Engineering 6 (2020) 227–233

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

Engineering Achievements

The Fuxing: The China Standard EMU

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1. Project overview

Since the first high-speed railway (HSR) intercity line was built between Beijing and Tianjin in 2008, China's HSRs have developed rapidly. In a short span of ten years, successive HSRs have entered operation between Zhengzhou and Xi'an, Beijing and Shanghai, Beijing and Guangzhou, Lanzhou and Urumqi, and around Hainan Island. By the end of 2018, the HSR route length in China exceeded 29 000 km, accounting for over two thirds of the world's total. The HSR network, which is backboned by four west–east and four north–south trunk corridors, opened to traffic ahead of schedule, and the construction of an HSR network underpinned by eight west–east and eight north–south lines is actively ongoing [1]. The HSR has filled the time–space gap between cities, facilitated business exchanges, driven regional economic and social development, profoundly influenced people's travel habits and lifestyle, and greatly enhanced overall wellbeing of the Chinese people.

Over the past ten years, as an important symbol of China's HSR, the electric multiple unit (EMU) has been manufactured in series based on different platforms. With continuous promotion of the technological innovation of China's railways, the China standard EMU was officially named the "Fuxing" and was put into batch operation in 2017, thus demonstrating that China has established a complete EMU technical standard system. The Fuxing EMU (Fig. 1) is a new-generation EMU with completely independent intellectual property rights, which has become a stunning product that symbolizes the technological strength of China. Its service has been continuously expanded to the Beijing–Shanghai, Beijing–Guangzhou, and Shanghai–Kunming Lines, in addition to other lines, and now covers 23 provincial capitals, municipalities, and capitals of autonomous regions. As of September 2019, the EMU fleet totaled 3480 units, including 557 standard Fuxing EMUs. According to statistics, in the first three quarters of 2019, 8538 trains were operated daily in the entire railway system, of which 71.6% were EMUs (and 12% were Fuxing EMUs), demonstrating the continuously expanding influence of the Fuxing EMU.

The development of the Fuxing EMU was a major railway equipment project led by the China State Railway Group Co., Ltd., that integrated the resources of relevant domestic enterprises, universities, and research institutions, thereby involving close collaboration between industry, universities, and research applications. Starting in 2013, the project went through the full process of technical specification preparation, technical program finalization, prototype development, type testing, application assessment, batch production, online operation, and development testing and batch application of the operation at 350 km·h^{-1}.

The Fuxing EMU is adapted to the operating environment and conditions of China's HSR and meets the requirements of a complex and diversified operation environment, which include long distances, long operation times, and continuous high-speed operation. The eight-car formation Fuxing EMU has a total length of ~209 m, a design operating speed of 350 km·h^{-1}, and a capacity of 576 passengers. It is applicable to ambient temperatures from −40 to 40 °C, and has a service life of as much as 30 years. The layouts of the two Fuxing EMU platforms, CR400AF and CR400BF, are shown in Figs. 2 and 3. On 21 September 2017, the first Fuxing EMU was operated at 350 km·h^{-1}on the Beijing–Shanghai HSR, shortening the travel time between Beijing and Shanghai from 5 to 4.5 h. In July 2018, 16-car Fuxing EMUs were put into operation, with a seating capacity of 1193. In January 2019, extra-long (17-car) Fuxing EMUs were put into operation on the Beijing–Shanghai HSR, increasing the passenger capacity to 1283—a 7.5% increase from the 16-car EMU. At present, the Fuxing EMU is produced based on these two platforms, with speeds of 350 and 250 km·h^{-1}, and a series product system is emerging.

