Current state and predicted technological trends in global railway intelligent digital transformation

Ping Li, Rui Xue, Sai Shao, Yuhao Zhu and Yi Liu
China Academy of Railway Sciences Corporation Limited, Beijing, China

Received 12 October 2023
Revised 15 October 2023
Accepted 15 October 2023

Abstract

Purpose – In recent years, railway systems worldwide have faced challenges such as the modernization of engineering projects, efficient management of intelligent digital railway equipment, rapid growth in passenger and freight transport demands, customized transport services and ubiquitous transport safety. The transformation toward intelligent digital transformation in railways has emerged as an effective response to the formidable challenges confronting the railway industry, thereby becoming an inevitable global trend in railway development.

Design/methodology/approach – This paper, therefore, conducts a comprehensive analysis of the current state of global railway intelligent digital transformation, focusing on the characteristics and applications of intelligent digital transformation technology. It summarizes and analyzes relevant technologies and applicable scenarios in the realm of railway intelligent digital transformation, theoretically elucidating the development process of global railway intelligent digital transformation and, in practice, providing guidance and empirical examples for railway intelligence and digital transformation.

Findings – Digital and intelligent technologies follow a wave-like pattern of continuous iterative evolution, progressing from the early stages, to a period of increasing attention and popularity, then to a phase of declining interest, followed by a resurgence and ultimately reaching a mature stage.

Originality/value – The results offer reference and guidance to fully leverage the opportunities presented by the latest wave of the digitalization revolution, accelerate the overall upgrade of the railway industry and promote global collaborative development in railway intelligent digital transformation.

Keywords Intelligent railways, Global railways, Best practices

Paper type Research paper

1. Introduction

The contemporary world is presently undergoing an era of intelligent digital transformation. Here, digitalization is fundamentally characterized by the profound analysis and manipulation of voluminous data, while intelligence takes center stage with elements like machine learning and artificial intelligence (AI). Intelligent digital transformation represents the seamless integration and application of both digitalization and intelligence. This societal transformation is instigating a metamorphosis of economic and social life, giving rise to the digital and intelligent economies, while propelling the digitization and innovation within industries and enterprises.

This research is supported by the China National Railway Group Science and Technology Research and Development Program (Grant N2022X002).

In recent years, nations across the globe have been confronted with multifaceted challenges in their railway systems. These challenges encompass the rapid escalation of demands in passenger and freight transport (World Bank, 2022), the customization of transport services (Winkler & Mocanu, 2020), the demanding requirement to reduce CO_2 emission (Balboa, Abreu, González-Villa, & Alvear, 2021) and the imperative expansion of transport safety (Falahati & Shafiee, 2022). Given the relatively fixed capacity of railway transportation infrastructure, the progression toward intelligent digital transformation in the railway sector has evolved into an inexorable global trend. Elevating railway transportation efficiency, refining the quality of passenger and freight transport services and raising the bar on railway transportation safety have become obligatory imperatives for railway development worldwide (Kuznetsova & Podbiralina, 2022). Leading railway nations are proactively embracing the global trends in the new technological revolution and industrial transformation, thus aligning with novel demands originating from economic and social development and competitive transport markets (Turkova, Arkhipova, Yusupova, & Zharkaya, 2022).

Driven by innovative strategic paradigms, railways worldwide are formulating intelligent technology strategies that align with their unique characteristics. Leveraging state-of-the-art technologies, including cloud computing, the Internet of Things (IoT), big data analytics, AI, mobile internet, satellite navigation and positioning and building information modeling (BIM), these nations are crafting blueprints for intelligent digital transformation. The aim is to create intelligent railway equipment endowed with self-diagnostic and self-decision-making capabilities. Consequently, they are steering intelligent railway construction with comprehensive digitalized management across the entire life cycle. The objective is to offer personalized transport services, real-time predictive safety operations and finely tuned operational management. This collective endeavor substantially raises the bar for intelligent digitalization in various facets of railway operations, encompassing passenger and freight services, engineering construction, vehicle maintenance and infrastructure upkeep.

In this context, the art of harnessing the opportunities heralded by the latest wave of intelligent digital transformation, to expedite the holistic upliftment of the railway industry, to sculpt a railway network that is both safe and efficient, to enhance the travel experiences of passengers, and thereby elevate railway competitiveness, and to catalyze global collaborative development in railway intelligent digital transformation, has emerged as a focal point of interest for both industry stakeholders and the scholarly community.

Previous literature reviews have predominantly focused on the academic landscape, providing insights into specific domains. For instance, Tang *et al.* (2022) provide a summary of AI research connected to rail transport through 139 scientific papers published in the past 10 years. Yet, the future trajectory of railway systems is profoundly influenced by national and corporate strategies, with substantial innovation unfolding in practical engineering contexts. Furthermore, most studies remain confined to isolated fields, like communication systems (Dirnfeld, Flammini, Marrone, Nardone, & Vittorini, 2020) or AI applications in maintenance (Pappaterra, 2022), leaving a void in a comprehensive exploration of the current state and vision for intelligent high-speed railways.

This paper highlights two pivotal contributions by examining the global railway intelligent digital transformation landscape through an industry-focused lens. First, it emphasizes the features and practical applications of intelligent digitalization technology in real-world settings, and then second, it reflects the consolidation of relevant technologies and scenarios. This approach not only elucidates the theoretical evolution of global railway intelligent digitalization but also provides a pragmatic guide and case studies for railway operators and policymakers. This paper is organized as follows: the first section undertakes a comparative and analytical examination of the current state and evolutionary trajectories of intelligent digital transformation in major railway nations, including France, Germany, Switzerland, Japan and China. And then the second section provides a comprehensive survey of the integration of digitalization and intelligent technologies within the railway domain, encompassing intelligent construction, equipment and operational facets. Finally, the paper culminates by delineating the global pathways for railway intelligent digital transformation.

2. Current state of global railway intelligent digital transformation

This study undertakes a comprehensive examination of the developmental pathways and practical implementations of railway systems across diverse nations. It draws upon data retrieved from official railway websites, comprising developmental blueprints and tangible case studies. Moreover, a profound understanding of these countries' railway progress and practical applications is achieved through meticulous research methodologies, including questionnaire surveys and expert interviews, specifically centered on the selected case studies. This section summarizes the level of digital and intelligent development of railways in multiple countries, including France, Germany, Switzerland, Japan and China, from two dimensions of development strategy and practical cases.

