# Research on the Application of SAE ARP 4754A in the Development of High-Speed Trains

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**Abstract:** The development process of civil aircraft is to implement the design process of complex products with system engineering for the requirements of stakeholders. As an important activity of system engineering, requirements validation aims to ensure the correctness and integrity of requirements. SAE ARP4754A and the development process of high-speed trains are studied in this paper to analyze the application of important activities specified in SAE ARP4754A in the high-speed trains development process. With the actual situation of the development process for high-speed trains considered, the requirement of "railworthiness" is suggested based on the systems development process and safety assessment in SAE ARP4754A. To suit the safety requirements, a preliminary development process of high-speed trains is put forward, including the requirements validation procedure designed on the basis of an analysis of stakeholders' requirements to help train designers with their requirements validation work.

**Keywords:** Systems engineering, development process of complex systems, high-speed trains, requirement validation procedure, standards

## 1. Introduction

High-speed trains are typical highly integrated and complex systems, which are composed of multiple systems and subsystems all with independent functions [1], including more than 120 sophisticatedly linked independent subsystems and over 40,000 components [2]. High-speed trains operating in China require more reliable design and stronger adaptability to diverse environments, as well as higher speed, better stationarity, lower energy consumption and more environment-friendly design, on account of the long run time in a single travel, large geographical span and complex operating environments. All these requirements have posed huge challenges to the development process of high-speed trains and their systems. [3] In traditional design practice of high-speed trains, existing experience and similar products are the main basis for product design, with a large number of trials and errors involved in the design and development process, which extends the design and production cycle, making it hard to respond to clients' latest demands [4, 5]. In addition, the characteristic of multi-level (e.g., the train level, the system level and the component level), interdisciplinary (e.g., mechanics, electronics, control and hydraulics) and cross-sector integration of high-speed trains causes mismatches between existing designs and clients' demands, with no efficient mechanism or process to guarantee a top-down level-by-level reflection and allocation [4, 6]. To build a development system that satisfies the diverse and customized requirements for design and development while realizing a top-down design process has become a problem urgently require solutions [4].

The synergy and integration among systems of high-speed trains are the conditions to ensure secure and reliable transport and operation as well as safety and comfort of passengers. From August 1, 2008 when the Beijing-Tianjin Intercity Railway started operating till September 30, 2017, high-speed rails in China have served an accumulative total of over 7 billion passengers, with the record of passengers served per day hitting 7.607 million. "Fuxing" bullet trains have been put into commercial operation with a speed of 350 km/h since September 21, 2017. [7] Rail passenger transport's pursuit of carrying more passengers at a higher speed puts forward extremely high requirements on the safety and ride comfort of high-speed trains. However, the long development cycle and the large number of participants involved would inevitably result in unfavorable factors like dispersed management and divided specialties, making it impossible to sufficiently satisfy the safety requirements at the train level in the design stage of a high-speed train [8, 9].

Up to now, studies on the development process of high-speed trains include research and analysis on reliability and safety design of key subsystems and critical components [8, 9 10, 11]. As for standardization, developed countries have established safety assessment and management systems and relevant technical standards for safety assessment [12], while China has, with a reference to serial international standards IEC 61508 and IEC 62278, formulated its own standards GB/T 20438, GB/T 21562-2008, GB/T 21562.2-2015 and GB/T 21562.3-2015.

Nevertheless, in the design and development of high-speed trains, the product design is still divorced from the reliability and safety design: (1) the requirement for reliability and safety design analysis has not been proactively implemented in the whole process of product design at the train level; and (2), the critical procedure of reliability and safety design is ignored throughout the process of design and development so that the product design considers functions and performance first and reliability and safety later, as a result of which some indexes of performance, reliability and safety may not meet the requirements [13]. These problems may impair the product's reliability in use, increase the possibility of faults, escalate costs for manufacturing and service assurance and bring more risks of financial losses and safety problems.

Therefore, it is pressing to put forward safety-based train and system development process to support the development process and safety analysis of Chinese high-speed trains at train and system levels [14].

## 2. Introduction of SAE ARP 4754A

### 2.1. Concept of "Airworthiness"

Airworthiness refers to an aircraft's suitability for flight. Technologies and activities of Systems Engineering are adopted to achieve and maintain airworthiness in all stages of an aircraft's life cycle, including conception, development, manufacturing, usage, maintenance, decommission and management. [15] Airworthiness requires the aircraft to conform to its type certificate and stay in condition for safe operation [15].

SAE ARP 4754A [16] Guidelines for Development of Civil Aircraft and Systems, formulated and compiled by International Society of Automotive Engineers (SAE International), is a guideline that defines systematic characteristics and scope of aircrafts so as to prove the compliance of highly integrated or complex aircrafts to regulations on airworthiness. In addition to highlighting the airworthiness certification, the document also takes the safety process as an integral part of the development of an aircraft and its systems while further clarifies the development process for aircraft and systems, so as to ensure a correct decomposition and implementation of the safety requirements as well as the correctness and completeness of all requirements.