Fig. 1. The Fuxing: The China standard EMU.

https://doi.org/10.1016/j.eng.2020.01.004
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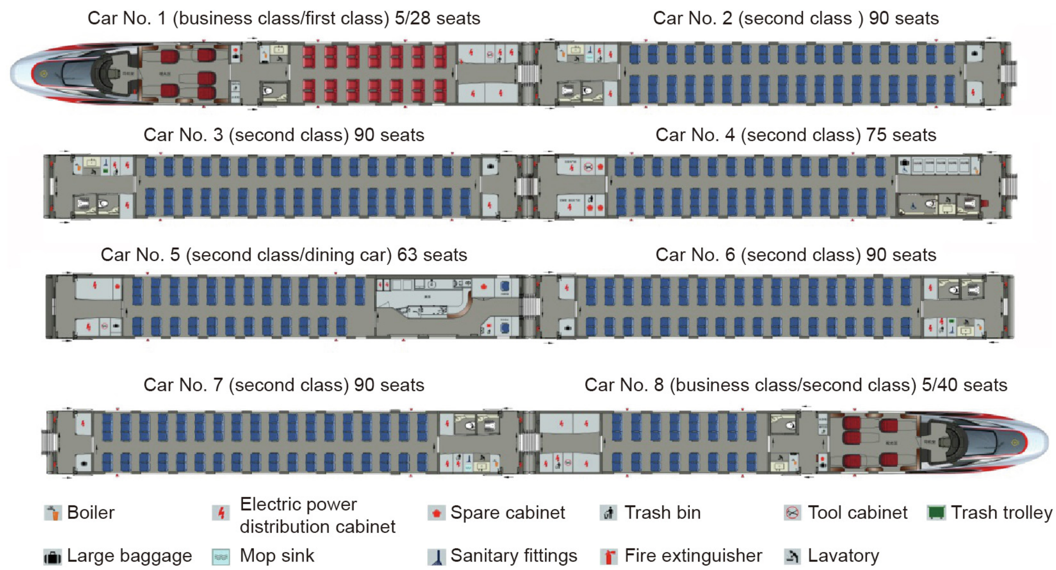

Fig. 2. Plane layout of the CR400AF EMU formation.

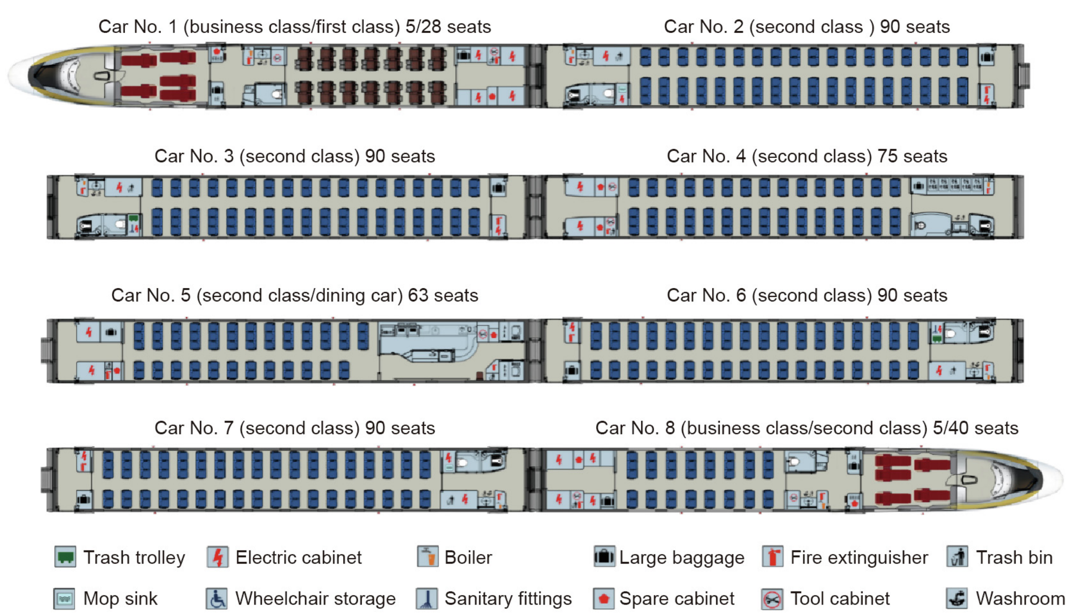

Fig. 3. Plane layout of the CR400BF EMU formation.

