exchange, real-time image recognition, and integrated data processing. With a maximum inspection speed of 80 km/h, it meets the requirement of "constant-speed inspection" on Shuohuang Railway. This vehicle can simultaneously perform defect detection and safety assessment for all infrastructure components, making it a critical technical asset for improving the inspection efficiency of heavy-haul railway infrastructure, guiding maintenance and repair, and ensuring transportation safety. It is also one of the most representative "digitalized" high-tech equipment in heavy-haul railways. The supporting ground data processing center features functions such as massive inspection data storage and management, graphical comprehensive linkage display and comparison of inspection data, closed-loop defect management, and comprehensive evaluation.

This vehicle achieved dynamic, synchronous, and integrated inspection of heavy-haul railway infrastructure conditions for the first time. It integrated the first comprehensive analysis system for inspection data based on a unified spatiotemporal coordinate system, enabling quality analysis of associated equipment using multi-disciplinary inspection data from the same spatiotemporal reference and comparative analysis of historical data from any number of previous inspections. It provided crucial technical support for the safe operation and maintenance of Shuohuang Railway's infrastructure and the transformation of its maintenance model.

It is noteworthy that at the technical architecture level, this vehicle adopted a "global best-in-class integration" strategy: the rail flaw detection system incorporated core technology from the U.S.-based SPERRY company, the subgrade and ballast detection module was equipped with ground-penetrating radar equipment from the UK-based DB company, and the overhead contact line detection system utilized apparatus from Germany's DB company. The remaining detection units integrated mature domestic technologies, achieving an organic fusion of international advanced solutions and independent innovation. The systemic architecture design was led by the Shuohuang Railway Company, which subsequently accomplished localized R&D breakthroughs in ballast fouling detection technology (Zhu *et al.*, 2022a, b; Qin, Xiao, & Chen, 2019; Zhang, Qin, Xiao, & Zhu, 2018) and 75 kg/m rail flaw detection technology. These research outcomes have consistently guided the industry's technological development direction.

4.2 Intelligent heavy-haul comprehensive inspection vehicle (starting from 2024)

In July 2024, the world's first intelligent heavy-haul comprehensive inspection vehicle (Figure 2) was officially launched on Shuohuang Railway and successfully completed its inaugural inspection mission, marking another major breakthrough in China's heavy-haul railway inspection technology. This vehicle is a new-generation intelligent inspection platform for heavy-haul railways independently developed by China with full intellectual property rights. It enables intelligent inspection of infrastructure operational status, defect identification, and safety early warning, providing robust technical support for ensuring railway operation safety and maintenance, and driving profound changes in the heavy-haul railway inspection and maintenance model.

The intelligent heavy-haul comprehensive inspection vehicle is equipped with more than ten world-leading inspection technologies, including rail flaw detection, track geometry, communication and signaling, and catenary inspection, achieving comprehensive and multi-dimensional intelligent inspection of heavy-haul railway infrastructure. Compared to the first-generation heavy-haul comprehensive inspection technology, this vehicle introduces new features such as human-machine intelligent interaction, unmanned and intelligent inspection, and panoramic realistic display, analysis, and identification of railway infrastructure and its environment. The most notable highlight of the inspection train is its intelligent control platform. This platform utilizes an intelligent software system to achieve unified centralized control of all onboard inspection systems, status monitoring, and automatic data aggregation. It establishes a spatially unified reference coordinate system, enabling associated display and comparative analysis of inspection data at the same time or cross-section. This functionality not only allows inspection personnel to intuitively understand the operational status of railway infrastructure, significantly improving inspection efficiency and accuracy, but also provides a scientific basis for subsequent equipment repair and maintenance.

It is noteworthy that this vehicle incorporates three domestically pioneered technologies: first, the comprehensive application of second-generation integrated inspection technology, a

Figure 2. Intelligent heavy-haul comprehensive inspection vehicle. **Source(s):** Authors' own work

dynamically integrated carrier platform, and vehicle-ground interaction functionality, improving inspection accuracy by 30% compared to the first generation; second, groundbreaking progress in the intelligent control platform, which features an intelligent software system enabling “one-key startup, unified monitoring, and vehicle-ground coordination,” filling the gap in full-process intelligent inspection for heavy-haul railways; and third, the upgrade and iteration of domestically produced inspection equipment, overcoming “bottleneck” technologies such as pantograph-catenary inspection device and rail flaw detection noise reduction, with the localization rate of key equipment exceeding 90%.

