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A CASE STUDY OF CHINA ON THE BALLASTLESS TRACK

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Abstract. Ballastless track systems have become a cornerstone of modern high-speed railway (HSR) infrastructure due to their superior long-term performance, structural stability, and reduced maintenance requirements. This paper provides a comprehensive review of the development and technological innovations in ballastless track structures, with a focused case study on China's experience. The study outlines five major phases in the evolution of ballastless track in China, ranging from early experiments with embedded block track to the importation, adaptation, and eventual independent development of advanced systems such as the CRTS I, II, and III. Through this progression, the paper highlights key innovations in materials, modular design, construction automation, and the integration of smart monitoring technologies. In addition, sustainability aspects such as noise and vibration reduction, use of eco-friendly materials, and lifecycle efficiency are examined. By consolidating technical knowledge and practical insights from China's large-scale implementation, the paper offers valuable reference for countries considering or planning HSR infrastructure based on ballastless track systems.

Keywords: High-Speed Railway, Ballastless Track, CRTS, Innovation, China, Track Structure, Infrastructure Development

1. INTRODUCTION

The advancement of HSR track structures has played a crucial role in the evolution of modern rail transportation, enabling unprecedented speed, efficiency, and sustainability [1]. As nations invest heavily in HSR infrastructure to enhance connectivity and economic growth, the demand for innovative track structures has become a key focus in railway engineering. HSR systems, typically operating at speeds exceeding 300 km/h, require track structures that ensure stability, durability, and minimal maintenance while maintaining safety and passenger comfort [2-4].

The two primary types of HSR track structures ballasted tracks [5-6] and ballastless tracks [7] have evolved significantly over the decades. While traditional ballasted tracks were initially used due to their cost-effectiveness, the growing preference for ballastless tracks is driven by their superior long-term performance, reduced maintenance needs, and enhanced operational stability. Countries such as China, Japan, and Germany have been at the forefront of adopting and refining ballastless track technologies, signaling a broader shift toward innovation in track structure design.

This paper explores key innovations in HSR track structures, focusing on advancements in materials, design methodologies, and technological enhancements. Additionally, sustainability considerations are becoming increasingly vital, with research emphasizing the role of green technologies in minimizing environmental impact. Smart rail technologies, wireless sensor networks for structural health monitoring, and improvements in track-bridge interaction modeling are among the latest developments shaping the future of HSR infrastructure.

A critical case study in this paper examines the evolution of China's HSR track structures, tracing their development from early research on EBT to the adoption and optimization of ballastless track systems designed for speeds of 350 km/h and beyond [8]. The study highlights the phased progression from importing mature technologies to achieving independent research and development (R&D) capabilities.

2. LITERATURE REVIEW

2.1. Historical Development: Evolution of High-Speed Railway Track Structures

In recent decades, HSR has emerged as a compelling alternative to traditional modes of intercity transport, particularly road and air travel. Compared to air transport, HSR offers competitive travel times on medium-range distances (typically 200–800 km), especially when considering door-to-door travel and terminal waiting times. According to [10], the break-even distance where HSR becomes faster and more efficient than air transport is approximately 600 km in most operational contexts.

Beyond travel time, HSR also offers advantages in terms of environmental performance and energy efficiency. It emits significantly less CO_2 per passenger-kilometer compared to air and automobile travel, making it an essential mode for low-carbon transport development [11]. In terms of capacity and land use, a high-speed rail line can carry the equivalent of multiple highway lanes or hundreds of flights daily, providing not only higher passenger throughput but also enhanced reliability and urban connectivity. Furthermore, from a socioeconomic perspective, HSR stimulates regional development, reduces road congestion, and contributes to modal shift from less sustainable transport forms [12].

The evolution of HSR track structures has been a cornerstone in the advancement of modern rail transportation, driven by the need for faster, safer, and more efficient travel. The development of these structures can be traced back to the mid-20th century, when the first HSR systems emerged as a response to growing demand for rapid intercity travel.