2. Highlighted technologies

Based on the premises of independence, type unification, and interoperability, the development of the Fuxing EMU adhered to the concept of independent innovation and development in both software and hardware. A standard technical platform for the China high-speed EMU has been established, and innovations and breakthroughs have been achieved for various performance indicators. Compared with the existing EMU, the China high-speed Fuxing EMU is more technically advanced, safer, more environmentally friendly and energy efficient, more comfortable, and more cost-efficient.

2.1. Technically advanced

An EMU should not only adopt high traction power, so as to generate sufficient traction and reach performance indices such as top speed, acceleration, and ramp jump-start, but also be equipped with a high-powered braking system, so as to provide synchronous braking force and reach the braking performance indices of speed governing and parking within a specified distance [2]. The Fuxing EMU is technically advanced in its traction, braking, and high-voltage (HV) systems.

(1) The traction power of the Fuxing EMU is 7% higher than that of the existing EMU, reaching 10 400 kW. It only takes the train 391 s to accelerate from standstill to 350 km·h^{-1}—a decrease of 81 s in comparison with the existing CRH380 EMU—and its acceleration distance is 6.4 km shorter.

(2) The braking system of the Fuxing EMU performs unified management, calculation, and distribution of the train braking force, fulfilling an electro-pneumatic compound control mode. With unified deceleration curve control, the train has an improved synchronous control performance; by making full use of adhesion and regenerative electric braking, the regenerative braking power is 1.3 times greater than the traction power, resulting in significant reduction of the brake pad wear.

(3) The Fuxing EMU is designed with an actively controlled pantograph and an integrally enclosed HV box structure. The external insulation of the HV equipment, with a lightning impulse withstand voltage that has been increased from 170 to 185 kV. The latter improves the lightning impulse resistance and the anti-pollution flashover capability of the HV system under severe weather conditions such as fog and smog.

2.2. A more intelligent safety guarantee

The Fuxing EMU adopts a sophisticated active and passive safety protection design, as well as advanced onboard and train–ground communication networks. It also applies technical means such as sensor collection, data processing, fault diagnosis, automatic control, and remote monitoring, thus establishing a more intelligent EMU safety system.

(1) The whole train is equipped with 2500 sensor detection/monitoring points (an increase of 500 detection points from the existing EMU), which can sense the running status of the EMU and the working status of the equipment in real time and in a smart way. When an abnormality is detected, the EMU can be automatically controlled to decelerate or stop in time.

(2) A variety of active safety warning devices and fail-safe designs have been established, and multi-level energy-absorption structures and a collision-resistant carbody structure design have been adopted, enabling full coverage of both active and passive safety measures.

(3) The train onboard control network adopts a train communication network (TCN) that complies with international standards, and the train onboard maintenance network is based on Ethernet. The driver's control instructions and the equipments status are transmitted through the train control network. And the fault-diagnosis information is transmitted via the maintenance network to complete software updates and data downloads. Benefit from the application of the Ethernet the data-transmission capacity has been increased to 100 Mbit·s^{-1}, and single-point maintenance of the onboard equipments can be realized.

(4) 3G/4G communication technology has been applied to realize the transmission of train–ground information. Ground monitoring personnel can obtain the running dynamics of the EMU in real time and can support the online data monitoring. The Wireless Transmitting Device (WTD) system could also provide the function of the wheel set bearing temperature data curve playback and the historical fault data statistics, as shown in Fig. 4. Until now more than 3000 EMUs have been equipped with the WTDs including the Fuxing EMU.

2.3. More environmentally friendly and energy efficient

Although railways already boast low energy consumption, little pollution, and large traffic volume, the goals of enhancing the operation speed, increasing the traffic volume, and extending the operation trigger are raising new challenges for the energy efficiency and environmental friendliness of the railway. The HSR involves huge and complicated systems engineering, and train operation is influenced by numerous factors. To achieve energy efficiency and environmental friendliness, the Fuxing EMU has made headway in decreasing its energy consumption and noise, adopting environmentally friendly materials, and enhancing its energy efficiency.