2.1 Railways in France

2.1.1 Development strategy. The railway department in France focuses on the development trends on transportation capacity, competitors, passengers and public funds. It plans to carry out technological breakthroughs in digitization, the IoT, AI, network security, energy saving and other areas to achieve low-cost and door-to-door services under new business models. It also explores the application of new technologies such as AI, energy storage, 3D printing, robotics, autonomous driving and new materials in specific railway scenarios. In 2015, Société nationale des chemins de fer français (SNCF) launched the "DIGITAL SNCF" strategy, which plans to rely on industrial internet, using target exclusive communication networks, data clouds, various sensors and other equipment and tools, supplemented by staff business processing, to connect the three major subjects of trains, railroad networks and station buildings through a network, forming connected equipment, connected rolling stock, connected railroad network and connected station. On the one hand, SNCF aims to achieve safe transportation, production efficiency, energy economy, work quality, etc., and on the other hand, it meets the needs of passengers for punctuality and comfort, establishing a competitive, convenient, sustainable and closely integrated railway system with future transportation for customers (Pinard, 2020).

(1) *Connected equipment* plans to use technologies such as 3D printing, device sensors, energy sensors, robotics and digital testing to achieve digitization of locomotives and vehicles, digitization of repairable components and digitization of information flow.

(2) *Connected rolling* stock is planned to deploy sensors on operational trains for data collection, and the collected train data will be intelligently analyzed through computers.

(3) *Connected railroad network* plans to improve the modernization level of infrastructure maintenance through real-time remote monitoring and digitization of various parts of the railroad network.

(4) *Connected station* is planned to install sensors in equipment and facilities such as elevators and platforms at the station to improve the effective utilization rate of equipment and save energy.

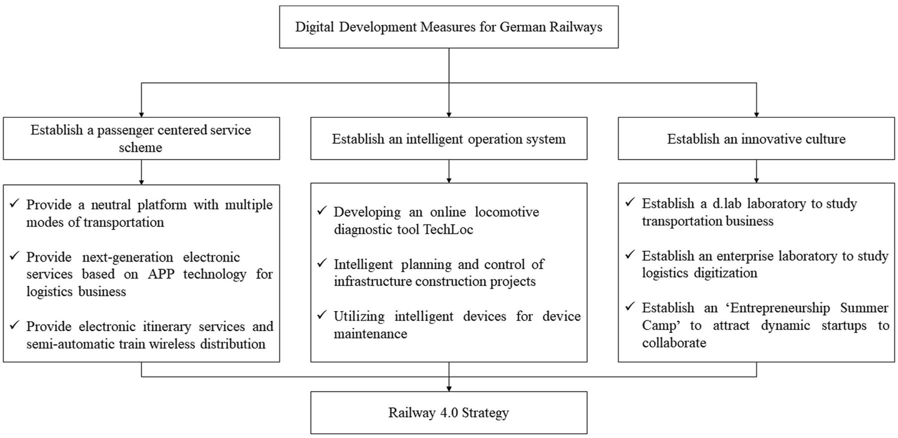
2.1.2 Practical cases. In the term of intelligent equipment, Alstom from France and Hamburger Hochbahn AG from Germany have jointly launched the Hesop system, which can recover over 99% of the traction energy generated during the braking process and redirect it to other places for reuse, thereby achieving energy-saving and consumption reducing effects.

At the same time, the system can be embedded as a module in the upgrade and renovation of existing systems, or it can be built into new lines during the construction phase. Currently, approximately 128 Hesop systems are operating on subway networks such as Milan, London, Dubai, Panama and Riyadh, as well as on trams such as Sydney and Milan (Lisienkova, Chelekova, Mitrofanova, Shindina, & Titova, 2022).

In the term of intelligent operation, Alstom in France has developed the HealthHub in recent years, which can automatically monitor the status of equipment such as locomotives, infrastructure, communication signals and accurately determine the replacement or maintenance time of equipment in a timely manner. SNCF utilizes the IBM Watson IoT platform, big data cloud computing technology and specialized industrial sensors to achieve remote monitoring of mobile devices such as trains and railway infrastructure, creating conditions for predictive maintenance (Yuan, 2021).

2.2 Railways in Germany

2.2.1 Development strategy. In 2016, Deutsche Bahn (DB) jointly signed a cooperation agreement with the German Federal Ministry of Transport and the German Railway Industry Federation on the "Railway Digitalization Strategy" (Railway 4.0). This is a technological transformation aimed at improving passenger satisfaction and delving into various aspects of the railway system, including production, operation, maintenance and customer interaction, fully supporting the German Transport 4.0 plan. The Railway 4.0 strategy includes Transportation 4.0, Logistics 4.0 and Infrastructure 4.0 and is supported by Production 4.0, Work Environment 4.0 and Information Technology 4.0. To achieve the Railway 4.0 strategy, DB has launched a series of projects and invested a lot of energy in promoting the digital development of railway transportation and operations (as shown in Figure 1). The main parts of Railway 4.0 strategy include establishing a multimodal ride hailing platform, developing mobile applications for logistics business, providing intelligent travel and route planning services for passengers, launching online diagnostic tools for locomotives, virtual planning and control systems for infrastructure construction projects, using digital equipment for maintenance work, gradually forming an intelligent operation system, promoting the development of railway research and innovation work by establishing relevant laboratories and organizing "Entrepreneurship Summer Camps" with other measures (Schindler, 2022).



Source(s): Authors own work

Figure 1.
Digital development measures for German railways

2.2.2 Practical cases. In the term of intelligent construction, Deutsche Bahn and multiple companies such as Siemens have collaborated to adopt additional technologies such as selective laser sintering and selective laser melting. Through these additional technologies, small components on photosensitive plates are connected to form 3D images of existing shapes, achieving 3D printing manufacturing of railway components. At present, 3D printing technology is mainly applied in small-scale manufacturing of railway vehicle components and customization of some products (Majko *et al.*, 2019).