The Japanese Shinkansen, inaugurated in 1964, marked a revolutionary milestone in HSR history. It introduced dedicated tracks designed specifically for high-speed operations, featuring continuous welded rails (CWR) to reduce vibrations and improve ride comfort. The Shinkansen's success demonstrated the importance of robust track structures in achieving operational speeds exceeding 200 km/h, setting a global benchmark for HSR systems.

In Europe, the development of HSR gained momentum in the 1980s with the introduction of the French TGV (Train à Grande Vitesse). The TGV utilized ballasted track structures initially but later transitioned to ballastless tracks (slab tracks) to enhance stability and reduce maintenance requirements. However, the use of ballastless tracks on LGVs remains limited, with only a few experimental sections deployed; the conventional ballasted system is still predominantly used.

In contrast, Germany pioneered the use of ballastless track systems with the introduction of the RHEDA 2000® system—a slab track structure that has become widely used on the country's high-speed lines. This transition from ballasted to ballastless design marked a major step toward long-term durability, higher ride quality, and reduced maintenance needs under intensive traffic loads.

The ballastless track system has become a significant component of high-speed railway infrastructure in Austria [9], primarily through the collaboration between ÖBB (Austrian Federal Railways) and PORR, a leading construction company. This system, known as Slab Track Austria (STA), has been instrumental in enhancing the performance and reliability of railway transport in Austria. STA was first tested in 1989 and became the standard for slab tracks in Austria by 1995. It has since been adopted for various applications, particularly in HSR contexts, where it supports travel speeds exceeding 300 km/h, with certification for speeds up to 330 km/h. The system is characterized by its elastically mounted track slabs, which contribute to its durability and low maintenance needs, boasting a life cycle of at least 60 years.

In the 21st century, the rapid expansion of HSR networks in China has pushed the boundaries of track structure innovation. Chinese HSR systems have adopted a combination of ballasted and ballastless tracks, leveraging modular designs and advanced materials to achieve unprecedented speeds and operational efficiency. The integration of smart technologies, such as real-time monitoring systems, has further enhanced the performance and safety of these track structures.

Throughout this evolution, key trends have emerged, including the transition from traditional ballasted tracks to ballastless systems, the use of advanced materials to improve durability, and the integration of digital technologies for predictive maintenance. These developments have not only enabled higher speeds but also addressed challenges related to wear and tear, noise reduction, and environmental sustainability.

2.2. Current Technologies: Overview of Existing Track Structures

Modern HSR systems rely on advanced track structures to ensure safety, stability, and performance at high operational speeds. The two primary types of track structures used in HSR systems are ballasted tracks and ballastless tracks (also known as slab tracks).

2.2.1. Ballasted Tracks

Ballasted tracks are the most traditional and widely used railway track structure due to their simplicity and proven performance. They consist of four main components. Rails, made of high-strength steel, guide and support train wheels. Sleepers (ties), typically concrete or timber, distribute loads from the rails to the underlying layers. Ballast, a layer of crushed stone, provides drainage, stability, and vibration reduction. Beneath the ballast, sub-ballast and subgrade further distribute loads and maintain foundation stability. This layered system ensures structural integrity and supports efficient railway operations.

2.2.2. Ballastless Tracks (Slab Tracks)

Ballastless tracks, also known as slab tracks, represent a modern alternative to conventional ballasted systems, offering improved durability, stability, and reduced maintenance. This design eliminates ballast and instead utilizes a continuous concrete or asphalt slab to support the rails. The key components include rails, which are mounted directly onto the slab or embedded within them; the slab, which provides a rigid and long-lasting foundation; a fastening system, comprising precision-engineered fasteners that anchor the rails and permit alignment adjustments; and underlying layers, consisting of a compacted subgrade and an integrated drainage system to ensure long-term structural integrity.

2.2.3. Hybrid and Emerging Track Structures

In recent years, hybrid track structures have been developed to balance the advantages of both ballasted and ballastless systems, aiming to optimize performance, cost, and maintenance. One example is the embedded rail system, where rails are set into concrete or elastomeric materials, offering the structural stability of slab tracks with enhanced flexibility. Another is the floating slab track, commonly used in urban environments to mitigate noise and vibration; this design incorporates elastic layers between the slab and subgrade, effectively isolating track-induced disturbances from surrounding structures.