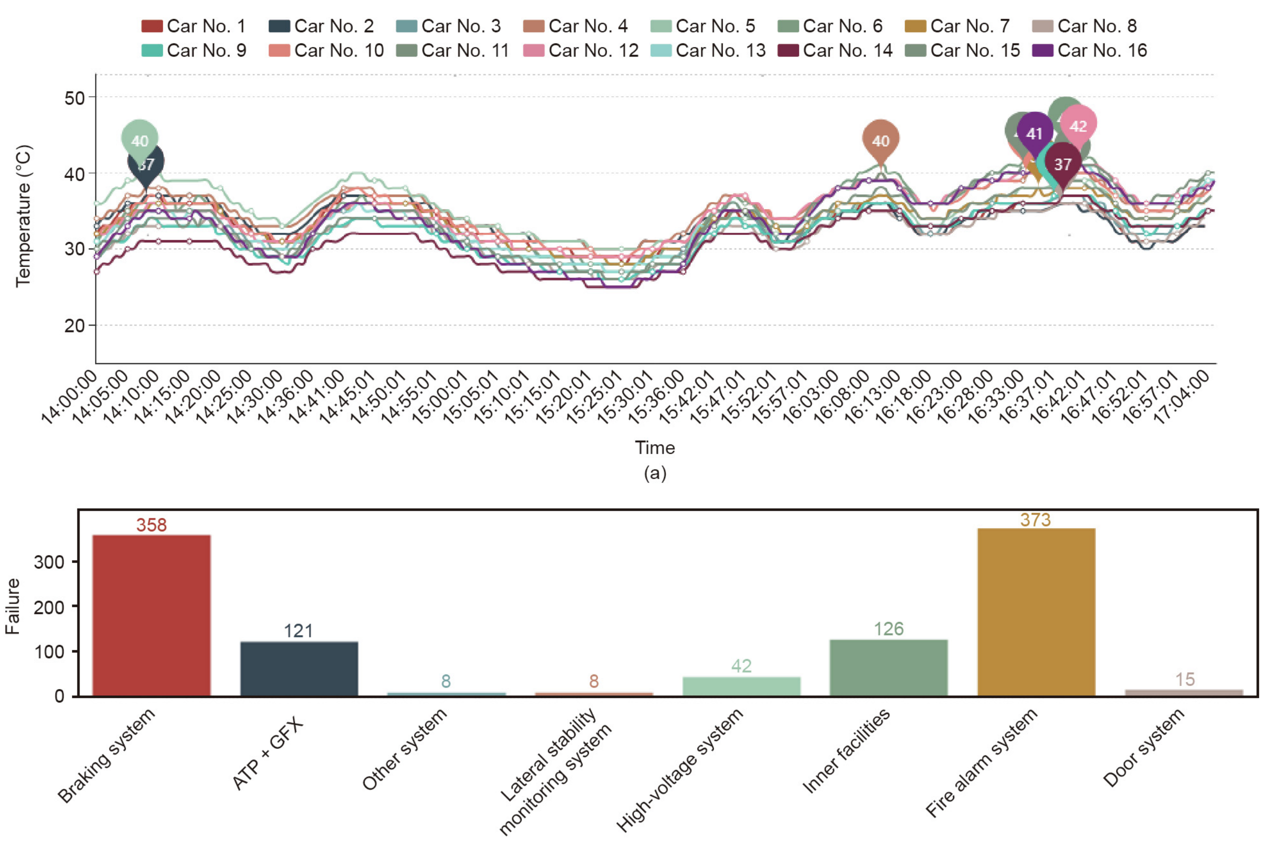

Fig. 4. Online data monitoring for the Fuxing EMU. (a) The wheel set bearing temperature data curve playback (Bogie No. 1 Shaft No. 1); (b) historical fault data statistics. ATP + GFX: auto speed protection system and ground neutral-section passing device.

