Received 23 June 2025
Revised 18 July 2025
Accepted 22 July 2025

# Reliability allocation of railway system based on fault tree

Pei Liu
*Railway Science and Technology Research and Development Center, China Academy of Railway Sciences Corporation Limited, Beijing, China*
Xing Fang
*China Academy of Railway Sciences Corporation Limited, Beijing, China, and*
Jiaxu Chen, Jingyu Zhang, Kexin Zhang and Mingming Wang
*Railway Science and Technology Research and Development Center, China Academy of Railway Sciences Corporation Limited, Beijing, China*

## Abstract

**Purpose** – This paper focuses on studying the reliability allocation for the railway system, aiming to improve the overall reliability of the railway system and ensure safety operation.
**Design/methodology/approach** – In view of the complex structure of the railway system, involving many subsystems, this paper analyzes the close dynamic coupling effect between railway subsystems. Based on this, taking the railway system failure as the top event, a fault tree is constructed in this paper. Then, a reliability allocation method based on the fault tree is employed to allocate the reliability index. Finally, a numerical experiment is implemented to show the performance of the reliability allocation method.
**Findings** – The results showed that each subsystem needs to improve its reliability to meet the specified railway system reliability requirements, and the traction power supply system is the most important subsystem, which is the most efficient in improving the reliability of the railway system.
**Originality/value** – For the first time, starting from a holistic perspective of the system, reliability allocation is carried out based on the importance of each railway subsystem.

**Keywords** Railway system, Composition structure, Fault tree construction, Reliability allocation

**Paper type** Research article

## 1. Introduction

The railway system is a complex system composed of many relatively independent and interrelated subsystems. The internal and external subsystems are correlated and matched with each other, and the interfaces are coordinated and highly integrated. Therefore, it is necessary to divide the subsystem of the railway system and identify the interface relationship of the railway system from the perspective of the internal and external interface relationship of the subsystem. Currently, some scholars have carried out related research on interface identification and management. For example, Morris (1983) introduced the project interface management comprehensively and pointed out that the project is an open system composed of many interacting subsystems. The interaction between the subsystems and between the project and the external environment constitutes the interface system of the project. Therefore, in order to successfully integrate the project, the interfaces between the project must be identified and managed. Hou *et al.* (2009) studied the system integration interface management method of the high-speed railway and put forward the basic method



*Funding:* This research was supported by the Research Project of China Academy of Railway Sciences Corporation Limited under Grant 2023YJ252.

Railway Sciences
Vol. 4 No. 4, 2025
pp. 550-562
Emerald Publishing Limited
e-ISSN: 2755-0915
p-ISSN: 2755-0907
DOI 10.1108/RS-06-2025-0020

of system integration interface management and formed a set of management procedures and technical specifications. Lv (2010) conducted in-depth research on the concept, organization, responsibilities and basic procedure of interface management of the high-speed railway construction.

Reliability allocation aims to allocate the reliability index of the system to each subsystem and clarify the index requirements of each subsystem so that the reliability index of each subsystem after allocation is more reasonable than before and then meets the specified system reliability requirements. The commonly used reliability allocation methods can be divided into two categories: unconstrained reliability allocation methods (such as Chen, 2003; Jia *et al.*, 2023; Wu, Xie, Wang, & He, 2023; Xu & Da, 2002) and constrained reliability optimal allocation methods (such as Ai, Cui, Li, & Zhang, 2022; Gui, 2020; Liu & Zhang, 2005; Liu *et al.*, 2024).

Reliability allocation is an important task in the design or maintenance of a railway system. For a complex railway system, it requires the reliability of each subsystem to be relatively balanced, and partial excellence is meaningless. Therefore, focusing on improving the weak points in the railway system has the greatest effect on improving the overall reliability. In reality, due to the various kinds of technical and economic constraints, it is technically difficult and time-consuming to improve the reliability of weak points. Therefore, it is necessary to comprehensively balance these contradictory requirements and apply various reliability allocation methods to determine the reliability characteristics of systems, subsystems and major equipment in the railway system to improve its design, maintenance and reliability (Yang, Hwang, Sung, & Jin, 1999).