3. INNOVATIONS IN HIGH-SPEED RAILWAY TRACK STRUCTURES

3.1. Material Innovations:

3.1.1. Advanced materials

The development and implementation of advanced materials have significantly enhanced the durability, performance, and sustainability of HSR track structures. Innovations in materials science have led to the adoption of composite materials, high-strength alloys, and other novel materials that improve track reliability, reduce maintenance costs, and increase overall efficiency.

Composite materials, formed by combining multiple constituents with distinct physical and chemical properties, are increasingly used in railway track construction due to their superior performance compared to traditional materials like steel and concrete. Their high strength-to-weight ratio reduces the load on supporting infrastructure and enhances energy efficiency in HSR systems. Unlike steel, composites resist corrosion and environmental factors such as humidity, temperature fluctuations, and chemical exposure, resulting in a longer lifespan. Their fatigue resistance and flexibility minimize wear and tear, lowering maintenance costs. Additionally, fiberreinforced polymer (FRP) composites are gaining popularity in rail sleepers and track components due to their lightweight nature, durability, and ease of installation.

3.1.2. Smart materials

Smart materials, capable of dynamically responding to environmental conditions and external stimuli, are revolutionizing railway infrastructure by enhancing efficiency and safety. Self-healing concrete, embedded with bacteria or chemical agents, automatically fills cracks, extending track lifespan and reducing maintenance. Advanced sensors integrated into tracks enable real-time monitoring, detecting structural issues early to facilitate predictive maintenance. Shape memory alloys, which revert to their original form after deformation, are ideal for high-stress track components. Additionally, piezoelectric materials harness mechanical stress to generate electricity, paving the way for self-powered monitoring systems and energy-efficient railway operations.

3.2 Design Innovations: Modular Track Systems

Modular track systems are a major advancement in railway infrastructure, offering flexibility, efficiency, and simplified maintenance through prefabricated, standardized components. These systems enable rapid installation by manufacturing track sections offsite, minimizing construction time and operational disruptions. Their interchangeable design allows for easy replacement of damaged components without extensive reconstruction, reducing maintenance efforts. Standardization also lowers overall costs by streamlining construction and labor requirements. Additionally, prefabricated modules undergo strict quality control, ensuring structural integrity and reducing defects. With adaptability to various environments, modular track systems are well-suited for HSR, urban transit, and heavy-haul freight networks.

3.3 Technological Innovations

3.3.1. Integration of IoT and AI for real-time monitoring and predictive maintenance

The integration of the Internet of Things (IoT) and Artificial Intelligence (AI) is revolutionizing railway infrastructure by enabling smarter, more efficient track moni-toring and maintenance. IoT sensors embedded in tracks continuously collect real-time data on structural conditions, temperature fluctuations, and load stress, ensuring constant oversight. AI-driven analytics process vast datasets to predict potential failures before they occur, reducing downtime and enhancing safety. Remote diagnostics and automated alerts allow railway operators to address issues proactively, improving response times. Additionally, AI-powered systems optimize maintenance schedules, minimizing unnecessary track closures and reducing operational costs.

3.3.2 Automation in track laying and maintenance

Advancements in automation have transformed track construction and maintenance, improving efficiency, precision, and reliability. Automated Track Laying Machines (ATLMs) accelerate installation, reducing labor requirements and increasing speed. Drones and robotic systems conduct high-precision inspections, detecting cracks, misalignments, and wear with greater accuracy. Emerging self-repairing technologies, utilizing robotics and smart materials, aim to minimize manual intervention in track maintenance. Additionally, AI-driven machines optimize ballast cleaning and track alignment, ensuring stability while reducing human error. These innovations collectively enhance railway infrastructure longevity and operational efficiency.

3.4 Sustainability Innovations

3.4.1. Eco-friendly materials and construction methods

The integration of eco-friendly materials and sustainable construction methods is essential in reducing the environmental impact of HSR track systems. The use of recycled plastics, bio-composites, and sustainable concrete alternatives minimizes waste and dependence on virgin raw materials. Innovations such as low-carbon cement and geopolymer concrete help cut greenhouse gas emissions associated with traditional cement production. Additionally, energy-efficient construction techniques, reduced material waste, and renewable energy sources in track manufacturing further enhance sustainability, making railway infrastructure more environmentally responsible.