In the term of intelligent equipment, Deutsche Bahn is synchronously promoting and deploying the construction of digital interlocking systems and European Train Control System (ETCS). The digital interlocking system is the first digital transmission of commands from interlocking equipment to outdoor signal equipment such as switches and signals through standardized interfaces. The outdoor signal equipment receives power locally from distributed point source terminals. IP transmission protocol can be used to transmit information through data networks. The control of outdoor signal equipment is executed by an object controller (electronic programmable controller), with a control distance much larger than electronic interlocking, which can significantly reduce the number of cables. The combination of digital interlocking technology and ETCS system can further improve the automation level of railways, enabling railway operations to achieve true technological progress and maximize benefits (Boockmeyer *et al.*, 2021).

In the term of intelligent operation, Deutsche Bahn and Siemens have launched the Velaro D (ICE3) high-speed multiple unit predictive maintenance and repair project. In this project, the mobile data service center will receive data from the rolling stock and analyze it in the central diagnostic system to calculate, process and predict faults. The predicted results will assist technical personnel in the maintenance workshop in carrying out vehicle maintenance operations (Mindur & Mindur, 2022).

2.3 Railways in Switzerland

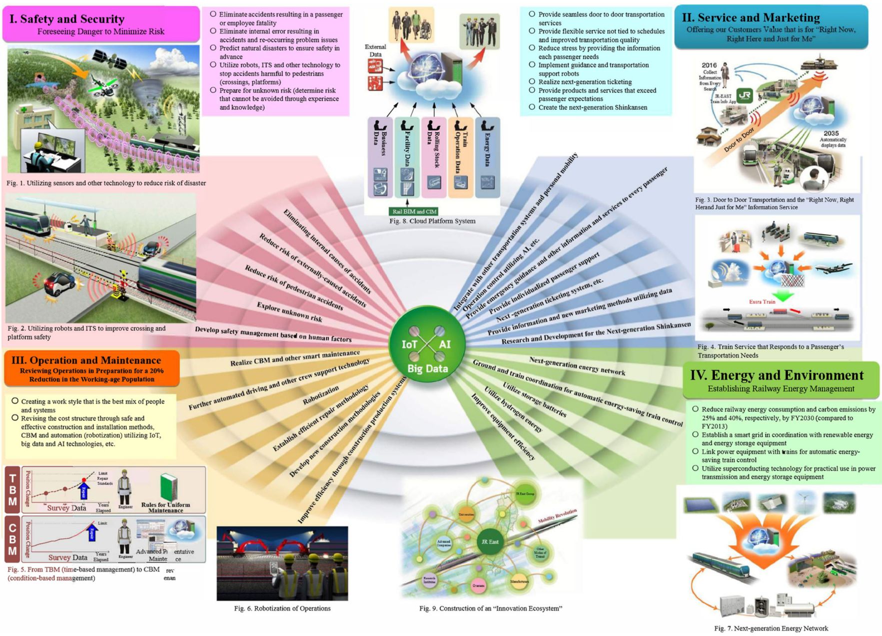
2.3.1 Development strategy. To improve the efficiency of high-speed railway operation through digitization and new technology applications, the Swiss Federal Railways proposed the SmartRail4.0 strategy in 2017, which proposes strategic goals for enterprises and customers from five aspects: cost, capability, availability, safety and service. In terms of cost, the plan is to reduce the annual operating costs by one third, providing customers with better prices and better service quality. In terms of capacity, it is planned to increase transportation capacity by 15–30% to improve operational flexibility. In terms of usability, it plans to improve the performance of the signal system by 50%, reduce travel interference and improve punctuality. In terms of safety, it plans to reduce 90% of railway operation failures and provide customers with a safer environment. In terms of services, railway enterprises are interconnected internally to provide customers with a better travel experience.

At the same time, SmartRail4.0 divides the strategic implementation process into three stages, clarifies the goals and tasks of each stage and plans for technologies such as ETCSL3-mobile blocking, centralized and simplified interlocking equipment, infrastructure construction automation and vehicle modularization (Lerida-Navarro, Nombela, & Tranchez-Martin, 2019).

2.3.2 Practical cases. In the term of intelligent operation, Swiss Federal Railways and Siemens have jointly built the world's first "cloud computing"-based scheduling control system, the Iltis system. By purchasing through licensed services, all functions of the Iltis scheduling control system can be obtained online. Swiss Federal Railways no longer needs to invest heavily in scheduling related hardware and software, and maintenance work is directly completed by Siemens without the need for technical personnel to be present on site. In addition, Swiss Federal Railways has also developed and deployed an adaptive train operation adjustment system (ADL system), which is put into use as an independent part of the entire railroad traffic dispatch control system (RCS system). The system has two main functions. One is to run conflict recognition and optimization functions, which provide train drivers with operational suggestions to prevent deep deceleration when encountering ground limit signals or parking signals by slowing down trains in advance to avoid braking and reacceleration, while achieving the goal of protecting the line and saving energy. The second is the EcoDrive function, which is used to control the arrival time of trains on the way and improve the accuracy of train arrival and departure (Graffagnino, Schäfer, Tuchschmid, & Weibel, 2019).

2.4 Railways in Japan

2.4.1 Development strategy. The new generation of intelligent technology is developing rapidly, facing significant technological changes from service to production fields. Currently, Japan is in a period of population decline, and railway transportation operations will undergo significant adjustments. In this context, JR-EAST (East Japan Railway Company), in order to fully leverage the innovative role of technology such as the IoT, big data and AI, formulated a 20-year "Medium and Long Term Plan for Technological Innovation" at the end of 2016 (as shown in Figure 2), aiming to achieve a "transportation revolution" based on new technologies such as the IoT, big data and AI from four aspects: safety assurance, strengthening services and marketing, optimizing application and maintenance and focusing on energy and environment. The revolution requires researching and building an innovative technology R&D system platform, achieving the transformation from "regular maintenance" to "state maintenance", providing door-to-door and personalized information services, building a new generation of energy management network platform, promoting the sharing,



Source(s): JR East website, https://www.jreast.co.jp/e/development/innovation/

Figure 2.
Visual framework and direction for JR East technological innovations

analysis, processing, and application of all business data of the company and continuously creating new value for the company.