Currently, the simplest method for allocating reliability is to distribute the reliabilities uniformly to all components. This simplifies the calculation, but the results deviate severely from the fact. Other methods for reliability allocation, such as uniform allocation, AGREE allocation, etc. are not generally considered as the best way to allocate reliability for the railway system; hence, it is necessary to carry out relevant research on railway system reliability allocation. In response to this problem, Chen *et al.* (2008) proposed a reliability allocation method for catenary systems based on fuzzy analytic hierarchy process (AHP) and group decision-making, established an AHP structure for reliability allocation and combined the independent decision-making of multiple experts to quantitatively analyze the uncertain factors affecting reliability distribution. And by calculating the relative importance of each unit of the system, the distribution of catenary system reliability is completed. Wang *et al.* (2017) applied the Bayesian network method to analyze the overhead catenary system (OCS) reliability. With the combination of the investigation results of the project and the fault tree algorithm analysis method, the Bayesian network model for the existing OCS and its key component is established, and the reliability analysis is made.

In this paper, we will construct the railway system failure fault tree by analyzing the composition structure of the railway system and apply a reliability allocation method based on the fault tree to realize the reliability assignment. It can be used to deal with setting the reliability goals for individual subsystems so that a specified reliability can be met.

The rest of this paper is organized as follows: Section 2 first gives a description of the composition structure of the railway system. Then, the fault tree of the railway system is constructed in Section 3. Section 4 introduces the reliability allocation method based on fault tree. Based on this, a numerical example is implemented to show the effectiveness of the reliability allocation method in Section 5. Finally, a conclusion is made in Section 6.

## 2. Composition structure of railway system

The railway system is a complex giant system, which is composed of lines, subgrades, tracks, bridges and culverts, tunnels, stations, catenary, power supply, communications, signals, operation dispatching, passenger services, rolling stock, environmental protection and other specialties. Different specialties constitute different subsystems of the railway system.

For example, lines, subgrades, tracks, bridges and culverts, tunnels, stations, etc. constitute the civil engineering subsystem. Each part of the system is interrelated and matched, structure coordinated and highly integrated to form an organic unity. The system structure and behavior are determined by the subsystem components' behaviors, coupling relationship and emerging behaviors. Starting from components, we study the system structure, function and behaviors based on the feature analysis of components. According to the functional characteristics of the system, the system can be divided into system layer, subsystem layer, component layer and part layer, as shown in Figure 1.

In Figure 1, the system layer refers to the railway system, which is composed of subsystems. Based on the railway technical standard system, the subsystems, respectively, the civil engineering subsystem, the mobile equipment subsystem, the communication and signal subsystem, the traction power supply subsystem, etc. There is a close dynamic coupling effect between railway subsystems. They interact and interconnection to form an inseparable large complex system. Each subsystem is composed of multiple key technical units. For instance, the mobile equipment subsystem is composed of key technical units such as the EMU (Electric Multiple Units) body, bogie, braking unit, traction unit and network control unit. Note that these units are also referred to as subsystem or system, owing to their inherent complexity. Each unit (subsystem/system) is comprising numerous components, and each component is composed of numerous parts. From this perspective, the railway system is like a multi-dimensional and intricate giant structure, evolving from points to lines, expanding from lines to planes, and ultimately rising from planes to a solid whole.

The railway system and subsystem are always in the dynamic process, especially under the condition of railway operation, leading to a stronger dynamic interacting effect. These interactions are transmitted through interfaces between subsystems and within subsystems. Take the wheel–rail interface as an example, vehicles and line infrastructure are coupled in real time during operation. The dynamic behavior of the vehicle and the geometric state of the track feedback each other, requiring rolling stock to have good dynamic performance to match. Meanwhile, rolling stock needs to deal with the wheel–rail relationship, pantograph-catenary relationship, train control information transmission and passenger service information transmission, etc. Communication and signal require operation scheduling, rolling stock, passenger service, traction power supply, etc. put forward specific requirements for transmission channel, local area network (LAN), wide area network (WAN), conference