3.4.2. Energy-efficient designs and recycling of track components

Energy-efficient designs and sustainable recycling practices are crucial for enhancing the environmental performance of railway infrastructure. Energy-harvesting tracks, incorporating piezoelectric and thermoelectric materials, generate electricity from train movement and temperature fluctuations, contributing to self-sustaining rail systems. Recyclable track components designed for easy disassembly and reuse support a circular economy, minimizing waste. Additionally, the use of lightweight composite materials and aerodynamically optimized track designs improves energy efficiency, reducing operational costs while maintaining structural integrity.

4. CASE STUDIES IN CHINA: EVOLUTION OF HIGH-SPEED RAILWAY TRACK STRUCTURES

The development of HSR infrastructure in China has been a remarkable journey, transitioning from early experimental designs to the establishment of a world-leading rail network. This section explores the phased evolution of track structures in China's HSR system, highlighting key innovations, challenges, and breakthroughs in the field.

4.1. Initial Research Phase: Embedded Block Track

This phase occurred approximately during 2000–2003, when researchers and engineers in China began investigating the Embedded Block Track (EBT) system as a more stable and durable alternative to traditional ballasted track structures, particularly for urban rail applications.

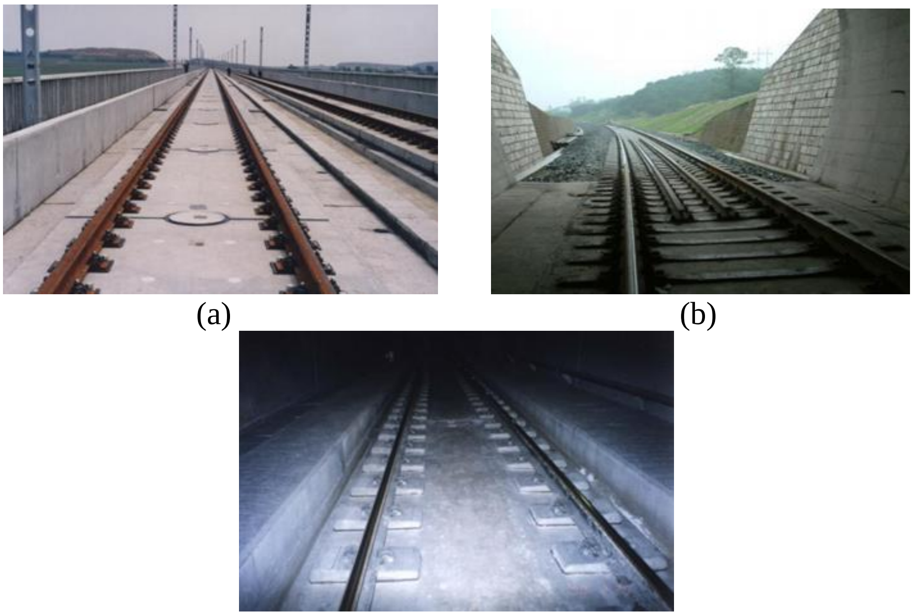
Fig 1. Embeded block track [8].

This research phase was instrumental in establishing engineering standards that later facilitated the widespread adoption of EBT (Figure 1) in metro and urban railway systems. Over 300 km of EBT track were constructed during this phase in cities such as Beijing and Chengdu, where it was deployed in actual service environments rather than in isolated test sections. The key advantages of this system include enhanced structural integrity, which minimizes track deformation under high-speed operations, and lower maintenance requirements, as its rigid structure reduces displacement and wear. Additionally, EBT significantly improves noise and vibration control, making it particularly suitable for underground transit and densely populated urban areas.