(1) The Fuxing EMU has been designed with a brand-new low-resistance streamlined head, an optimized roof equipment installation structure, and a full-envelope outer windshield to produce a smooth vehicle body, as shown in Fig. 5. The running resistance has been reduced by 7.5%–12.3% in comparison with the existing EMU. When operating at 350 km·h^{-1}, the per capita energy consumption per hundred kilometers has been reduced by about 17%.

(2) The external noise of the Fuxing EMU is better than that of the existing EMU. When running at 350 km·h^{-1}on the Beijing–Shanghai HSR, the external noise has been reduced by about 1–3 dB.

(3) Many environmentally friendly and green materials have been used in the construction of the Fuxing EMU, including water-based coatings, which are nontoxic, odorless, and energy efficient.

(4) The efficiency of the traction system has been improved, and the energy consumption of the cooling system has been reduced. Regenerative braking technology has been applied to reduce the brake pad wear and realize the recycling of electric energy.

2.4. A more comfortable riding experience

Based on research data, passengers' concerns regarding the comfort factor on a high-speed EMU are noise, transient air pressure, undesirable odors, the quality of the lavatory facilities, temperature, vibration, seat width, and air freshness, in sequence [3]. The Fuxing EMU presents notable improvements in terms of internal noise, transient air pressure, smoothness, passenger seating space, and seat spacing.

(1) The interior noise level of the Fuxing EMU is superior to that of the existing EMU. When the Fuxing EMU runs on the Beijing–Shanghai HSR at 350 km·h^{-1}, the noise inside the driver's cab and within the passenger's compartment is reduced by about 1–3 dB, and the noise at the pantograph end of the passenger's compartment is reduced by 6–7 dB.

(2) The change rate of the pressure wave is 20% lower than that of the existing EMU, further reducing passengers' ear discomfort when the train is in a tunnel or passing another train.

(3) The average value of lateral stability of the carbody has been reduced by 21% and the average value of vertical stability of the carbody has been reduced by 11%, enabling the Fuxing EMU to run more smoothly and comfortably.

(4) The width of the EMU carbody has been increased to 3360 mm, the height has been increased to 4050 mm, and the cross-section area has been increased by 7%–10.5%, giving passengers more space between seats and a more comfortable sitting environment. Fig. 6 shows the layout of the business seats, restaurant bar, first-class seats, and second-class seats.

(5) Free Wi-Fi is available for passengers, providing a mobile office environment and enriching the travel experience.

2.5. More cost-efficient

The interoperability of an EMU, the type unification of its spare parts and major components, and a unified maintenance cycle are significant parts of comprehensive support for the HSR. They serve as a basis for the safety and operation of a high-speed train, and are major measures toward boosting the efficiency and availability, and increasing the service life.

(1) The mileage for Level I maintenance is uniformly 6000 km and the mileage for Level III maintenance is uniformly 1.2×10^6 km (changed from 6×10^5 km). Twelve high-level maintenance cycles are reduced during the full service life of the Fuxing EMU.

(2) The entire service life of the Fuxing EMU is as long as 30 years—ten years longer than the life of the existing EMUs.

(3) Through unified interconnection, intercommunication, and interoperability, EMUs of the same speed level produced by different manufacturers can be coupled for operation, while EMUs of different speed levels can serve to rescue each other, making the operation organization more flexible, improving the utilization efficiency of the EMUs, and reducing the operation cost.

(4) The main components of the Fuxing EMU have been unified, including 86 items in ten major systems; this reduces the number of types of spare parts as well as the purchase and operation costs.