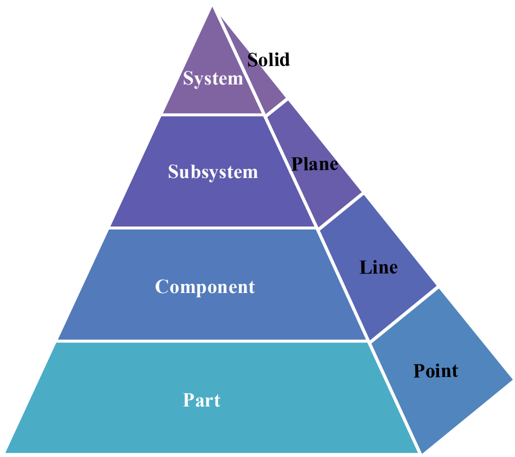


**Figure 1.** The hierarchical division of system structure. Source: Authors' own work

television and video monitoring and exchange of vehicle control data with rolling stock. For traction power supply, it needs the electrical characteristics of the rolling stock and the relevant data of the pantograph parameters, needs the power supply capacity and location of the communication and signal and puts forward the demand of power communication to communication specialty as well as the setting data of the track circuit and block partition. Operation management should maintain a real-time and smooth connection with signal, traction power supply, passenger service and other specialties. At the same time, the passenger service receives information such as the transportation plan and train running status from operation schedules and transmits the passenger service status information to operation schedules. In addition, the natural environment, as the external environment of the railway system, has a great impact on train operation and infrastructure. In conclusion, these complex interrelationships within the railway system have significantly increased the difficulty of reliability assessment and reliability allocation.

## 3. Fault tree construction of railway system

Fault tree analysis is a detective and detailed method to describe an accident resulting from a chain of events. According to the relationships and interactions among the events, it is easy to construct a fault tree logic diagram with the aid of logical gates. The procedure for constructing a fault tree is as follows:

*Step 1*: Be familiar with the system. In this step, it is required to accurately understand the details of the system, including the problems solved by the system, the environment faced of the system and so on.

*Step 2*: To determine the top event. On the basis of understanding the system, several fault forms that need to be solved are found as top events to construct the fault tree.

*Step 3*: To determine the main process. The main process is to construct the fault tree step by step in a deductive way according to the law of the development of certain things.

*Step 4*: To determine the boundary conditions. The boundary conditions are studied to determine the extension of the fault tree throughout the construction process.

*Step 5*: To construct the fault tree. Starting from the top event, we analyze all possible reasons level-by-level until all relevant basic events are found out. Then, a fault tree logic diagram can be constructed through the detective analysis with the support of logic gates.

In this paper, we will construct a fault tree for the railway system. Firstly, by Section 2 we can deeply understand the railway system through different majors and interfaces among them. Secondly, this paper mainly studies the whole railway system, so the railway system failure can be regarded as the top event to construct the fault tree. Thirdly, based on the mobile equipment, infrastructure and other accident data, we can extract the main influencing factors of railway operation safety and explore the underlying causes of accidents. Then, according to the analysis results, human errors, machine failures and environmental influences are the main influencing factors, among which the machine failures can be explored from their component structure. Therefore, the boundary conditions of the fault tree for the railway system can be extended to human errors, natural disasters and machine parts. Based on this, we can construct a fault tree logic diagram of the railway system with the aid of logical gates. Note that human errors in this paper are not considered when constructing the fault tree. In fact, human errors account for a high proportion of accidents. This paper mainly focuses on studying the influence of railway system composition on the whole system without considering human errors. For the railway system, the constructed fault trees are respectively shown in Figures 2–9.