Safety assurance actively promotes technological transformation, equipment update research and development, as well as the development of safety education and training technologies. It plans to establish a security assistance system that utilizes technologies such as the IoT, big data and AI to capture the precursors of accidents, uncover unpredictable risks and take preventive measures in advance.

Strengthening services and marketing can provide passenger flow and vehicle equipment information, provide real-time information on buses, taxis and other means of transportation, as well as weather, and provide personalized customized information services for passengers on the future passenger service system.

Optimizing application and maintenance gradually promotes the practicality of the "state repair" system, accelerates the development of autonomous driving technology and the use of intelligent robots and AI as auxiliary technologies. In addition, with the significant reduction of frontline technical workers, the structure of application and maintenance costs will be changed through technological innovation, achieving a work mode that closely integrates "people and systems."

Focusing on energy and environment, the JR East is committed to implementing an end-to-end energy management network platform, covering power generation through to transmission and distribution. The strategy includes the extensive integration of renewable energy and energy-efficient storage technologies. Primary objectives are to achieve a 25% reduction in railway energy consumption and a 40% decrease in carbon dioxide emissions by 2030, benchmarked against 2013.

2.4.2 Practical cases. In the term of intelligent operation, Japan Railway (JR) has deployed Mitsubishi Electric's fourth generation Train Control and Monitoring System (TCMS), and the vehicle network adopts international standards, increasing the speed from 10 Mbps to 100 Mbps. The system structure control has shifted from decentralized to centralized mode, achieving real-time control of all trains. The functional safety of the entire vehicle system has been improved to the SIL2 level of the international standard IEC62425. The software with improved product functionality is open to users to meet their modification needs. The TCMS function achieves remote maintenance support system (WMDS) through mobile communication network. In the database of the TCMS system, energy-saving operation plans for each specific line will be stored. When the train reaches certain positions, the TCMS system will display the corresponding energy-saving curve and operating speed on the display of the operation console for the driver to adjust and reference. It will also record the energy consumption of the train during operation and notify the WMDS system. WMDS collects the energy consumption of each train operation to form a database and regularly evaluate the actual energy consumption of the train and the planned operation plan based on the energy consumption database data, in order to make the best energy-saving operation plan (Cao, An, Su, Xie, & Sun, 2022).

Space time scenario analysis developed by Nokia Bell Labs applies machine learning based AI to images taken by traditional railway crossing cameras. Through scenario analysis deployed on edge computing resources, potential problems are identified in real time and alerts are provided for unauthorized intrusion into remote facilities (Hoydis, Hosseini, Ten Brink, & Debbah, 2013).

The Odakyu Electric Railway Company currently has 229 crossings and 137 radar systems for target detection on its 120.5-km track. This application applies machine learning to the images generated by existing level crossing surveillance cameras to evaluate whether they can provide better performance than radar, thereby reducing downtime and operating costs.

JR East has launched a mobile app application that has six services, including train guide, ticket booking, station guidance, running train information list, real-time departure information guidance and current train travel position. It can provide real-time travel position information of main trains in 22-line areas (including Shinkansen) within 100 kilometers of Tokyo Circle (Amoroso & Ogawa, 2011).

2.5 Railways in China

2.5.1 Development strategy. In January 2004, the State Council of the People's Republic of China (hereinafter referred to as the State Council) approved the implementation of the "Medium and Long Term Railway Network Plan," which included the development of high-speed railways in the national railway development strategy. In 2008 and 2016, the State Council approved two adjustments to the medium- and long-term railway network planning, continuously increasing efforts to promote the development of high-speed railways. On August 1, 2008, the Beijing–Tianjin Intercity Railway was opened, marking the beginning of the large-scale construction and operation of China's high-speed railway, which was the first new high-speed railway with high standards and a designed speed of 350 km/h. Afterward, China Railway successively built a number of high-speed railways with a design speed of 350 km/h and world-class standards, including Zhengzhou–Xi'an Railway, Shanghai–Nanjing Railway, Beijing–Shanghai Railway, Beijing–Guangzhou Railway and Harbin–Dalian Railway. As of the end of 2021, the operating mileage of China's high-speed railways has exceeded 40000 kilometers, accounting for more than two-thirds of the world's total high-speed railway mileage and ranking first in the world. Relying on the large-scale construction and operation of high-speed railways, China has established a comprehensive high-speed railway technology system covering six aspects: high-speed train units, track engineering, train control, traction power supply, operation management, and risk prevention and control. A large number of autonomous new equipment have been developed and applied. The overall technical level of China's high-speed railways has entered the world's top list, and some technical fields have reached world leading levels (Wang, 2019).

In recent years, with a focus on the strategic goal and mission of Outline of Powerful Nation Railway Advance Planning, China Railway has carried out intelligent innovation and application based on the Beijing–Zhangjiakou High-Speed Railway and the Beijing–Xiongan Intercity Major Project, forming a system of core technologies, key equipment, integrated applications and other innovative achievements for intelligent construction, intelligent equipment, and intelligent operation. The "Intelligent High Speed Railway System Architecture 1.0" has been issued, which provides a top-level guidance for the intelligent upgrading of new and existing high-speed railways.

In order to implement the national strategy and support the high-quality development of railways, China Railway has issued the "Outline of Railway Leading Plan for a Strong Transportation Country in the New Era," proposing the goal of building intelligent high-speed railways and accelerating the realization of intelligent railways. In order to further leverage the role of intelligent technology in ensuring safety production, improving efficiency and optimizing service quality, China Railway has recently released multiple planning documents, proposing the target tasks of Intelligent High-Speed Railway 2.0. The "14th Five-Year Plan" of China Railway proposes relevant goals and task measures for the development of intelligent railway 2.0 technology, empowering railway intelligence with modern technology, and deepening innovation in key technologies of intelligent railways. The "14th Five-Year Plan for Railway Science and Technology Innovation and Development" proposes the tasks of deepening intelligent railway technology innovation, striving to lead the development of intelligent railways, and promoting the development of intelligent railways from 1.0 to 2.0. The "14th Five-Year Plan for Railway Network Security and Informatization" focuses on the intelligence of information infrastructure and specifies that by 2025, China's standard Intelligent Railway Information System (CRIS) will be basically completed (Luo, Li, & Jia, 2020).