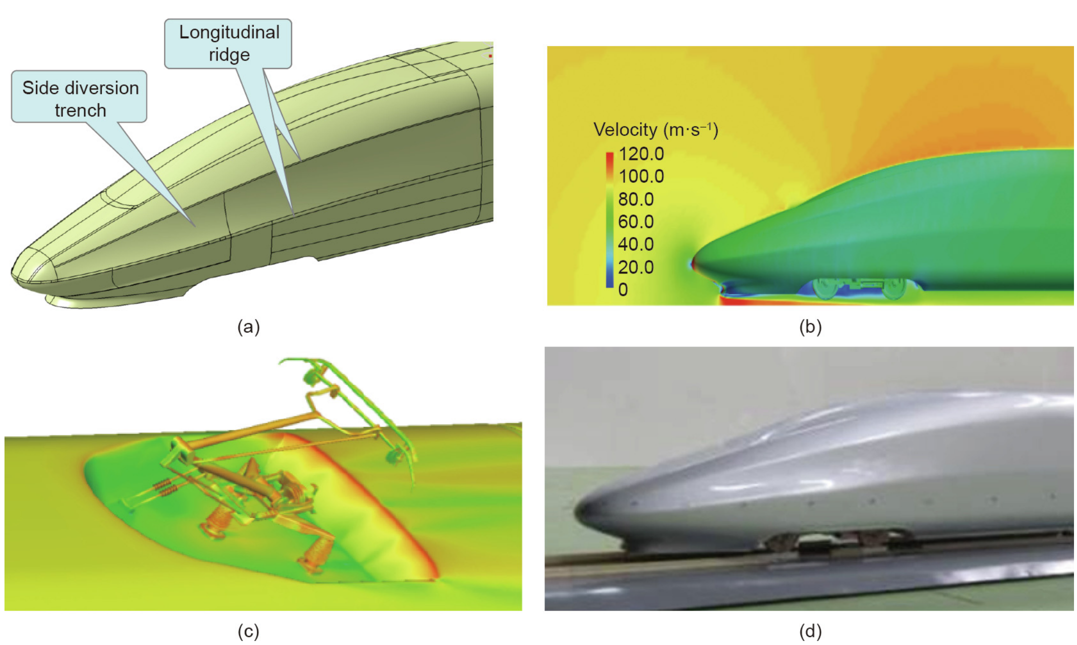

Fig. 5. The Fuxing EMU has been designed to increase its energy efficiency. (a) The streamlined head design; (b) the flow field around the head; (c) a smooth vehicle body; (d) the aerodynamic wind-tunnel test.

Fig. 6. The Fuxing EMU has been designed to increase passenger comfort. (a) Business seats; (b) restaurant bar; (c) first-class seats; (d) second-class seats.

2.6. A standard system

The technical standard system of the Fuxing (i.e., the China standard EMU) covers 13 categories of technical standards that include the basic and general parts, the carbody, the running gear, and so forth. Among the 260 important standards that have been applied to the Fuxing EMU, 84% are Chinese standards such as national standards, railway industry standards, China Railway standards, and technical documents. Some international standards from standardization organization such as the International Union of Railways (UIC), International Electrotechnical Commission (IEC), and International Organization for Standardization (ISO) have also been adopted.

3. Development and testing process

3.1. Development

(1) **Schemes of the head contour and carbody.** The research and development team initially designed 46 conceptual schemes for the head contour. After hundreds of simulation calculations in 18 categories such as aerodynamic resistance, aerodynamic lift, lateral force, and the tunnel effect, six head contour options were selected. Combined with wind-tunnel and dynamic model testing, the schemes were verified and iteratively optimized for multiple objectives. The final head contour schemes of "flying dragon" and "golden phoenix" were determined.

(2) **Schemes of critical and key systems.** The traction system and braking system were designed according to top-level indices such as the maximum continuous operating speed, dead weight of the EMU, operating resistance, and braking distance. According to the analysis and evaluation based on traction power and braking force demand, a distributed power supply mode in a four motor with four trailer (4M4T) formation was determined.

The general and core system designs, including the hardware and software of main systems such as the traction/auxiliary converter, traction motor, brake system, bogie, traction transformer, and network system, passed overall testing that included a scheme review, prototype development, type testing, ground combination testing, and other stages before the loading test.