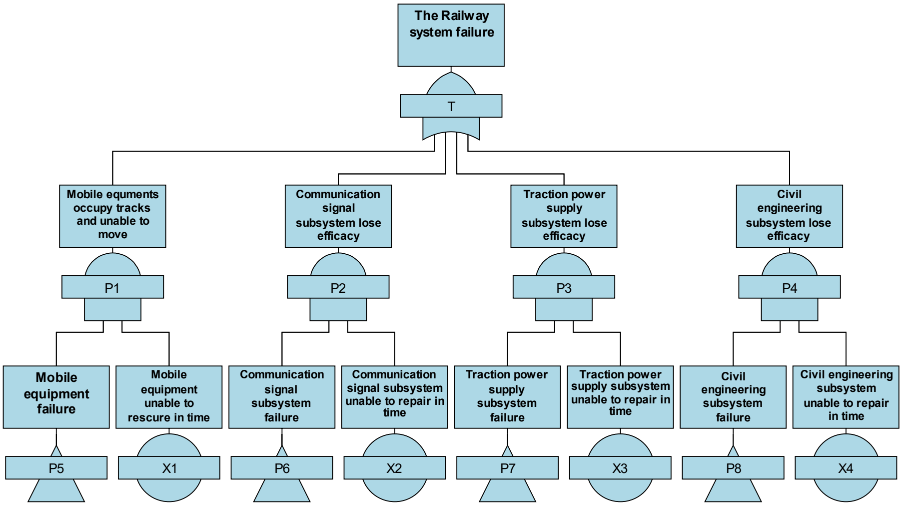


**Figure 2.** The fault tree of railway system. Source: Authors' own work

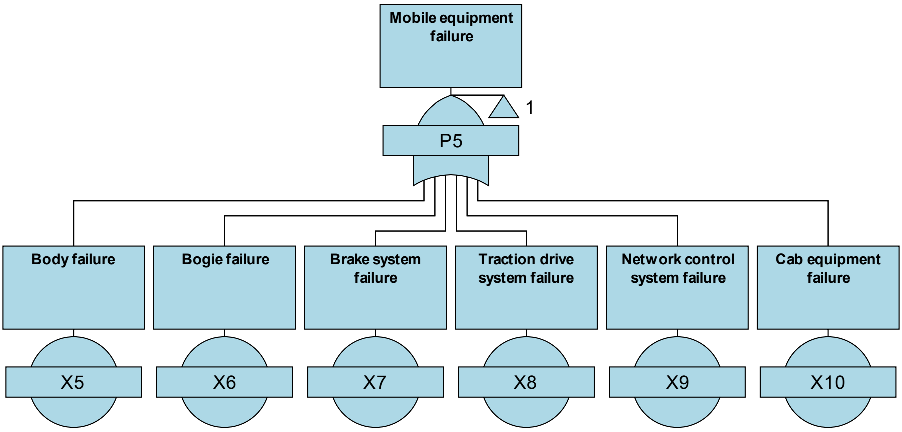


**Figure 3.** The fault tree of mobile equipment. Source: Authors' own work

## 4. Reliability allocation based on the fault tree

Reliability allocation aims to allocate the reliability index of the system to each subsystem and clarify the index requirements of each subsystem so that the reliability index of each subsystem after allocation is more reasonable than before, and then meet the specified system reliability requirements. There are many reliability allocation methods, and the selected allocation indicators are generally failure rate, importance and complexity. In the actual allocation process, it is necessary to consider factors such as economy, convenience and so on, and then choose the best allocation plan to meet the system reliability index with the least economic cost.

The commonly used reliability allocation methods are the equal distribution method, the proportionate consolidation method, the score distribution method, etc. In this paper, we focus on studying the system reliability allocation based on the fault tree and finally allocate the

