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Indigenous and Integrated Innovation Driving the Boom in China's High-Speed Rail Technologies

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1 Foreword

In the early 21st century, the chronic shortage of railway transport capacity has become the primary bottleneck inhibiting the continual high-speed growth of China's society and economy. Given its robust transport capacity, outstanding safety records, high level of comfort, friendly environment, and good sustainability, high-speed rail has turned out to be the megatrend of railway development and is an inevitable choice in response to the severe shortage of transport capacity. As a core part of the high-speed rail technology and equipment system, a high-speed train is a complex mechanical-electrical system that integrates multi-interdisciplinary and large-scale technologies. To this end, the Ministry of Science and Technology and the Ministry of Railways jointly launched the China High-Speed Rail Proprietary Innovation Joint Action Plan (also referred to more simply as the "Action Plan") in February 2008, followed by the 12th Five-Year Special Plan for High-Speed Railway Technology Development (known as the "Special Plan") promulgated by the Ministry of Science and Technology in 2012. Through worldwide resource integration and joint research and development, these plans have been completed successfully, resulting in major socio-economic benefits.

2 The course of indigenous innovation in China's high-speed rail

The course of implementation for the integrated innovation of China's high-speed rail can be summarized as follows.

2.1 An innovation model with integration advantages

Based on China's realities, and by drawing on the models from such major technology innovation projects as the Apollo Program, nuclear bombs, human-made satellites, and the Japan/Europe high-speed rail R&D programs, we have integrated and optimized China's typical technology innovation models to create to create an organic combination of the transversal model, characterized by inter-ministerial cooperation, and the longitudinal model, characterized by integrating resources on the industrial chain. We have thus employed a composite model, and used the "government-industry-university-researcher-user" innovation resource-integration mechanism under this model.

2.2 Scientific planning and rational design

By guiding, organizing, and implementing our entire course of engineering using a system engineering methodology, we regarded the proprietary innovation of high-speed rail as a hierarchical, granulated, inter-connected, and complete system in order to develop a series of plans on objectives, tasks, resources, milestones, and industrial chains. We controlled the whole innovation process with different levels of plans, norms, and organizational mechanisms.

2.3 Demand-driven and objective-oriented

The "demand gap" and "technology gap" were identified through a comprehensive analysis of China's demand for constructing and operating high-speed railways (represented by the Beijing—Shanghai High-Speed Railway) and the status quo and development trend of high-speed rail technologies in Europe, Japan, and other developed countries. On this basis, we developed the Top-Level Technical Criteria for China's New Generation High-Speed Rail, and set up relevant technological objectives represented by an experimental speed of 420 $\mathrm{km{\cdot}h^{-1}}$, a top operational speed of 380 $\mathrm{km{\cdot}h^{-1}}$, and a sustained operational speed of 350 $\mathrm{km{\cdot}h^{-1}}$.

2.4 Top-level design and orderly implementation

The top-level design allowed us to deliver hierarchical, granulated, and reasonable planning on the innovation tasks; to precisely identify and discriminate between "strategic," "tactical," and "focal" tasks; and to identify such key technologies as high-speed rail integration, high-speed bogies, traction and transmission, carriages, a control network, a traction power supply, operation control, and operation organization, as well as innovation tasks such as R&D and associated systems and equipment. The Ministry of Science and Technology also gave full play to its role in strategic guid-

Figure 1. A cold-resistant and wind/sand-proof high-speed train.

ance, strategic coordination, strategic adherence, and strategic correction. Through the three major national technology plans, all levels of tasks relating to the proprietary innovation of high-speed rail were implemented and coordinated in an orderly fashion. In this way, China proudly built a complete innovation chain that boasts the largest scale, the most complete configurations, and the deepest integration of industry-university-research in the world.

2.5 Innovation support and an application-driven process

By giving full play to the experimental, operational, and market conditions shaped amid the construction and operation of high-speed rail, China has gradually verified and finalized the existing designs in the target application environments provided by the successively and successfully launched Beijing—Tianjin Inter-City High-Speed Railway, Wuhan—Guangzhou High-Speed Railway, and Beijing—Shanghai High-Speed Railway. Thus, China has developed a unique high-speed rail technology innovation process that is characterized by the cycle of R&D → Manufacturing → Operation → Verification → Further R&D → Further Operation, as well as by the orchestration of R&D with operation, and continuous interaction between innovation and application.