SAE ARP 4754A provides, based on requirements of the stakeholders, a highly comprehensive and integrated development process model of an aircraft and its systems, which divides the whole process into planning, aircraft/system development and integration processes [17], as shown in Figure 1. In this model, the plan process serves as a foundation of the development process and the key activities include top-level planning, process assurance, confirmation and validation of integrating process and requirements, etc. [17] The document requires the design and development processes of a civil aircraft and its systems to comply with ideas and methodologies of Systems Engineering, with rational and feasible plans made and the whole processes strictly implemented according to plan so as to manufacture a successful product ultimately. After taking the operating environment and overall functions of an aircraft into consideration, the document adds the safety process as an integral part of development and then finalizes the aircraft/system development process to ensure the aircraft's safety.

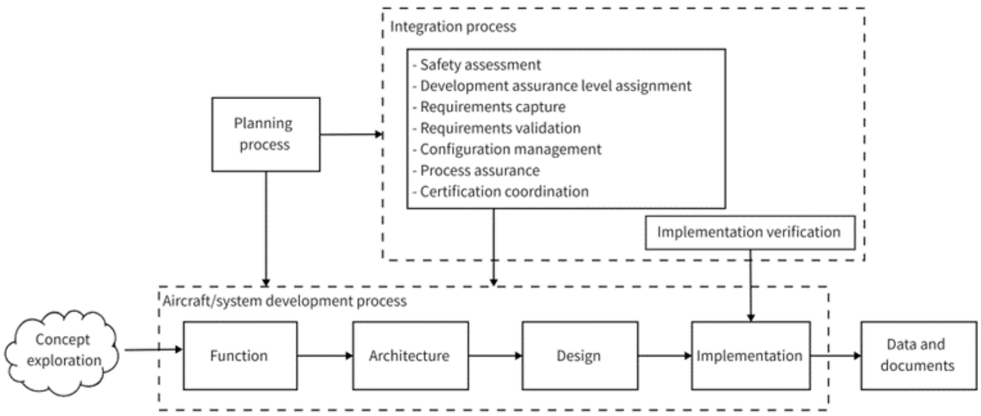


Fig. 1. System development process model defined by SAE ARP 4754A.

## 2.2. Complex System Development Process Based on SAE ARP 4754A

SAE ARP 4754A can be seen as an application of Systems Engineering theories and methodologies in aviation. As an iteration process that integrates, develops and operates a real system, Systems Engineering is a set of interdisciplinary methods and approaches that may successfully implement a system and aim to satisfy all the requirements over the system in a nearly optimal way [18, 20]. The International Council on Systems Engineering (INCOSE) suggests establishing a standard V-Model in the INCOSE Systems Engineering Handbook [17, 19], as shown in Fig. 2, the core of which "depicts the evolving baseline from user requirements to identification of a system concept to definition of systems components that will comprise the final product".

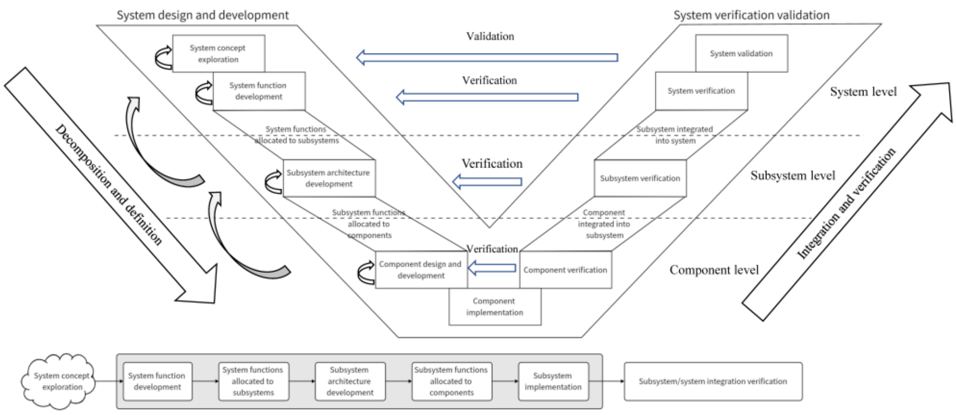


Fig. 2. Systems engineering V-model.

According to Systems Engineering procedures, the aircraft/system development process that includes the development of aircraft/system functions, functions allocation, software/hardware development, and aircraft/system implementation and integration is a typical V-Model development process that follows the development patterns of a complex system. Meanwhile, the integration process defined by SAE ARP 4754A also specifies requirements on safety-related activities in aircraft/system development, such as Functional Hazard Assessment (FHA), Preliminary System Safety Assessment (PSSA), System Safety Assessment (SSA), Common Model Analysis (CMA), System Safety Program Plan (SSPA) and safety-related flight operations or maintenance tasks. By doing so, the necessary connection between aircraft safety and system development is established and functions of the aircraft can be easily decomposed to three levels: aircraft level, system level and component level [17].

Given that the high-speed trains, similar to civil aircrafts, are typical complex systems that are highly comprehensive and integrated, highlighting safety, reliability and comfort requirements, SAE ARP 4754A is based on systems engineering theory, which emphasizes a top-down design process and employs an interdisciplinary approach that enables system implementation.