(3) **Technical scheme for operation-safety technology.** The concept of a passive safety design was integrated into the structural design of the carbody, and a special collision energy-absorbing device was developed. The energy-absorbing element is made of metal thin-wall pipe fittings that feature low cost and high energy-absorbing efficiency. The design is a five-hole combined structure that mainly consists of octagonal pipes and the surrounding hexagonal pipe fittings. Guiding profiles have been arranged to control the backward direction of the coupler base in order to ensure the orderly and controllable deformation of the energy-absorbing device in the case of a collision. Testing and verification (Fig. 7) of the energy-absorbing elements, components, and driver's cab showed that the coordinated action of the components and the integrated design of the energy-absorbing and bearing structure can ensure high-capacity and stable energy-absorption performance over long-distance operation.

(4) **Interoperability and type-unification technology.** Since 2003, through independent innovation based on importing technologies, China's railways have established four technical platforms: the CRH1, CRH2, CRH3, and CRH5. The existing EMU models, which were developed based on different technology platforms, are non-interoperable. Once a certain EMU breaks down, the same type of EMU is required for rescue. In addition, the maintenance workshop must be provided with all the parts and compo-

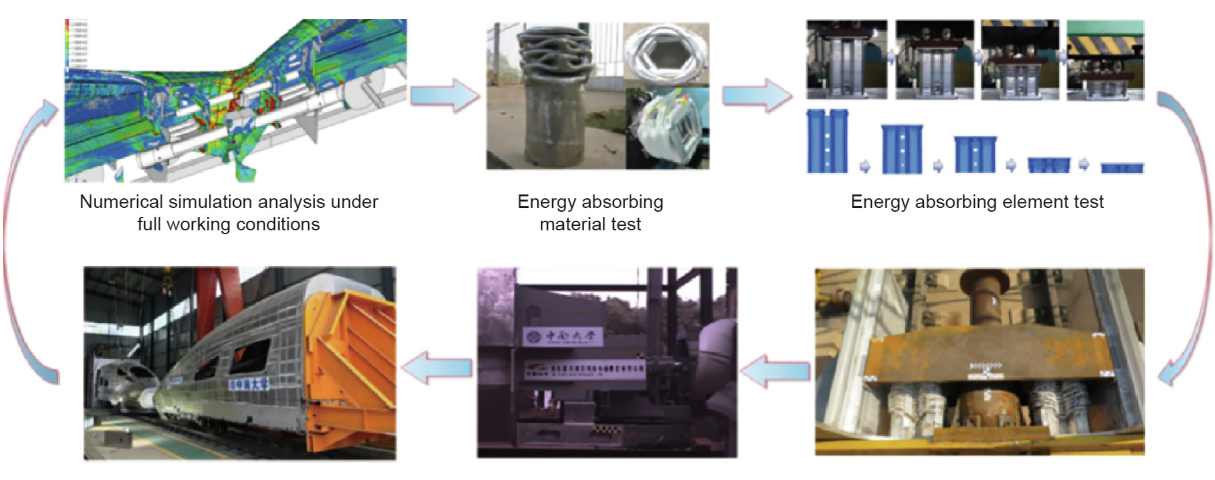

Fig. 7. Design and verification of the collision-resistance system of the Fuxing EMU.

nents for different EMU models, resulting in high operation and maintenance costs.

All of the assemblies and components of the Fuxing EMU were designed independently. A total of 86 components of 11 systems were designed according to the design requirements of type unification, thus realizing the interchangeability of EMU components and reducing the number of types of spare parts and components and the maintenance cost. In addition to the type unification of parts and components, software controls were developed independently. The software and hardware of key systems such as the traction, braking, and network systems were all independently developed; the unified driver and passenger operation interfaces and the unified operation mode (Figs. 8 and 9) allow the coupled operation of different EMUs, and thus improve the operation efficiency (Fig. 10).