At the same time, with the promotion of regional coordinated development strategy, optimization and adjustment of transportation structure, and expansion of investment and construction scale, the demand for interregional, intercity and suburban transportation and the layout of adjacent road networks are accelerating. In December 2020, the General Office of the State Council issued the "Opinions on Promoting the Accelerated Development of Urban Area (Suburban) Railways" formulated by relevant departments and units such as the National Development and Reform Commission, requiring the expansion of information and intelligent applications such as network queries and mobile payments, relying on 5G, the IoT, AI, big data, etc., to provide safe, efficient, convenient and thoughtful transportation services. Same in December 2020, the Zhejiang Provincial Department of Transportation released the "Zhejiang Provincial Digital Transportation Construction Plan (2020-2025)", which clearly focused on the Hangzhou-Shaoxing-Taiwan Smart Railway, exploring the construction of high-speed rail autonomous driving, railway mobile IoT, smart stations, smart trains, etc., and promoting the all-weather digital monitoring and warning of railway perimeter safety, railway inspection, and intelligent maintenance operations. In November 2022, the China Association of Local Railways announced the "Key Points of the 14th Five-Year Plan for the Development of Local Railways in China," proposing the overall development concept of local railways for "1334," achieving integrated operation, promoting information interconnection and exchange between different rail transit systems and improving the level of informatization and intelligence.

Intelligent high-speed rail has become an important carrier for implementing new development concepts, cultivating a digital economy market and continuously leading the development of high-speed railways in the world. Currently, China has built the world's most developed high-speed rail network, with massive operational data and rich application scenarios. The existing high-speed railway faces many complex geological, climatic and natural environmental tests during its operation, which puts forward higher requirements for the safety, reliability and transportation efficiency of the existing high-speed railway. The development of intelligent technology based on the integration of emerging information technology and various specialties of existing high-speed railways has become the main mode of transformation and upgrading of existing high-speed railways. During the 14th Five-Year Plan period, the intelligent development of high-speed rail faced both significant development opportunities and numerous challenges in terms of national policies, international railway trends and industry development requirements.

2.5.2 Practical cases. In the term of intelligent construction, China's railway construction BIM technology is gradually being piloted and applied, and significant progress has been made in the preparation of relevant standards, greatly promoting the improvement of China's high-speed railway construction management level. The process management has been strengthened by putting experiments first and conducting process simulation for key and difficult projects. In terms of optimizing the implementation plan, BIM modeling and Virtual Reality (VR) simulation technology have been successfully applied to optimize the design plan of large railway passenger stations. In terms of optimizing construction organization, three-dimensional models are combined with collaborative management platforms to assist in reviewing the construction organization design of bridges crossing large rivers and long tunnels under complex conditions, optimizing technical schemes, engineering measures and resource allocation. At the same time, in terms of progress control, we attempted to use QR code technology to compare actual progress with planned progress in real-time, achieving dynamic management and timely warning of construction progress plans, improving the efficiency of progress control work and optimizing resource allocation (Lu, Liu, Liu, & Liu, 2019).

In the term of intelligent equipment, drones are increasingly being applied to the railway industry in China. Unmanned aerial vehicles (UAVs) can play an important role in surveying routes, inspecting environmental changes around the route and monitoring disasters along the route, and have thus gained recognition from some railway related units in China. The Shanghai Railway Bureau has used drones as an important means of identifying safety hazards at flood control points, combined with other measures such as flood control channels, to build a three-dimensional flood control and emergency response system, with a comprehensive focus on 473 flood control points to ensure prevention in advance. Guangzhou Railway Group uses drones to carry out high-speed railway power supply safety monitoring and introduces the 6C system (high-speed railway power supply safety detection and monitoring system) in Guangzhou power supply sections, which uses remote wireless monitoring transmission systems, including drone detection, to directly view the status of trains in operation. This not only achieves a 360-degree inspection without dead corners, but also improves labor productivity and standardized operation level, enables railway staff to promptly identify and eliminate equipment safety hazards and ensures the safety of train operation (Tao *et al.*, 2020).

In the term of intelligent operation, China Railway has realized paperless electronic tickets, noninductive check-in and out of the station and other digital, intelligent and convenient services by mobile and terminal applications such as mobile phones, Alipay, WeChat payment, UnionPay cloud flash payment, Applepay and QR code, which has greatly improved the travel experience of passengers (Shan, Zhang, Ning, Li, & Dai, 2023).

2.6 Comparative analysis

By analyzing the current development status of foreign railways, it can be found that the overall trend of intelligent development of global railways is to deeply integrate advanced technologies such as BIM, big data, IoT, AI and modern communication with various fields such as railway infrastructure, transportation equipment, dispatch and command, transportation services, maintenance and repair, achieving controllability and digitization of engineering construction, automation and intelligence of transportation equipment, flexibility of dispatch and command comprehensive, personalized and comfortable transportation services, as well as real-time safety monitoring and predictive operation and maintenance. On this basis, through the interconnection of communication data, various links and fields of high-speed railway are organically combined to optimize resource allocation and maximize comprehensive efficiency.

Infrastructure controllability and digitization actively utilizes advanced information technology and digital technology, strengthens the control of infrastructure construction costs and construction processes, ensures the quality and reliability of railway infrastructure, reduces the full life cycle cost of infrastructure and improves the controllability of railway engineering construction projects. By utilizing digital technology, important infrastructure such as tracks and switches can be transformed into digital modules to achieve rapid and efficient planning of operating lines and to improve the efficiency of line utilization.

Automation and intelligence of operational equipment develops a computer system that integrates object recognition, analysis and judgment, automatic control and other functions to achieve automatic train operation. It builds an intelligent perception system with self-detection, self-diagnosis and self-decision-making functions, utilizing various sensors, monitoring devices and train information transmission and control technology to monitor the working status of important components that affect the safety and reliability of train operation, achieving safe and reliable operation of trains under sustained high-speed conditions.

Flexibility and comprehensiveness of dispatch and command can be achieved by fully utilizing new technologies such as big data and scientifically predicting passenger and freight traffic, comprehensively analyzing the operating conditions of various railway facilities, weather and climate conditions and other factors. Flexible and dynamic train operation plans are formulated to achieve the best match between transportation capacity and volume, maximize the efficiency of train use and reduce operating costs.