5. Analysis of application effectiveness of technologies and equipment

The development of infrastructure inspection technologies on Shuohuang Railway has evolved through distinct phases: from sole reliance on traditional inspection methods in the early operational stage, to the deployment of the first-generation inspection vehicle in 2014, and further to the application of the intelligent heavy-haul comprehensive inspection vehicle in 2024. The application outcomes are prominently reflected in four key dimensions: enhanced safety, improved quality, reduced manpower, and lower costs.

Data indicate that in the first year of its deployment, the inspection vehicle detected over 25,000 defects. By 2024, the number of detected defects had decreased to approximately 3,800, demonstrating a consistent declining trend in defect occurrence. This has fundamentally strengthened the safety barrier of railway transportation. Relying on comprehensive inspection technologies and data support, the TQI has been consistently maintained below 6 mm, significantly enhancing the overall smoothness and structural stability of the track. The integrated operational model of the heavy-haul comprehensive inspection vehicle has completely replaced the manual inspection workload equivalent to 300 ground personnel, achieving a substantial reduction in labor costs.

In terms of daily maintenance, the technology saves over 40 million yuan annually in maintenance expenses for the permanent way department. In the realm of overhaul projects, it achieved cost savings of 350 million yuan in major and medium repairs in 2024, with projected savings of 110 million yuan in 2025, resulting in systematic optimization of operation and maintenance costs.

6. Development trends

With the continuous deepening of research on the degradation mechanisms of heavy-haul railway infrastructure and the iterative advancement of inspection technologies and equipment, intelligent integrated inspection technology has emerged as an industry trend rapidly replacing traditional manual inspections and compact instrument-based detection. Currently, alongside the high precision of electronic measurement technologies, the low latency of edge computing, and the scenario-specific breakthroughs in artificial intelligence technologies, the future development of heavy-haul railway infrastructure inspection technologies and equipment will focus on the following core directions to further enhance inspection efficiency, accuracy, and intelligence levels.

6.1 Deep integration of comprehensive inspection technologies and equipment

Leveraging multi-physical field sensing fusion technology and multi-system collaborative control architectures, comprehensive inspection equipment will evolve from “single-dimension inspection module stacking” to “multi-dimensional inspection function deep coupling.” By expanding the coverage of inspection methods and enriching the data acquisition dimensions for infrastructure, an integrated inspection system for “full-parameter infrastructure” will be established. This will enable comprehensive, synchronous, and high-precision perception of heavy-haul railway infrastructure conditions, providing complete data support for subsequent degradation trend prediction and operational maintenance decision-making.

6.2 Onboard computing power: efficient processing of multi-source heterogeneous data

As the volume of inspection parameter acquisition for heavy-haul railway infrastructure grows exponentially and large-scale AI models are deployed in practical scenarios, high-computing-power embedded computing units need to be deployed on comprehensive inspection vehicles. Utilizing the low-latency characteristics of edge computing and lightweight deployment solutions for large models, real-time onboard processing of massive multi-source heterogeneous inspection data will be achieved. This will significantly reduce the bandwidth pressure for data transmission between vehicles and ground systems, improving the efficiency of real-time feedback on inspection results and the speed of decision-making responses.

6.3 Unmanned operation of comprehensive inspection technologies and equipment

While current intelligent heavy-haul inspection vehicles already possess basic vehicle-ground mutual control capabilities, further improvements are needed in the deployment of vehicle-ground collaborative control equipment. By reducing onboard inspection personnel (transitioning gradually from “manned” to “unmanned” operations), remote tuning of inspection system parameters, intelligent processing of inspection data, and abnormal alarm notifications will be realized. This will establish an unmanned inspection mode characterized by “autonomous closed-loop operation,” adaptable to complex scenarios such as remote mountainous areas, nighttime operations, and harsh weather conditions, thereby reducing labor intervention costs and safety risks.