Although the EBT was not used on mainline high-speed tracks, the knowledge and experience gained during this phase directly influenced the subsequent development of ballastless track structures for HSR in China. The insights gained from this phase laid a strong foundation for future track innovations, particularly influencing the transition from traditional ballasted tracks to ballastless track systems. As HSR networks expanded globally, the advancements made during the EBT research phase played a pivotal role in shaping modern track technologies, ensuring greater safety, efficiency, and sustainability in railway infrastructure development.

4.2. Trial of ballastless track

Conducted around 2003–2004, the second phase marked a significant transition from traditional ballasted tracks to ballastless track systems. This phase focused on testing and evaluating various ballastless track designs to enhance operational efficiency and track longevity. As illustrated in Figure 2, three distinct ballastless track structures were trialed during this period: slab track, embedded long sleeper track, and elastic bearing block-type track.



(a) (b)

(c)

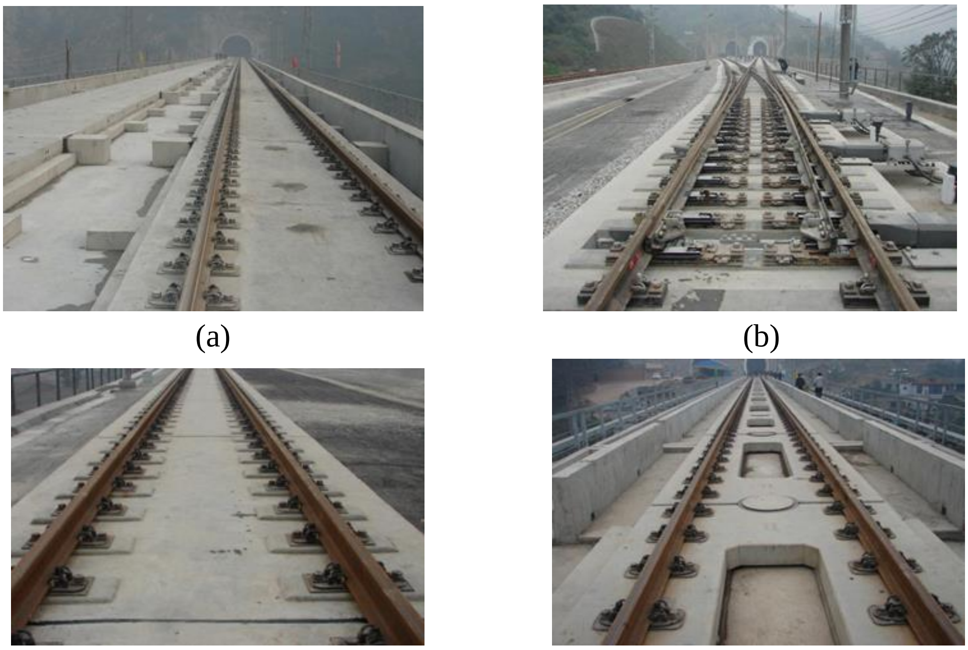
Fig 2. a) Slab ballastless track; b) Embedded long sleeper Track; c) Elastic bearing block-type track [8].

The slab track system features continuous reinforced concrete slabs that provide a highly stable foundation for the rails. This design minimizes deformation and significantly reduces maintenance needs, making it particularly suitable for viaducts and bridges where structural integrity is critical. The embedded long sleeper track incorporates long prestressed concrete sleepers embedded within a rigid foundation. This design enhances load distribution and track alignment, leading to improved ride comfort and operational safety. The elastic bearing block-type track (Low-Vibration Track – LVT) consists of discrete elastic blocks that support the rails, effectively reducing vibrations and noise. This system is particularly beneficial for urban railway networks and tunnel environments, where controlling noise and minimizing structural vibrations are critical concerns.

The outcomes of this phase provided valuable insights into the performance, durability, and maintenance requirements of ballastless track systems. The successful trials demonstrated the potential of these innovations to enhance safety, reduce long-term costs, and improve overall operational efficiency.

4.3. Phase 3: Imported Mature Technologies

Between 2004 and 2006, China focused on the importation and testing of mature ballastless track technologies from leading international railway systems. The primary objective of this phase was to evaluate the feasibility and performance of various designs under local operating conditions. During this period, a total of 13 km of ballastless track was laid for comprehensive trials, enabling researchers to assess their structural integrity, durability, and adaptability to China's HSR environment.