Personalized and Comfortable Transportation Services develop new passenger service systems for ticketing, payment, shopping, business, information, security, inbound services throughout the entire process of passenger travel and station bus services, consummate the passenger information service system and continuously improve the convenience of railway services, while focusing on the research of comfort technology, developing entertainment facilities and meeting the increasing demand for travel comfort and entertainment from passengers.

Real-time and predictive testing and maintenance explores real-time monitoring of infrastructure and mobile equipment status based on technologies such as sensors and communication networks, applies big data and intelligent technologies to conduct in-depth analysis of data, diagnoses faults and predicting trends in the operational status of facilities and equipment, thereby achieving a transition from restorative and preventive maintenance systems to predictive or condition-based maintenance.

In addition, the key directions of digital and intelligent technology innovation in global railways mainly focus on automatic train operation, BIM technology in engineering construction, new generation train control and dispatch command systems, seamless transportation, energy conservation and environmental protection and other aspects. Automatic train operation has become an important part of the development of railway intelligence, and door-to-door services for global railway transportation and seamless transportation across multiple modes of transportation have become important goals for future railway transportation intelligence. The application of BIM technology has become an important means of intelligent infrastructure. The new generation of train control and scheduling systems has received high attention from multinational railways, focusing on the development of new generation train control system equipment such as centralized interlocking, moving block, ETCS and real-time train positioning, to achieve intelligent equipment. Green and low-carbon has become one of the important indicators for future railway transportation. In addition, many national railway companies are actively exploring areas such as standardized interfaces, 3D printing, e-commerce, digital workshops, robotics and predictive maintenance.

3. Prediction of railway digitization and intelligent technologies

Intelligent digital transformation is important means to create international competitive advantages and expand development opportunities. The deep integration of digital and intelligent technologies with railway business has entered a period of accelerated innovation breakthrough, deep penetration and widespread application. The digital and intelligent technologies follow a wave-like pattern of continuous iterative evolution, progressing from the early stages, to a period of increasing attention and popularity, then to a phase of declining interest, followed by a resurgence and ultimately reaching a mature stage. In particular, new technologies represented by digital twins, blockchain, 5G, explainable AI, privacy computing, knowledge graphs, etc., are accelerating their entry into the mature stage. With the drive of various factors such as algorithms, hardware and scenarios, the technologies provide new empowering means for intelligent construction, intelligent equipment and innovative intelligent operations.

3.1 Intelligent construction technology

In the current and future period, the world railway construction will still maintain a large scale. There is an urgent need for the modernization and large-scale development of engineering construction projects by digital and intelligent means. Comprehensive optimization of the whole life cycle operation process and management process such as design, construction and operation can promote the efficiency of railway construction, project quality, construction safety, energy conservation and environmental protection level to achieve new improvement (Mulholland & Feyen, 2021). In the field of intelligent construction, technologies such as digital twin and model-data integration can further deepen the technical application of collaborative design, digital manufacturing, intelligent engineering and assembly construction for the whole life cycle (Sresakoolchai & Kaewunruen, 2023).

In the field of survey and design, research on intelligent survey technology for railway engineering are conducted by integrating air and sky survey technologies. It has made breakthroughs in intelligent mining and rapid extraction of multisource heterogeneous multimodal geo-geological information, geo-geological full-space fusion modeling and three-dimensional fine expression, promoted intelligent railway line selection and integrated design, developed a three-dimensional integrated design platform and significantly improved the ability to digitize railway engineering design deliverables.

In the field of engineering construction, the construction of less manned factories is continuously promoted, including less manned girder and rail prefabricated parts factories, less manned plate (sleeper) factories and less manned turnouts/fasteners. Intelligent construction technologies for bridges, tunnels, roads and rails are systematically applied. Intelligent technologies are gradually maturing and being applied in major projects, such as prefabricated assembled structure and construction of tunnel by drilling and blasting method, intelligent control system of concrete proportioning, intelligent filling system and fine-tuning system of track slab.

In the field of construction management, there will be a shift from BIM technology to digital twin. Breakthroughs in digital twin model-based construction progress control, quality and safety risk control, construction organization optimization, completion delivery and operation and maintenance system transformation and other technologies.

3.2 Intelligent equipment technology

As the railway speed continues to increase, the intelligent equipment develops in the direction of higher speed, more comprehensive, more integrated, more intelligent and more reliable. The goal of safe, efficient and intelligent management of railway mobile equipment and infrastructure will be realized (Fraga-Lamas, Fernández-Caramés, & Castedo, 2017).

In the field of mobile equipment, self-perception, self-operation, self-monitoring, self-diagnosis, self-decision-making, self-protection and even self-recovery has become the direction of the future development of intelligent EMUs. Realization of automatic driving, intelligent adjustment of in-vehicle environment, human–computer interaction, fault prediction, health status assessment, operation and maintenance decision-making through traction, braking, network control and other key systems, which involves multi-dimensional status monitoring technology, optimization technology for control, diagnosis and fault isolation functions of EMUs and remote transmission technology. A large number of key technologies have made breakthroughs, and further realize in-depth cross-professional data fusion analysis, such as for integrated inspection vehicles, intelligent detection for key components of EMUs, vehicle-land efficient interaction and collaboration and remote wireless control, unmanned operation of the inspection system.

In the field of communication signals, a large number of key technologies have been broken through, such as multiobjective optimization technology of vehicle control model, train operating environment and situation awareness, and self-determination of driving mode. Realize the leap from GoA2 level to GoA3 level automatic driving. At the same time, combined with the direction of the world's communication development, especially 5G-R special network technology, promote cloud network integration of railway communication, and enhance the ability of intelligent network operation and scheduling, intelligent perception and management, and flexible and efficient use.

In the field of traction power supply, attention will be paid to "network-source-storage-vehicle" collaborative energy supply technology and lightweight, intelligent traction substation and contact network equipment. It realizes the whole life cycle intelligent operation and maintenance through the application of digital twin and other new technologies (Chen, Song, Zeng, Du, & Guizani, 2021).