Therefore, combining the characteristic of multi-level, interdisciplinary and cross-sector integration of high-speed trains with the urgent need to establish a safety-oriented development process for the train and system. This paper studies the safety-based development process of high-speed trains on the basis of aircraft and system development processes and methods specified in SAE ARP 4754A.

## 3. A Safety-Based Development Process of High-Speed Trains And Systems

### 3.1. Concept of “Railworthiness”

The “railworthiness” of high-speed trains is defined, on the basis of the definition and properties of airworthiness [21, 22], with characteristics and operating environment of high-speed trains in China taken into consideration, as the safety and physical and functional completeness of the overall performance and maneuvering characteristics of high-speed trains and systems (including subsystems and components) under expected operating environment and service restrictions.

Here, “safety” safety can be defined as that state for which the risks are judged to be acceptable, and “completeness” is the qualitative or quantitative attribute indicating that a system or item can operate normally and reliably, sometimes described as the possibility for the system or item to fail to meet the standards of normal operation.

It can be seen that “railworthiness” is an intrinsic property of a high-speed train that maintains the minimum safety level acceptable for its service and operation, the boundary conditions for which are the expected operating environment and service restrictions (e.g., speed, height, weight and balance) of the train. This property requires the high-speed train to always comply with its specifications and design and sustain a safe operation [15], so as to ensure a safety level acceptable to stakeholders travelling by high-speed rail and driving the train. Such a property can be achieved and maintained through activities at different phases throughout the lifecycle of the high-speed train, namely, its design, manufacturing, testing, usage, maintenance and management. “Railworthiness” is represented, technically, by the physical completeness, functional completeness and system safety of the high-speed train and, managerially, the management over technical conditions and process control.

### 3.2. A Safety-based Development Process of High-Speed Trains

According to the definition of “railworthiness” for high-speed trains in this study, activities in the development process of high-speed trains have to be based on the three elements: physical completeness, functional completeness and system safety. Therefore, a development process of high-speed trains is suggested, as shown in Fig. 3, based on Systems Engineering theories and the aircraft and system development processes specified in SAE ARP 4754A, with the safety requirements taken into account.

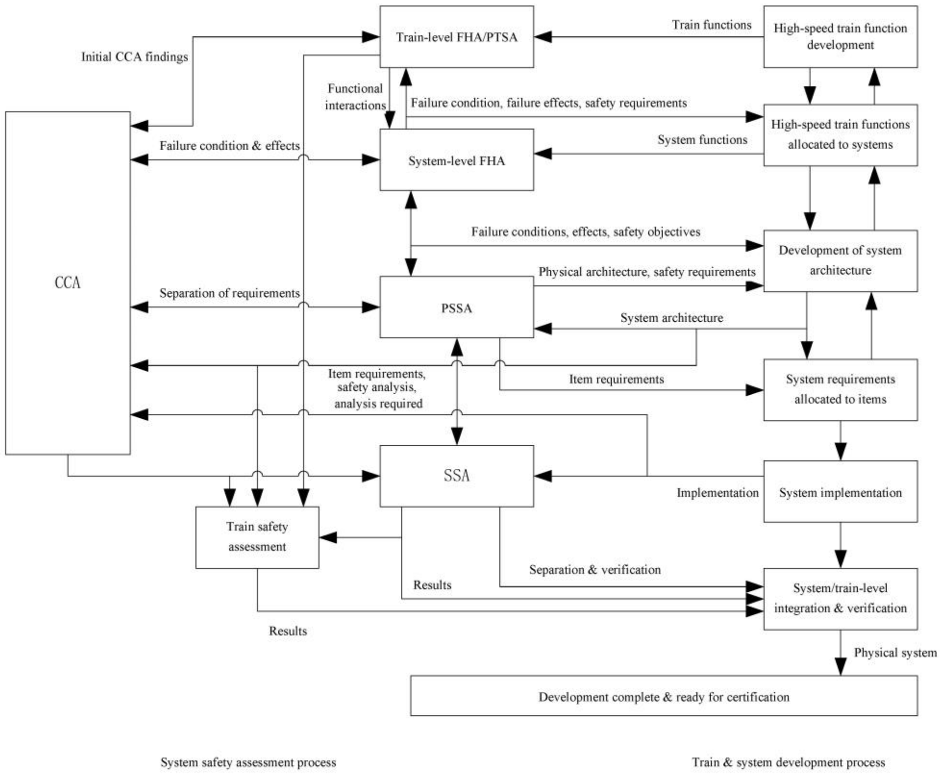


Fig. 3. A safety-based development process of high-speed trains.

At the right of Fig. 3 is the train and system level development process of high-speed trains. The physical completeness and functional completeness of a train and its systems have to be implemented through a repeatedly iterating requirements-driven top-down process that includes integration, development and operation with Systems Engineering techniques combined, to develop systems that satisfy the requirements with optimal overall performance [20].