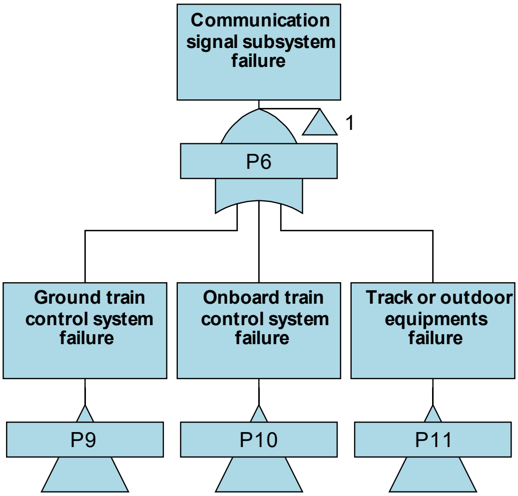


**Figure 4.** The fault tree of communication signal subsystem. Source: Authors' own work

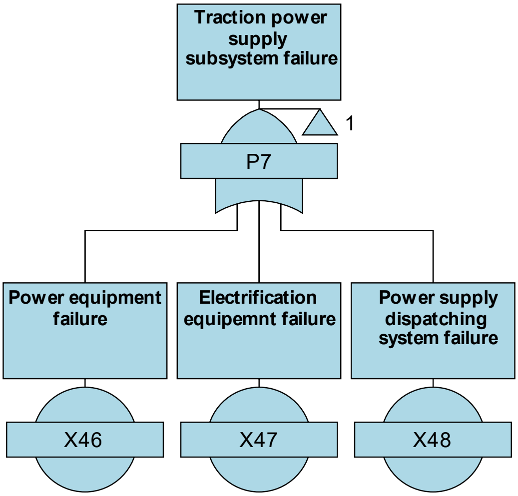


**Figure 5.** The fault tree of traction power supply subsystem. Source: Authors' own work

reliability index to the components of the system. In view of the fact that the failure probability is the most direct evaluation index of the components, the failure probability is selected as the allocation index, resulting in a more intuitive result.

At present, the commonly used reliability allocation methods based on fault tree include the reliability allocation method in the basis of the minimum cut set or the minimum path set and the reliability allocation method on the basis of the minimum workload. Here, the reliability allocation method on the basis of the minimum cut set is to allocate the system reliability index to the minimum cut set and then allocate the reliability between the basic events that constitute the minimum cut set (Xie, 2017). For the railway system, the number of the minimum cut sets in the constructed fault tree is very large. Therefore, the reliability allocation method on the

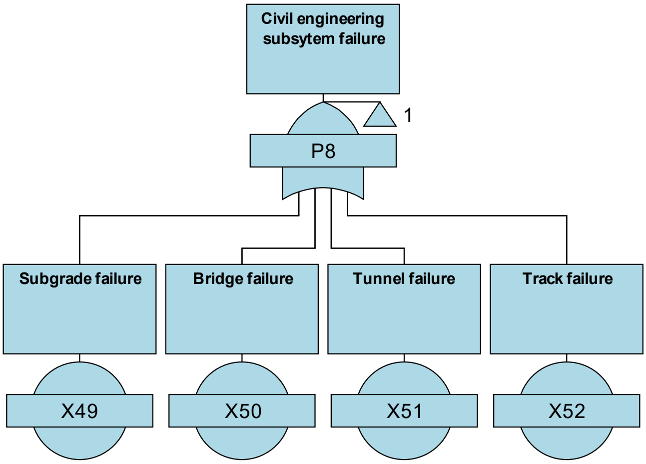


**Figure 6.** The fault tree of civil engineering subsystem. Source: Authors' own work

basis of the minimum cut set will increase the calculation and reduce the efficiency of allocation. The reliability allocation method on the basis of the minimum workload is to allocate the system reliability index layer by layer according to the structure of the fault tree. During this process, the events with the lowest reliability at each layer are selected to allocate to meet the overall reliability index, which can greatly improve the allocation efficiency. However, in the railway system fault tree, it is very important of the second-layer events (the top event is the first-layer). Therefore, if the reliability of events with relatively low reliability is not improved, the allocation result obtained is not optimal.