In the field of detection and monitoring, it builds a Cloud-Edge integrated video-intelligent analysis and early warning system; constructs a coordinated three-dimensional monitoring system covering natural disasters, perimeter intrusion, foreign object encroachment and environmental hazards along the railway line; and realizes "perception–transmission–analysis" railway line safety environment control integration (Massaro *et al.*, 2021).

3.3 Intelligent operation technology

Railway has a complex network structure, long operating mileage, large differences in regional environments, large passenger flow and diverse travel needs, and it is faced with the requirements of network-based transport organization mode and technological innovation. Therefore, there is an urgent need to research personalized service, intelligent operation, integrated operation and maintenance and other intelligent operation technologies.

In the field of passenger transportation services, the key technology direction is MaaS + full-trip intelligent service technology for the deep integration of multiple modes of transportation (Van den Berg, Meurs, & Verhoef, 2022). Breakthroughs will be made in the areas of passenger all-trip travel planning, intelligent human-computer interaction, and multimodal transportation of passengers by airplane, highway, ship and land traffic. By combining station business, it promotes the deep integration of IoT, digital twin, AI and other technologies with station situational projection, security checking and distinguishing images, video analysis of passenger behavior and refined control of passenger transportation equipment.

In the field of transportation organization, the intelligent integrated dispatching system is constructed to meet the requirements of multilevel linkage and integrated command. It realizes major functions such as the intelligent organizing of "one map a day," intelligent adjustment of operation plans and digital management of dispatching orders. It makes breakthroughs in key technologies such as coordinated optimization of point and line operation, coordination of stops and capacity operation and feedback of comprehensive evaluation and adjustment of train operation charts and further realizes automated organizing of train operation charts.

In the field of maintenance, it optimizes data analysis algorithms, enhances data element-driven capabilities and promotes the realization of predictive and correlation analysis applications for multi-factor coupling scenarios such as integrated operation and maintenance of permanent way, electrical service engineering and power supply, PHM of EMUs and integrated operation and maintenance of wheels and rails (Torralba, García-Castellano, Hernandez-Gonzalez, Garcia-Martin, Pérez-Mira, Fernandez-Sanzo, & Gutierrez-Rumbao, 2020).

3.4 Basic platform technology

Railway has generated a large number of models and dynamic and static inspection and monitoring data since the design stage. However, traditional models and data cannot meet the needs of full life cycle management and cross-disciplinary collaboration due to problems such as decentralized storage, different standards, and inability to correlate. Therefore, it is necessary to solve the effective integration of models and data of the same business object at different points in the whole life cycle, so as to ensure the forward non-destructive transfer of data and models in the whole life cycle of design, construction, and operation, as well as the reverse iterative feedback optimization.

By establishing a model-data integration platform, it creates a model library and data lake with hierarchical and subdomain storage. And weave and aggregate the representation model, mechanism model and dynamic-static monitoring information of the same infrastructure object to provide unified data service, BIM service, GIS service, AI service and other public services for business applications.

4. Conclusion

In the current digital economy, data emerge as a pivotal catalyst propelling industries toward comprehensive digital transformation and intelligent evolution. Notably, the rapid advancement of cutting-edge technologies, including general AI, digital twinning and the IoT, has significantly augmented data acquisition, connectivity, sharing and integration capabilities. The fusion of representational models, mechanistic models and a wealth of dynamic and static data holds the promise of establishing the DIKW (Data–Information–Knowledge–Wisdom) paradigm, endowing the world with essential digital infrastructure for the creation of intelligent railway systems.

Presently, nations across the globe actively harness new technologies such as big data, AI, the IoT and mobile connectivity to explore the possibilities of intelligent applications across various facets, spanning infrastructure, mobile equipment, passenger services and safety. Notably, China has accomplished a pioneering achievement with the world's first high-speed intelligent railway—the Beijing–Zhangjiakou High-Speed Railway. This milestone has introduced concepts of an intelligent high-speed railway technology system, a comprehensive data system, and a standardized framework. Concurrently, the International Union of Railways (UIC) has issued a white paper delineating the technological foundations of intelligent high-speed railways. Looking toward the horizon, propelled by emerging technologies, intelligent high-speed railways are poised for a transformative journey characterized by integrated modeling and data-driven construction, synchronized operations throughout their life cycles and comprehensive coordination of all internal and external business components. This, in turn, will offer passengers travel services that are not only more convenient but also safer, efficient, environmentally conscious and supremely comfortable.

In light of these technological advancements and the paradigm shift toward intelligent railways, it is imperative for railway companies and policymakers to proactively embrace and implement strategies for digital transformation. Such strategies should encompass the seamless integration of cutting-edge technologies, the establishment of robust data systems and the development of industry standards. This shift toward intelligent railway systems promises to significantly enhance passenger services and safety, drive operational efficiency and contribute to environmental sustainability.

The development of intelligent high-speed railways carries profound practical and social implications. Beyond enhancing efficiency and sustainability in transportation, it promises to mitigate environmental impact and elevate passenger experiences in terms of convenience and comfort. On the global stage, there exists a pressing need to recognize the social and economic benefits inherent in these advancements and foster international collaboration in the development of intelligent railway systems. This will ensure their widespread success and adoption, making them a global asset for the betterment of societies and the environment.

References

Amoroso, D. L., & Ogawa, M. (2011). Japan's model of mobile ecosystem success: The case of NTT DoCoMo. *Journal of Emerging Knowledge on Emerging Markets*, *3*(1), 27.

Balboa, A., Abreu, O., González-Villa, J., & Alvear, D. (2021). Intelligent emergency management system for railway transport. *Transportation Research Procedia*, *58*, 193–200.

Boockmeyer, A., Friedenberger, D., Pirl, L., Schmid, R., Polze, A., Herholz, H., . . . Wilhelmi, C. (2021). From ccs-planning to testautomation: The digital testfield of deutsche bahn in scheibenberg-a case study. In *2021 IEEE International Conference on Cloud Engineering (IC2E)* (pp. 258–263). IEEE.

Cao, Y., An, Y., Su, S., Xie, G., & Sun, Y. (2022). A statistical study of railway safety in China and Japan 1990-2020. *Accident Analysis and Prevention*, *175*, 106764.

Chen, Y., Song, B., Zeng, Y., Du, X., & Guizani, M. (2021). Fault diagnosis based on deep learning for current-carrying ring of catenary system in sustainable railway transportation. *Applied Soft Computing*, *100*, 106907.