(a) (b)

(c) (d)

Fig 3. a) Longitudinal connected slab track on bridge; b) Embedded long sleeper ballastless track in turnout; c) Twin-block ballastless track on subgrade; d) Frame-slab track on bridge [8].

Several key ballastless track types were tested during this phase. The longitudinal connected slab track on bridges consisted of continuous reinforced concrete slabs that provided enhanced structural stability and minimized deformation under high-speed train loads. This system ensured seamless load transfer and significantly improved ride quality. Another notable track type was the embedded long sleeper ballastless track in turnout, designed specifically for switching zones and turnouts. This system incorporated long prestressed concrete sleepers embedded in a rigid base, enhancing track stability and ensuring precise alignment for smooth train operations.

Additionally, the twin-block ballastless track on subgrade was tested, featuring twin-block sleepers embedded into the subgrade. This design improved track flexibility and impact resistance, making it a viable option for subgrade sections. Finally, the frame-slab track on bridges was introduced as a precast slab system designed for elevated railway sections. This system offered high durability, reduced maintenance requirements, and enhanced track smoothness.

The significance of this phase was profound, as it provided a systematic evaluation of different ballastless track structures under real-world conditions. The findings from these trials facilitated the adaptation and optimization of imported designs to meet local geotechnical, climatic, and operational requirements.

4.4. Phase 4: Optimization of Track Structures for 350 km/h Conditions

This phase, from 2007 to 2009, was dedicated to optimizing track structures to support train speeds of up to 350 km/h. China successfully mastered imported technologies and developed the CRTS I and CRTS II slab track systems during this period. This phase marked a crucial transition from adopting foreign designs to creating an independent, optimized track system tailored to China's expanding HSR network.

(a) (b)

(c)

Fig 4. a) J-Slab-->CRTS I slab track; b) Bogl-->CRTS II slab track; c) Rheda 2000-->CRTS I double-block track [8].

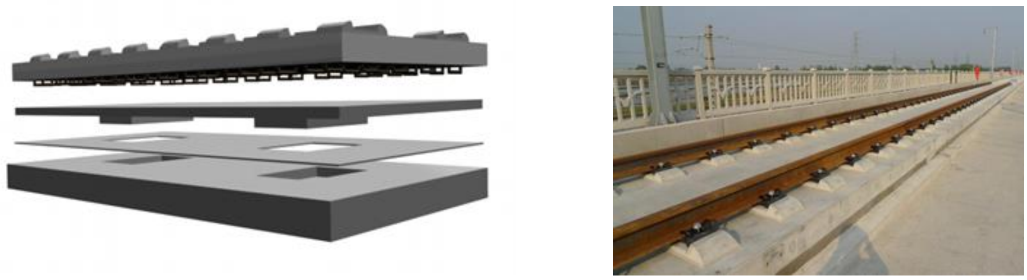
Several key track systems were developed and refined during this phase. The J-Slab to CRTS I slab track, derived from Japan’s J-Slab technology, incorporated high-precision prefabricated slabs that significantly improved track stability and smoothness. This system was particularly effective in ensuring seamless load dis-tribution and reducing maintenance needs, as demonstrated in the Figure 4a. Another major development was the Bogl to CRTS II slab track, based on Germany’s Bogl system. The CRTS II system introduced continuously reinforced concrete slabs, enhancing durability and resistance to high-speed vibrations. The Figure 4b provides a cross-sectional view of its multi-layered structure, highlighting its contribution to extended track lifespan.

Additionally, the Rheda 2000 to CRTS I double-block track was adapted from Germany’s Rheda 2000 system. This track type utilized doubleblock sleepers embedded in concrete, offering superior shock absorption and efficient load distribution. The Figure 4c illustrates its application in tunnel environments, where stability and noise reduction are critical factors.

The significance of this phase was profound, as it led to substantial improvements in track performance. The CRTS series enhanced stability, longevity, and ride comfort, making it a viable solution for ultra-high-speed operations. Furthermore, the adoption of slab-based and double-block track systems significantly reduced long-term maintenance costs, ensuring more sustainable railway operations. Most importantly, this phase paved the way for China's independent research and development in HSR infrastructure, setting the stage for further advancements in later phases.