Throughout the suggested development process, requirements are cascaded in the top-down iterative process and reflected level by level, as a result of which all requirements can be satisfied in a nearly optimal way. Main activities in the process include defining requirements, functions and architectures of the train/system, completing allocations at all levels and implementation of systems, which are, specifically, system requirements, derived system requirements, system architecture, allocation of system requirements to subsystems, subsystem architecture, allocation of subsystem requirements to equipment, allocation of equipment requirements to software and hardware, implementation of software and hardware, and system integration [17].

The left of Fig. 3 is the system safety assessment process used to support the development process of complex systems, including the generation and verification of safety requirements. This process offers safety assessment methodologies for system functions and the implementation of their specific architecture, which can be used to define possible hazardous events, then identify all related failure conditions, clarify all failure groups that may cause these failure conditions to occur, and, finally, determine whether the safety requirements are satisfied [16]. The main activities here include FHA, PSSA, ASA/SSA and CCA (Common Cause Analysis).

As indicated in the figure, the safety assessment process is embedded in the system development process and keeps updating along with the iteration of system development. The system safety assessment starts at the concept stage and brings forward safety requirements from then on. As the design of the system always improves, the revised design has to be re-assessed, therefore, generates new safety requirements, which, in turn, may call for more changes in design. The safety assessment process will not end until the final design is verified to have satisfied all the safety requirements.

## 4. A Safety-Based Requirements Validation Process of High-Speed Trains and Systems

### 4.1. General Requirements Validation Process

As mentioned above, the high complexity of current high-speed trains and their systems has resulted in diversified and mutually-influencing requirements on the design, comfort, safety and environmental adaptability of systems/subsystems/products. The limitations of traditional design thinking make it difficult to ensure the correctness and completeness of systems and meet stakeholders' demands and safety requirements, causing not only huge repetitions in design and extension of development process, but also considerable cost increase [23, 24].

The requirement engineering based on SAE ARP 4754A covers the whole process from bringing to implementing the requirements. A top-town requirement engineering has to be conducted to avoid the gap between design/verification and requirements caused by unclear communication on requirements. In this process, requirements validation and verification activities play a vital role in the development process. This is to verify the correctness and completeness of the captured requirements through process control.

Therefore, a railworthiness-based requirements validation process of high-speed trains is proposed in this study, in accordance with the aircraft/system requirements validation process of civil aircrafts [25]. The process based upon safety requirements ensures the high-speed train and its systems can satisfy the requirements of clients, users, maintenance personnel and all other stakeholders. The requirements validation process is used to guarantee the completeness and correctness of requirements and goes through the high-speed train development process. Fig. 4 shows a general process of requirements validation.

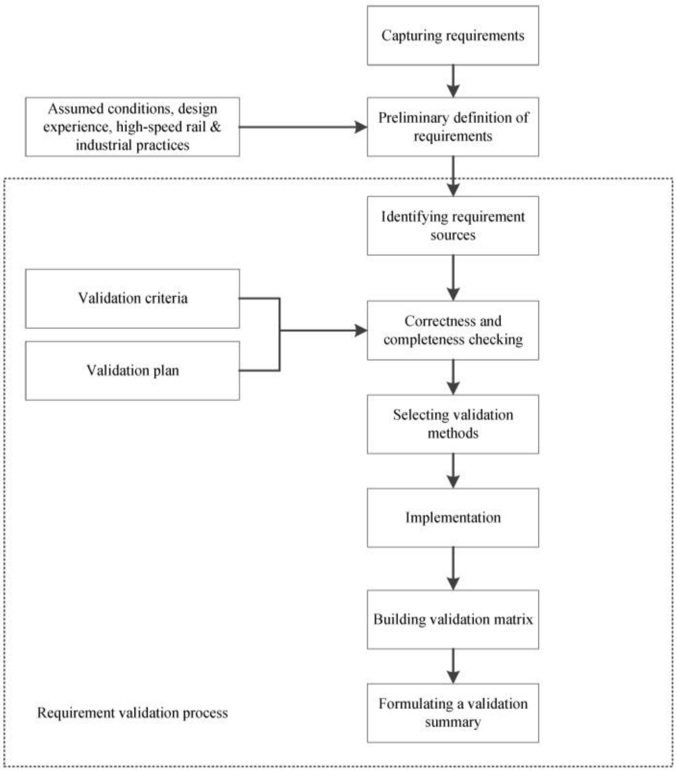


Fig. 4. A general requirements validation process.

As similar to the general requirements validation process of civil aircrafts, the identification of requirement sources for high-speed trains in this process involves the identification of all elements at the direct above level that are related to requirements at the current level (e.g., requirement documents, related laws and regulations, and domain knowledge and industrial standards at the direct above level), since they are required inputs for activities at this level.

Upon the completion of correctness and completeness checking over requirements at different levels of the train and its systems according to the validation criteria and plan, methods like traceability analysis, requirement modeling and simulation analysis, testing, similarity analysis and engineering review should be selected, as per requirements validation methods specified in SAE ARP 4754A, to carry out validation, with all relevant evidence documented (e.g., analysis report, engineering review summary, and modeling and simulation results) [25]. In order to ensure the confidence coefficient, validation evidence corresponding to all validation methods has to be recorded and includes the sequential numbers, contents, validation methods, validation status, validation opinions and validation evidence for the requirement items, so that a validation matrix is formed.