Dirnfeld, R., Flammini, F., Marrone, S., Nardone, R., & Vittorini, V. (2020). Low-power wide-area networks in intelligent transportation: Review and opportunities for smart-railways. In *2020 IEEE 23rd International Conference on Intelligent Transportation Systems (ITSC)* (pp. 1–7). IEEE.

Falahati, A., & Shafiee, E. (2022). Improve safety and security of intelligent railway transportation system based on balise using machine learning algorithm and fuzzy system. *International Journal of Intelligent Transportation Systems Research*, *20*, 117–131.

Fraga-Lamas, P., Fernández-Caramés, T. M., & Castedo, L. (2017). Towards the internet of smart trains: A review on industrial IoT-connected railways. *Sensors*, *17*(6), 1457.

Graffagnino, T., Schäfer, R., Tuchschmid, M., & Weibel, M. (2019). Energy savings with enhanced static timetable information for train drivers. In *Rail Norrköping Conference*.

Hoydis, J., Hosseini, K., Ten Brink, S., & Debbah, M. (2013). Making smart use of excess antennas: Massive MIMO, small cells, and TDD. *Bell Labs Technical Journal*, *18*(2), 5–21.

Kuznetsova, G. V., & Podbiralina, G. V. (2022). Transport digitalization. In *Intelligent Systems in Digital Transformation: Theory and Applications* (pp. 579–608). Cham: Springer International Publishing.

Lerida-Navarro, C., Nombela, G., & Tranchez-Martin, J. M. (2019). European railways: Liberalization and productive efficiency. *Transport Policy*, *83*, 57–67.

Lisienkova, T., Chelekova, E., Mitrofanova, I., Shindina, T., & Titova, J. (2022). An approach for increase of digital/IT innovation adoption for sustainable development of transportation system. *Transportation Research Procedia*, *63*, 564–574.

Lu, C., Liu, J., Liu, Y., & Liu, Y. (2019). Intelligent construction technology of railway engineering in China. *Frontiers of Engineering Management*, *6*, 503–516.

Luo, Q. Z., Li, N., & Jia, G. Z. (2020). Research on China's railway development strategy. *Science and Technology Herald*, *38*(9), 26–31.

Majko, J., Saga, M., Vasko, M., Handrik, M., Barnik, F., & Dorčiak, F. (2019). FEM analysis of long-fibre composite structures created by 3D printing. *Transportation Research Procedia*, *40*, 792–799.

Massaro, A., Dipierro, G., Selicato, S., Cannella, E., Galiano, A., & Saponaro, A. (2021). Intelligent inspection of railways infrastructure and risks estimation by artificial intelligence applied on noninvasive diagnostic systems. In *2021 IEEE International Workshop on Metrology for Industry 4.0 and IoT (MetroInd4.0&IoT)* (pp. 231–236). IEEE.

Mindur, L., & Mindur, M. (2022). The development of high-speed rail in the federal republic of Germany between 2002-2020. *Zeszyty Naukowe. Transport / Politechnika Śląska*, *117*, 151–174.

Mulholland, E., & Feyen, L. (2021). Increased risk of extreme heat to European roads and railways with global warming. *Climate Risk Management*, *34*, 100365.

Pappaterra, M. J. (2022). A literature review for the application of artificial intelligence in the maintenance of railway operations with an emphasis on data. In *European Dependable Computing Conference*, Cham (pp. 59–75). Springer.

Pinard, J. (2020). Developing 'transient urbanism' as a new urban and real estate strategy: The case of the French National Railway Company (SNCF). In *Transforming Cities Through Temporary Urbanism* (pp. 141–154). Springer, Cham.

Schindler, C. (2022). Rail transport technology 4.0. In *Handbook Industry 4.0: Law, Technology, Society* (pp. 601–641). Berlin, Heidelberg: Springer.

Shan, X., Zhang, Z., Ning, F., Li, S., & Dai, L. (2023). Application and realization of key technologies in China railway e-ticketing system. *Railway Sciences*, *2*(1), 140–156.

Sresakoolchai, J., & Kaewunruen, S. (2023). Railway infrastructure maintenance efficiency improvement using deep reinforcement learning integrated with digital twin based on track geometry and component defects. *Scientific Reports*, *13*(1), 2439.

Tang, R., De Donato, L., Besinović, N., Flammini, F., Goverde, R. M., Lin, Z., . . . Wang, Z. (2022). A literature review of Artificial Intelligence applications in railway systems. *Transportation Research Part C: Emerging Technologies*, *140*, 103679.

Tao, H., Li, C., Zhao, D., Deng, S., Hu, H., Xu, X., & Jing, W. (2020). Deep learning-based dead pine tree detection from unmanned aerial vehicle images. *International Journal of Remote Sensing*, *41*(21), 8238–8255.

Torralba, A., García-Castellano, M., Hernandez-Gonzalez, M., Garcia-Martin, J. P., Pérez-Mira, V., Fernandez-Sanzo, R., . . . Gutierrez-Rumbao, F. J. (2020). Smart railway operation aid system for facilities with low-safety requirements. *IEEE Intelligent Transportation Systems Magazine*, *13*(3), 253–267.

Turkova, V., Arkhipova, A., Yusupova, G., & Zharkaya, G. (2022). Digitalization of railway service with the use of post-covid-19 events. *Transportation Research Procedia*, *63*, 584–590.

Van den Berg, V. A., Meurs, H., & Verhoef, E. T. (2022). Business models for mobility as an service (MaaS). *Transportation Research Part B: Methodological*, *157*, 203–229.

Wang, T. J. (2019). Research on China's intelligent high-speed railway development strategy. *China Railway*, 1, 9–14.

Winkler, C., & Mocanu, T. (2020). Impact of political measures on passenger and freight transport demand in Germany. *Transportation Research Part D: Transport and Environment*, *87*, 102476.

World Bank (2022). Railways in developing countries: A global review.

Yuan, Z. (2021). Transformation plan for remote control of relay logic check equipment. *Railway Signaling and Communication Engineering*, *18*(6), 92.

Corresponding author
Rui Xue can be contacted at: xuerui160@126.com