Based on the above analysis, this paper shall employ the reliability allocation method to allocate the reliability index of the railway system based on the fault tree. For the complex system, the commonly used allocation process firstly allocates the system reliability index to the subsystems and then the subsystem reliability index to the components. However, due to the high reliability of some components, it is difficult to allocate indexes to the components due to the lack of corresponding failure data, and the reliability allocation result still remain in subsystems. Therefore, this paper only studies how to allocate reliability for the top event. Firstly, we need to calculate the importance of the second layer to the top event, and the specific calculation process can be expressed as follows:

$$I_i = \frac{\partial p_s}{\partial p_i}, 1 \leq i \leq n \tag{1}$$

where $p_s$ represents the failure probability of the top event and $p_i$ is the failure probability of the second-layer event. Secondly, assuming that the adjustment failure probability of each event $i$ is $\Delta q_i$, the adjustment failure probability can be expressed as follows (Xie, 2017):

$$\Delta q_1 : \Delta q_2 : \cdots : \Delta q_i : \cdots : \Delta q_n = I_1 : I_2 : \cdots : I_i : \cdots : I_n \tag{2}$$

Then, it is easy to obtain the new failure probability of each event $i$ after allocation, i.e.

$$p_i^* = p_i + \Delta q_i, 1 \leq i \leq n \tag{3}$$

Therefore, assuming that the target system failure probability is $p_s^*$ and the events are independent, according to the structure function of the fault tree and the probability calculation method, the failure probability $p_s^*$ can be easily expressed. If the events and the top event

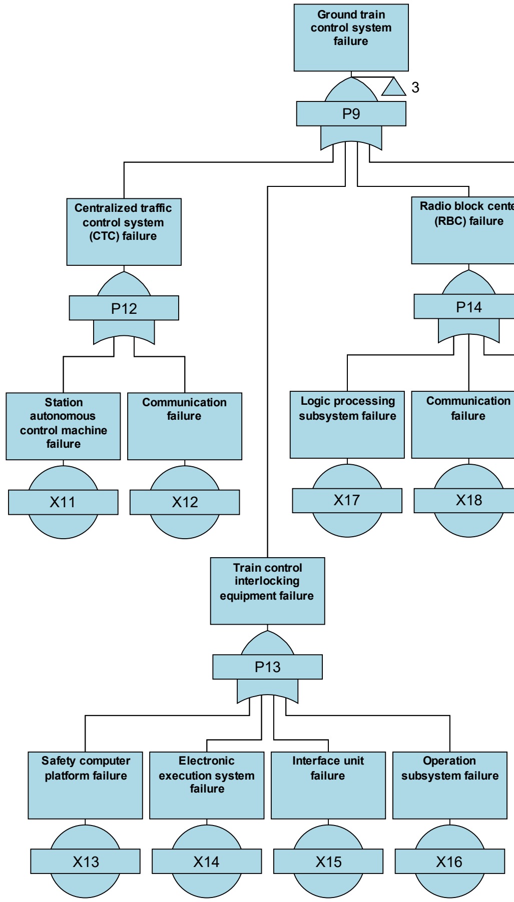


**Figure 7.** The fault tree of ground train control system. Source: Authors' own work

belong to the logical relationship of OR, the failure probability $p_s^*$ satisfies the following condition:

$$p_s^* = 1 - \prod_{i=1}^{n} \left(1 - p_i^*\right) \tag{4}$$

By calculating, we can get the adjustment failure probability of each event and then obtain the failure probability of each event that meets the target reliability.

## 5. Numerical examples

In this section, we will use an example to verify the efficiency of the reliability allocation methods. As we all know, the railway system is a complex system, and its subsystems involve many components. In reality, the failure data of some components are difficult to obtain. Therefore, this paper adopts the reliability allocation method to assign the top event index for the railway system.