Similar to the requirements validation process of civil aircrafts, the validation summary that reports on all validation activities is the output of the validation process of high-speed trains and systems. The summary should give an overall illustration of validation activities, including the compliance with and deviation from the validation plan, the requirements validation matrix and the description of related supporting data and assumptions [25, 26].

### 4.2. A Safety-Based Requirements Validation Process of High-Speed Trains

The requirements validation process of high-speed trains is a top-down allocation of requirements over the train and systems. The requirements allocation at all levels has to be focused on the safety requirements, ensuring that all allocated and downward-delivered requirements are correct and complete, in avoidance of the delivery of wrong requirements into development at the lower level or any omission of requirements. See Figure 5.

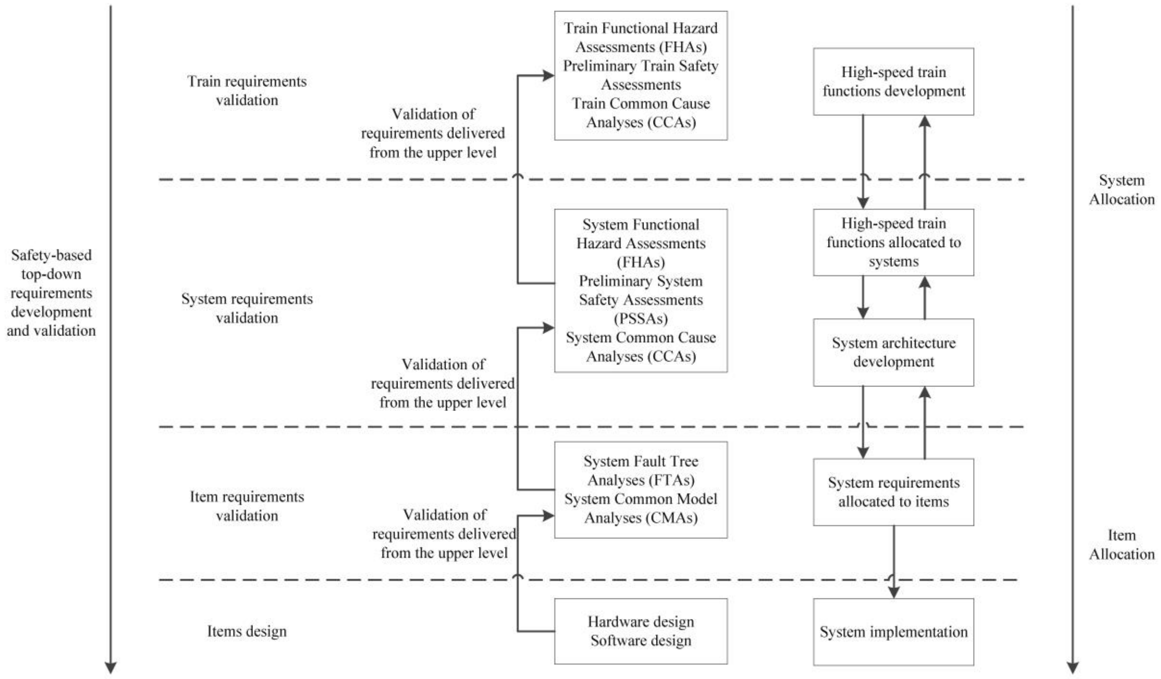


Fig. 5. A safety-based requirements validation and development process of high-speed trains.

Requirements have to be validated in the process of requirements definition at the train level, system level and component (item) level to make sure that they satisfy not only the requirements for train and system design, but also the safety requirements. Therefore, the requirements validation process and safety assessment activities have to be iterated as same as the system development process, with the assessment results well documented.

Furthermore, a bottom-up compliance verification has to be carried out in the meantime of the top-down requirements allocation as an assurance that the developed equipment/systems can satisfy each and every requirement and the manufactured product does not fail the objectives of the high-speed train. In this way, the double assurances that work both top-down and bottom-up is able to ensure the correctness and completeness of the whole development process while satisfying all requirements of the train and its systems.

## 4.3. A Safety-Based Wheelset Requirements Process and Requirements Analysis

Wheelsets, as the part of a high-speed train in direct contact with the railway, are critically important mechanical components of the train, the structure of which is two wheels firmly attached to left and right ends of an axle, as shown in Figure 6. They have to bear all the static and dynamic loads of the train and deliver them to the rails, while distributing any load generated by bumps on rail to different components, to guarantee the operation and steering of the train on rail. Recent years have seen growing difficulties in requirements validation, development and requirements analysis of wheelset products in the face of manufacturers, due to the increasing demand over domestic bullet trains and high-speed trains, vast differences in wheelset structures provided by different suppliers, varied requirements over inspection and maintenance, imperfect mechanism for wheelset requirements analysis and other factors. In view of this, this study adopts a safety-based wheelset requirements validation and development process and analyzes wheelset requirements on the basis of Model-based Systems Engineering (MBSE) theories and methods to improve the reliability of this development process.