6.4 Green and environmental protection

Driven by the dual objectives of the “Dual Carbon” strategy and the development of new quality productivity, green transformation has become a core direction for the iterative upgrading of detection technologies and equipment for heavy-haul railway infrastructure. The underlying logic is to build a clean and low-carbon detection and maintenance system through power system innovation, operational process optimization, and full lifecycle management, thereby shifting heavy-haul railway detection from “high-energy-consumption inspection” to “green operation and maintenance.” Green development primarily focuses on the clean replacement of power sources. Supported by power electronics and clean energy technologies, traditional internal combustion power is gradually being replaced by new power systems such as hydrogen fuel cells and dual-source power supply, reducing carbon emissions and pollutants like nitrogen oxides at the source. Meanwhile, technologies such as braking energy recovery and intelligent hybrid power switching improve energy utilization efficiency, forming a synergistic “hydrogen-electric” green power architecture. Green design of detection equipment is also advancing, with low-noise power components and optimized aerodynamic structures reducing operational noise pollution. Environmentally friendly couplants and biodegradable consumables are replacing traditional chemical products to minimize the environmental impact of detection processes. Modular design enhances the recycling and reuse rate of core components, promoting resource circularity. At the detection mode level, digital technologies are leveraged to optimize the allocation of inspection resources across the network. Intelligent scheduling systems optimize detection routes and operational sequences, reducing energy waste from unnecessary empty runs and repeated inspections. Furthermore, the deep integration of green detection equipment with intelligent sensing technologies improves both energy and carbon efficiency while ensuring detection accuracy. In the future, the greening of heavy-haul railway detection equipment will extend across the entire chain, forming a full-lifecycle low-carbon technology system encompassing power supply, equipment manufacturing, and operational implementation, thereby providing critical technical support for the sustainable maintenance of heavy-haul railway infrastructure.

6.5 Equal axle load detection

Driven by the continuous increase in axle loads of heavy-haul railways and the demand for precise operation and maintenance, integrated detection vehicles based on a 25-ton equal axle load platform have emerged as a key development direction to overcome the limitations of traditional detection technologies. Their core value lies in replicating the actual wheel-rail interaction environment of heavy-haul trains, thereby addressing the deviations in track dynamic response and defect characterization caused by axle load differences inherent in 15-ton detection vehicles. This provides technical support for infrastructure condition assessment that closely aligns with real operational conditions. In the future, equal axle load detection vehicles will expand into multi-dimensional detection capabilities, integrating functions such as subgrade dynamic stress and bridge structural response monitoring. By combining with digital twin technology, a comprehensive data link will be established, improving defect identification models and irregularity management standards for heavy-haul lines. This will advance heavy-haul railway detection from “simulated assessment” to “real-scenario replication,” offering core technical support for infrastructure lifespan prediction and maintenance strategy optimization.

6.6 Normalized inspection and standardization

To achieve normalized monitoring of heavy-haul railway infrastructure and effectively address the blind spots formed during the “inspection gaps” of comprehensive inspection vehicles, equipping in-service heavy-haul trains with customized, compact, and low-power inspection systems will remain a core research direction. Simultaneously, to address the disparities in interface protocols, data formats, and calibration methods among inspection systems from different manufacturers and train models, it is essential to develop group-level or industry-level technical standards. This will promote cross-platform compatibility and sharing of inspection data, providing continuous and unified data support for the lifecycle condition assessment of heavy-haul railway infrastructure.

7. Conclusion

The technology and equipment for heavy-haul railway infrastructure inspection have undergone significant technological transitions—from manual inspections and compact mechanical instrument-based detection to dynamic collaborative inspection via comprehensive inspection vehicles, and finally to the fully autonomous operation of intelligent comprehensive inspection vehicles. This evolution demonstrates clear trends toward deep integration, intelligence, and standardization.

Currently, represented by the Shuohuang Railway, the new generation of intelligent inspection systems leverages multi-sensor fusion, high-precision positioning, domestically produced core equipment, and integrated intelligent control platforms. These systems achieve multi-dimensional synchronous perception of infrastructure conditions, intelligent defect identification, and precise maintenance decision-making driven by big data. The application outcomes are notably reflected in a more than 30% improvement in inspection accuracy, significant reductions in operational maintenance costs and labor dependency, and continuous optimization of the TQI. Looking ahead, heavy-haul railway detection technology will advance comprehensively across multiple fronts: equipment integration, deployment of embedded edge computing, fully unmanned operational processes, vehicle-ground collaborative control, routine inspection mechanisms, energy conservation and environmental protection, equal axle load detection, and standardization initiatives. These advancements aim to establish an intelligent sensing and maintenance decision-support system covering the entire infrastructure lifecycle, thereby providing core technological assurance for the safe, efficient, and green operation of China’s heavy-haul railways.

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