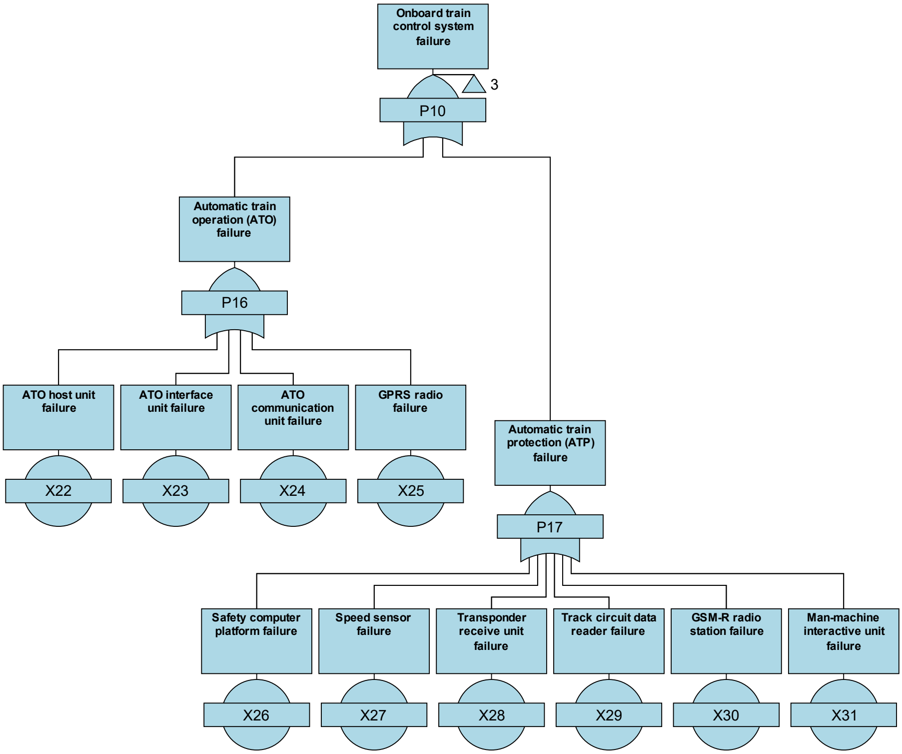


**Figure 8.** The fault tree of onboard train control system. Source: Authors' own work

According to the fault tree constructed in Section 3, taking the railway system failure as the top event $T$, the constructed fault tree structure function can be expressed as

$$T = P1 \cup P2 \cup P3 \cup P4 \tag{5}$$

where $P1$, $P2$, $P3$ and $P4$ are the notations of the mobile equipment subsystem, communication signal subsystem, traction power supply subsystem and civil engineering subsystem. Suppose $P1$, $P2$, $P3$ and $P4$ are independent events and the failure probability of each event is $p_1$, $p_2$, $p_3$ and $p_4$, respectively. Based on the formulated fault tree, the failure probability of the top event can be calculated by giving the failure probabilities of the events. Then, the failure of the top event $T$ can be expressed as:

$$p_T = 1 - \prod_{i=1}^{4} (1 - p_i) \tag{6}$$

In the railway system, we assume that the failure probabilities of the mobile equipment subsystem, communication signal subsystem, traction power supply subsystem and the civil engineering subsystem are $1.2 \times 10^{-4}$, $8.9606 \times 10^{-5}$, $4.6822 \times 10^{-4}$ and $3.6805 \times 10^{-5}$, respectively. Note that the failure probabilities given here are desensitized by multiplying a multiplier. By calculating, the failure probability of top event $T$ is $7.145 \times 10^{-4}$, i.e. the railway system reliability is 99.9286%.

In order to improve the reliability of the railway system, we need to reduce the system failure probability. In this paper, we suppose that the target system failure probability is