Fig. 6. Structure of a high-speed train wheelset.

As similar to the safety-based requirements validation process of a whole high-speed train, the requirements validation and development process of wheelsets require also to base the allocation of requirements to all components upon the safety requirements, in order to ensure the requirements are fully delivered and improve the reliability of and facilitate following development procedures. The specific process is shown in Fig. 7.

Model-based wheelset requirements analysis means to use tools of MBSE product requirements analysis in the requirements analysis of wheelset products, which includes three aspects: the constructions of the wheelset's requirement model, function and physical architecture model.

### 4.3.1 Requirement model

The requirement model of wheelsets includes the overall requirements on wheelsets from top to bottom levels and the set of logical correlations among them. These requirements can be divided into functional requirements and performance requirements according to their different emphases. The main function of the requirement model is to transfer vague expectations and requirements proposed in the process of product design into specific problems to be solved. The requirement model is also in a hierarchical structure as corresponding to the multi-level systems, on the top of which are users' requirements of use and expectations of various stakeholders. The top requirements are then divided into functional and performance requirements, which are then decomposed in the overall product system level by level, from systems to components, till the requirements are fully satisfied by product design. Figure 8 illustrates the construction process of the requirement model of wheelsets.

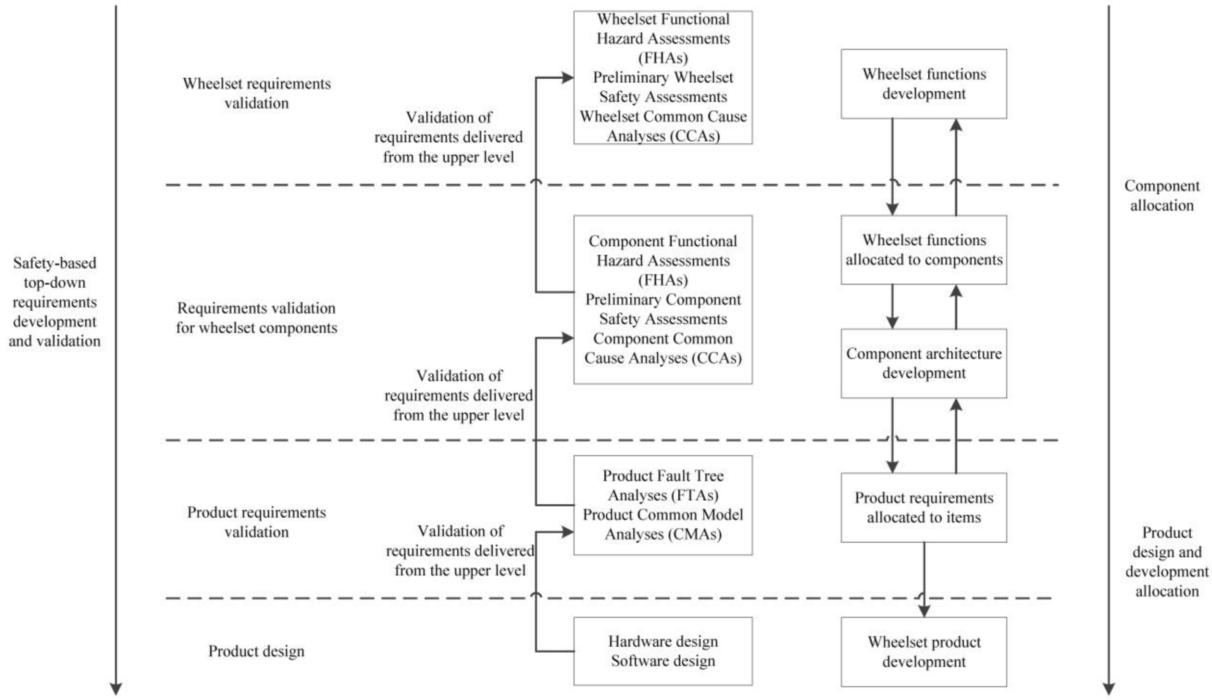


Fig. 7. A safety-based wheelset requirements validation and development process.