3.2. Testing process

Since July 2015, the two Fuxing EMUs have undergone 66 vehicle-type tests at the testing loop line of the China Academy of Railway Sciences Co., Ltd. and the Datong–Xi'an Railway to assess the train dynamics, pantograph and catenary current collection, traction performance, braking performance, aerodynamics, and so forth. The China Academy of Railway Sciences Co., Ltd. has conducted a full-scale verification on the performance of the Fuxing as the China standard EMU. In November 2015, the highest test speed of the Fuxing EMU on the Datong–Xi'an passenger-dedicated line reached 385 km·h^{-1}.

A large number of research experiments have also been carried out, along with the type tests, for the purpose of deepening fundamental HSR theories and improving the HSR technical standards and systems. On 15 July 2016, two China standard EMUs completed the 420 km·h^{-1} train intersection and coupled operation test on the Zhengzhou–Xuzhou passenger-dedicated line, setting the highest speed record for commercial EMU trains. The test-monitoring system and train-crossing test are shown in Figs. 11 and 12. From July to October 2016, the Fuxing EMU successively completed operation assessments such as the unloaded operation test and the simulated loaded operation test on the Wuhan–Guangzhou and Harbin–Dalian lines.

In June 2018, the Fuxing EMU's automatic driving system was tested in the Liaoning section of the Beijing–Shenyang HSR. Applying the "Chinese train control system 3 plus automatic train operation" (CTCS3 + ATO) technology, the system supports functions such as automatic train departure, automatic sectional operation, automatic stopping at stations, automatic door opening after a stop, and automatic joint control between the train door and the platform screen door, among others. The system can also automatically adjust the maximum speed according to different section requirements.

4. Summary

Since the start of its commercial service, the 350 km·h^{-1} Fuxing EMU has shown good technical performance, a high level of safety, good reliability, and superior riding comfort. The overall operation is stable and the passenger experience is good. The Fuxing EMU has won widespread praise from the public. As China's high-speed EMU train platform, the Fuxing EMU can also be customized according to the actual requirements of the market as a complete set of EMU products with international competitiveness.

Research on the frontier of rail-transit technologies is being continuously promoted. In terms of the research and

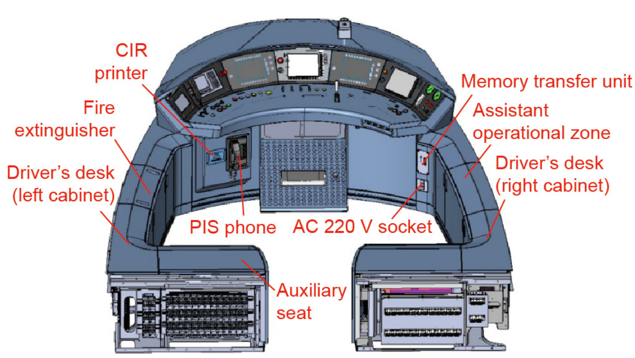

Fig. 8. Layout of the electric cabinet in the cab of a Fuxing EMU. CIR: cab integrated radio communication equipment; PIS: passenger information system.

Fig. 9. The photo of the driver's cab of a Fuxing EMU.

Fig. 10. Different EMU models in coupled operation.

Fig. 11. The Fuxing EMU test-monitoring system.

Fig. 12. The Fuxing EMU intersection test.

application of new technologies, the low-noise control of future trains during high-speed operation, lightweight vehicles, and the application of 5G network technology will bring new challenges and opportunities to the HSR sector. In terms of riding comfort, since wheel-rail impact during high-speed train operation leads to increased vibration and noise, riding comfort and noise control have become the focus of attention. In terms of energy efficiency, lightweight vehicles will help to significantly reduce both the energy consumption and braking load. In terms of intelligence, with the development and application of 5G technology, which features high bandwidth and a short time delay, mass data about the train status can be transmitted more rapidly between the train and ground, which will make the train operation safer, more intelligent, and more reliable.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eng.2020.01.004.

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