3 Technological achievements of the proprietary innovation of China's high-speed rail

By systematically studying the wheel-track, fluid-structure interaction, and pantograph-catenary relationships, and on the premise of ensuring global-leading top-level technical indicators, China successfully developed the CRH380 series of high-speed trains. The fully proprietary CRH380A high-speed train set the world record of a 486.1 $\text{km}\cdot\text{h}^{-1}$ top experimental speed on the Beijing—Shanghai High-Speed Railway, with an average failure rate of only one incidence per 1 000 000 km of operation. CRH380-series high-speed trains are now efficiently running on the world's largest high-speed railway network, which stretches 160 000 km across China.

In terms of safety, serviceability, energy efficiency, noise level, comfort, and other outstanding indicators, the technological achievements of the CRH380A high-speed train can be briefly described as follows:

(1) Low-resistance, streamlined locomotive: By employing aerodynamics simulation technology and multi-objective optimization design technologies, and by submitting to wind-tunnel and noise experiments, the developed locomotive features a resistance coefficient that is less than 0.13, with a tail-end lift coefficient that is less than 0.08.

(2) Vibration-mode system matching: By optimizing the design parameters of the bogie and of the internal structure of the carriage, we have effectively suppressed the structural resonance vibration arising from the high-speed operation of the train, improved the first-order vertical bending free-vibration frequency of the carriage structure by nearly 10%, and controlled the first-order vertical bending vibration frequency at 10.8 Hz, thus allowing good matching between carriage, bogie, and route.

(3) Superb air tightness: The carriages adopt a differential pressure control model based on air-tight pressurization technology, with an air tightness capacity reaching either +6000 Pa or –6000 Pa. The time used to reduce the internal pressure of the carriages from 4000 Pa to 1000 Pa is greater than 180 s, and the pressure fluctuations are less than 200 $\text{Pa}\cdot\text{s}^{-1}$.

(4) High-performance bogie: The bogie used in the system has new anti-roll and anti-yaw vibration mechanisms and improved secondary suspension flexibility, and achieves a critical instability speed of 550 $\text{km}\cdot\text{h}^{-1}$. At 380 $\text{km}\cdot\text{h}^{-1}$, the digression coefficient is lower than 0.13, providing a sufficient safety allowance. The stability, shock absorption effect, and running safety of this bogie has outperformed existing international standards.

(5) Noise control: A variety of new noise-absorption and barrier materials and structures have been applied in order to restrict the carriage noise to within 67–69 dB at a running speed of 350 $\text{km}\cdot\text{h}^{-1}$.

(6) Light-weight and energy-efficient structure: A host of new materials and structures have been used to restrict the axle load of the train to below 15 t. While maintaining a running speed of 380 $\text{km}\cdot\text{h}^{-1}$, the energy consumption per passenger per 100 km is less than 5.2 kWh. By employing a high-performance regenerative braking technology, the energy feedback rate can reach as high as 90%.

(7) Braking safety: The braking length at 350 $\text{km}\cdot\text{h}^{-1}$ is 5908 m, which is lower than the standard value of 6500 m. The braking length at 380 $\text{km}\cdot\text{h}^{-1}$ is about 7162 m.

(8) Pantograph-catenary current collection: By employing a semi-active-control pantograph that has undergone extensive wind-tunnel tests, wearing tests, static tests, and route-optimization tests, the average contact pressure is lower than 200 N and the arcing spark rate is lower than 6.25 $\text{times}\cdot\text{km}^{-1}$, clearly meeting the single-pantograph and double-pantograph operation requirements at the top running speed of 380 $\text{km}\cdot\text{h}^{-1}$.

(9) System serviceability: By employing a RAMS-based design, manufacturing, operation, and maintenance technology, and by improving the on-train state monitoring network/system, we have not only achieved a total-state fault-safety mechanism, but also maintained an outstanding average failure rate of only one incidence per 1 000 000 km of operation.

4 Conclusion

Backed by certain major fundamental research and high-tech development/support programs, China has successively kicked off such initiatives as "Research on Critical Technologies for Smart High-Speed Rail Systems and R&D of Typical Trains," "Research on the Serialized Critical Technologies and Serial Models of High-Speed Trains" and "Research on Critical Energy Conservation Technologies and Equipment for High-Speed Rail." Targeting intelligentization, pedigree-orientation, and eco-friendliness, we have successfully developed intelligentized and cold-resistant intercity high-speed trains. China's high-speed rail innovation focuses on the application of new materials, new structures, and new energy sources; takes system safety, inter-operation, comprehensive efficiency improvement, and sustainable technologies as its major strategic directions; and maintains systematic technology optimization and improvement, allowing for constant improvements in safety, comfort, and energy efficiency.