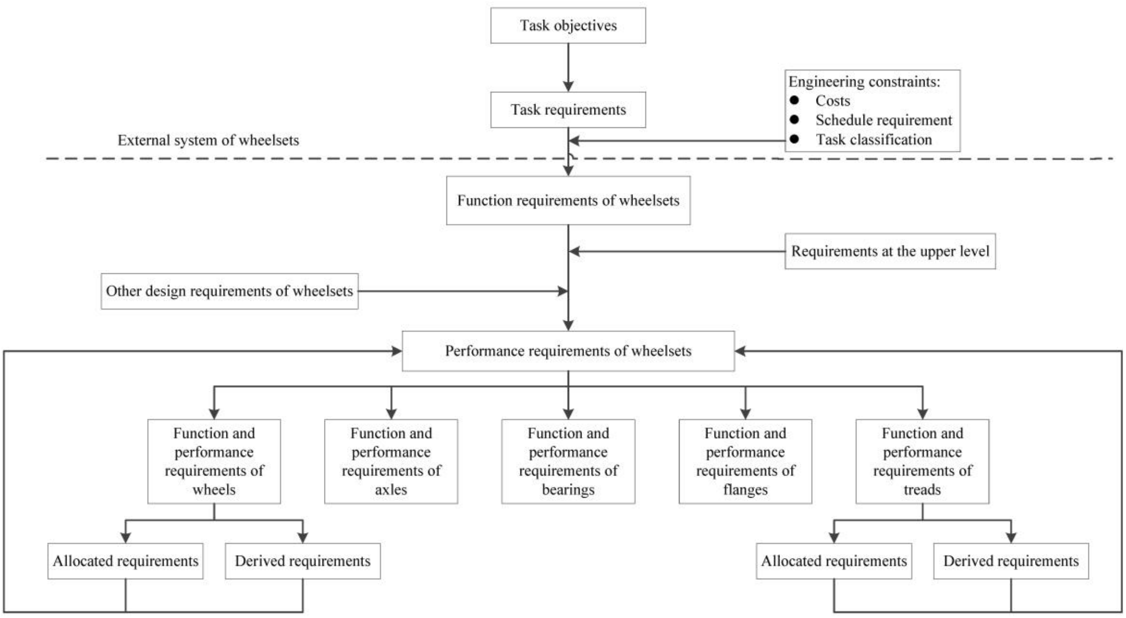


Fig. 8. Construction process of requirement model of wheelsets.

### 4.3.2 Function model

The function model of wheelsets is the set of all functions needed for the overall system to accomplish its task objectives. It carries function analyses through logical decomposition on the basis of the requirement model, assorts task events based on the task process, then identifies functions at each level from the task events and induces the functions at all levels into clear function modules. In addition, all functions have to be matched with entries in the requirement model during the construction of the function model, so that each requirement item has its corresponding function(s). Fig. 9 indicates the construction process of the function model of wheelsets.

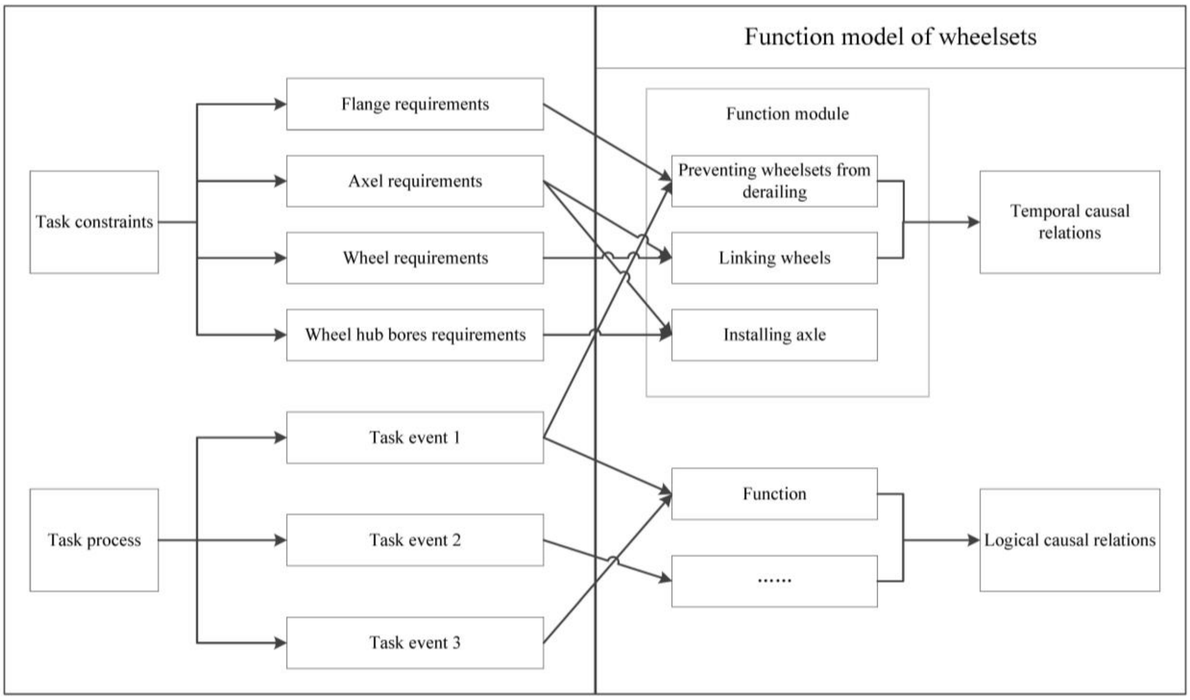


Fig. 9. Construction process of function model of wheelsets.