4.5. Phase 5: Independent R&D Phase

Starting in 2009 and continuing to the present, this phase marks China's transition to fully independent R&D and deployment of its own advanced track systems, represented by CRTS III. Designed to optimize performance for China's rapidly expanding HSR network, this system addresses key technical challenges and sets new benchmarks for durability, stability, and operational efficiency.



(a) (b)

Fig 5. CRTS III slab ballastless track [8].

The CRTS III slab ballastless track was developed to overcome limitations in previous track designs, providing enhanced stability, reduced maintenance needs, and an extended service life. Figure 5a highlights its multilayered structure, which consists of several critical components. Self-compacting concrete ensures high structural strength and long-term durability, while prefabricated concrete track slabs enhance ride quality and track stability. The isolation layer plays a vital role in reducing vibrations and improving noise absorption, making it particularly suitable for high-speed operations in urban and ecologically sensitive areas. Additionally, the base plate provides a solid foundation for effective load distribution, minimizing deformation and ensuring longlasting performance. Figure 5b also showcases the realworld application of this advanced track system, demonstrating its seamless integration into China's modern HSR infrastructure.

The significance of this phase extends beyond infrastructure improvements. The successful development of the CRTS III system demonstrates China's self-sufficiency in HSR technology, reinforcing its position as a global leader in railway engineering. This system has become a standardized track solution for nationwide HSR projects and serves as a foundation for future international applications. Moreover, its design supports the development of next-generation ultra HSR networks, paving the way for further advancements in rail transportation technology.

To provide a clearer overview of the technical and operational distinctions between China's three major slab track systems, Table 1 summarizes the key characteristics of CRTS I, CRTS II, and CRTS III. The comparison highlights differences in structural design, installation method, vibration control, maintenance needs, and performance capabilities.

Table 1. Comparison of CRTS I, CRTS II, and CRTS III Slab Track Systems.

Feature	CRTS I	CRTS II	CRTS III
Development Period	2007–2009	2007–2009	2009–present
Origin	Derived from Japan’s J-Slab	Derived from Germany’s Bögl system	Independently developed in China
Slab Type	Prefabricated single slabs	Continuously cast-in-place concrete slabs	Prefabricated modular slabs
Fastening System	Embedded dowel + fastener	Embedded bolts and anchors	Improved anchoring with better isolation
Vibration Control	Limited	Moderate	Enhanced with isolation layers
Installation Method	Manual + mechanical alignment	On-site casting with higher complexity	Prefabricated, modular assembly
Main Application	Early HSR segments, viaducts	Mainline HSR, bridges	Urban HSR, complex terrains
Maintenance Needs	Moderate	Lower than CRTS I	Lowest among all CRTS systems
Design Speed Capability	Up to 300 km/h	Up to 350 km/h	350+ km/h
Durability (Design Life)	~50 years	~60 years	≥60 years

5. CONCLUSIONS

The continuous advancement of HSR track structures is essential for ensuring the efficiency, safety, and sustainability of modern rail transportation. This paper has explored the historical development, current technologies, and key innovations in HSR track structures, highlighting significant progress in materials, design, and technological applications. The shift from traditional ballasted tracks to advanced ballastless systems has been driven by the need for enhanced stability, reduced maintenance, and improved long-term performance.

A case study of China’s HSR development has demonstrated the phased evolution of track structures, from early research and adoption of imported technologies to independent innovations capable of supporting speeds of 350 km/h and beyond. These developments underscore the importance of sustained research and engineering excellence in shaping the future of high-speed rail.

Despite significant progress, long-term service observations of ballastless track systems in China have identified several recurring issues, including transverse or longitudinal slab cracking, layer debonding, and localized differential settlement—especially at transition zones such as bridge–embankment interfaces. Other challenges involve insufficient vibration isolation and stress accumulation under thermal loads. While not yet widespread, these defects require proactive design adjustments and continuous monitoring to ensure long-term durability and ride comfort.

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