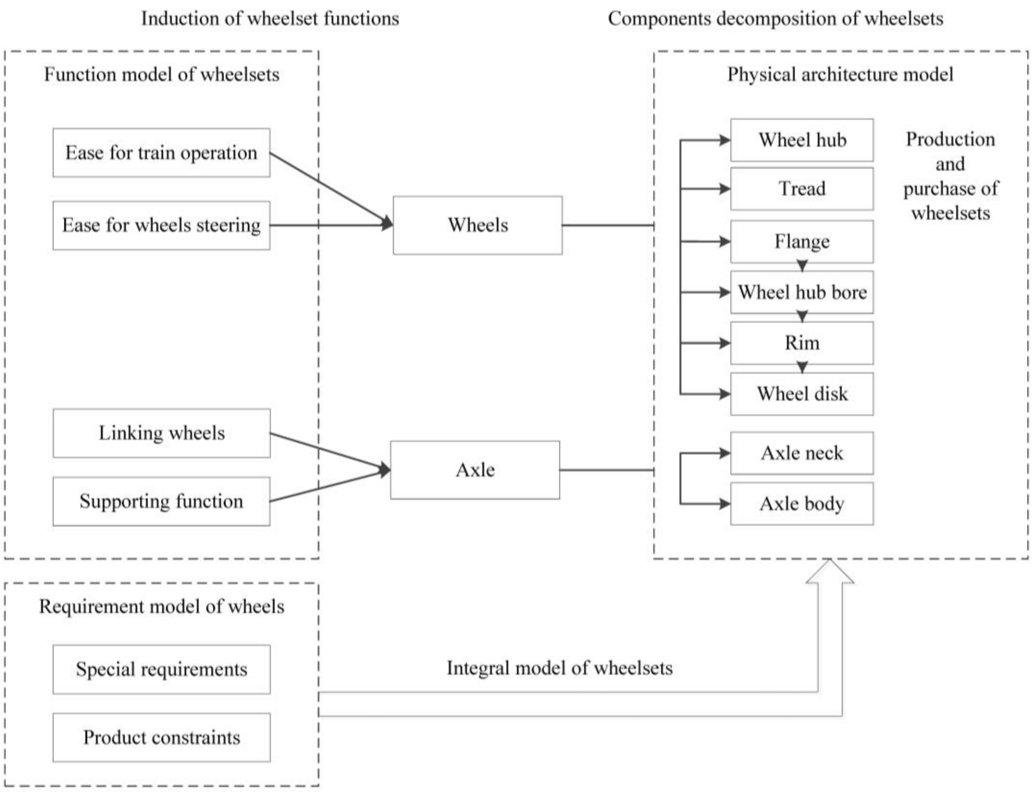


Fig. 10. Construction process of physical architecture model of wheelsets.

### 4.3.3 Physical architecture model

The physical architecture model of wheelsets describes all components of the product and their interface relationships. The physical architecture model has to be constructed on the basis of the requirement model and the function model, giving a comprehensive account on performance index, product efficiency, development costs, product interface, technical risks and other factors, comparing multiple plans to select an architecture that both meets clients' requirements and functions of the wheelsets. Figure 10 illustrates the construction process of the physical architecture model of wheelsets.

## 5. Conclusion

Through analyzing and summarizing the SAE ARP 4754A standard and the development process of high-speed trains, this study focuses on the application of the development process and system safety analysis methods specified in SAE ARP 4754A in the development of high-speed trains. The "railworthiness" requirement of high-speed trains is suggested on the basis of existing development process of high-speed trains and possible improvements on it as inspired by SAE ARP 4754A. A safety-based high-speed train development process is then formulated, with a requirements validation process for high-speed trains preliminarily defined as a guidance for the requirements validation practice of designers. Finally, the critical components of a high-speed train, wheelsets, are taken as an example to illustrate their requirements validation and development process, with requirement analysis conducted by MBSE methods to improve their reliability in use.

In engineering practice, research and applications have been carried out for the reliability and safety design of key subsystems and key components in the development process of high-speed trains, and these works have provided a certain basis for the application of the method in this paper. However, the development process of high-speed trains and aircraft is not exactly the same, even though SAE ARP 4754A provides methods that can be referred to, whether these methods can be effectively applied to actual production still needs further demonstration and continuous modification and improvement in practical application, at the same time, we should also note that the development process and safety assessment activities of high-speed trains are still independent from each other. And at present, the main obstacle lies in the implementation environment and tools. Therefore, promising research emphases in the future are Model-based Safety Analysis (MBSA) and system design with digital tools and MBSE methods adopted, and integration techniques and standardization of safety analyses [23, 24].

## Conflict of Interest

The authors declare no conflict of interest.

## Author Contributions

Lefei Li gave comprehensive guidance on the research ideas of this paper, Pidong Wang combined theoretical knowledge to write the first draft, Fengfeng Huo, Zhongtao Qi, Jianliang Ren supplemented and improved the research background and research significance based on practical experience, Hongqiao Zhu proofread the final draft, and all authors had approved the final version.

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The second author Dr, Wang Pidong sadly passed away on March 10th, 2022 as a result of Epstein-Barr virus. Because of his significant in this study, all contributing authors agree to keep him as the second author of this manuscript.

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