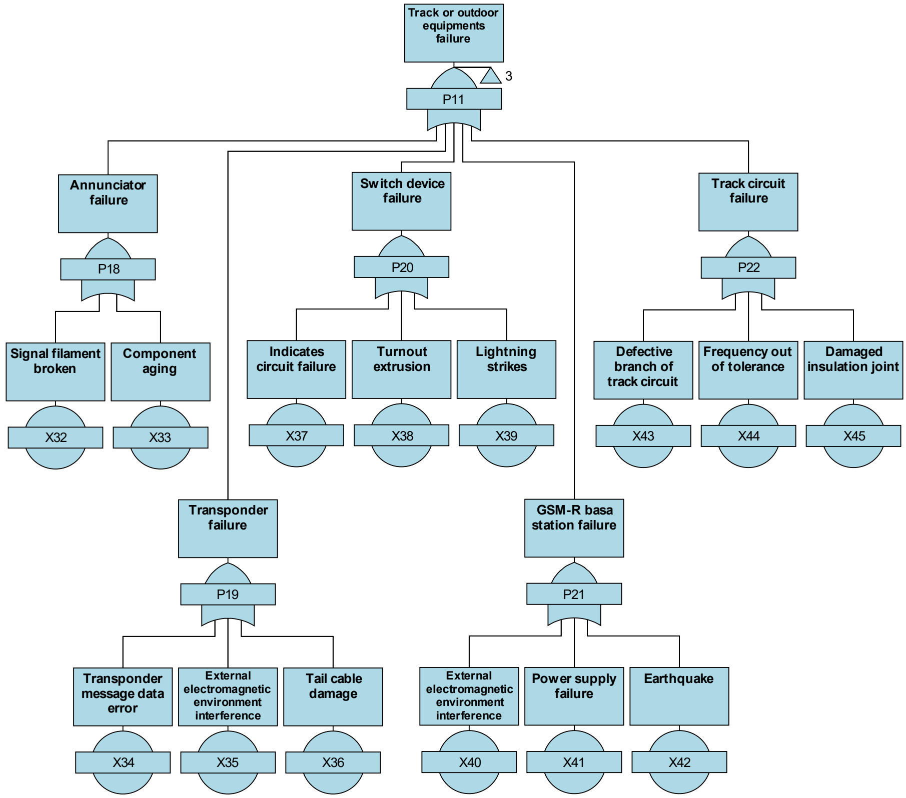


**Figure 9.** The fault tree of track or outdoor equipment. Source: Authors' own work

$P_s^* = 5.9026 \times 10^{-4}$ (the corresponding railway system reliability is 99.9410%), and then we will adopt the reliability allocation method to assign the reliability index to different subsystems.

Based on the probability importance calculation formula, the probability importance of different subsystems to the top event is shown in Table 1.

As can be seen from Table 1, the traction power supply subsystem has the highest importance to the top event, while the civil engineering subsystem has the lowest importance. Therefore, adjusting the failure probability of the traction power supply subsystem has the most obvious change to the top event failure probability and is also the most effective in improving the reliability of the railway system.

**Table 1.** The probability importance of each subsystem

| Notation | Event | Probability importance |
|---|---|---|
| $P1$ | The mobile equipment subsystem failure | 0.99941 |
| $P2$ | The communication signal subsystem failure | 0.99938 |
| $P3$ | The traction power supply subsystem failure | 0.99975 |
| $P4$ | The civil engineering subsystem failure | 0.99932 |

**Source(s):** Authors' own work

Based on the probability importance results and the target system failure probability $P_s^* = 5.9026 \times 10^{-4}$, we redistribute the reliability indexes for different subsystems. According to the reliability allocation method, we formulate the following equations:

$$\begin{cases} \Delta q_1 : \Delta q_2 : \Delta q_3 : \Delta q_4 = 0.99941 : 0.99938 : 0.99975 : 0.99932 \\ p_1^* = p_1 + \Delta q_1 = 1.2\times10^{-4} + \Delta q_1 \\ p_2^* = p_2 + \Delta q_2 = 8.9606\times10^{-5} + \Delta q_2 \\ p_3^* = p_3 + \Delta q_3 = 4.6822\times10^{-4} + \Delta q_3 \\ p_4^* = p_4 + \Delta q_4 = 3.6805\times10^{-5} + \Delta q_4 \\ p_s^* = 1 - \prod_{i=1}^{4}\left(1-p_i^*\right) = 5.9026\times10^{-4} \end{cases} \tag{7}$$

By calculating, the results are shown in Table 2.

According to the results shown in Table 2, we know that in order to improve the reliability of the railway system, the target failure probability of the mobile equipment subsystem, communication signal subsystem, traction power supply subsystem and civil engineering subsystem needs to be adjusted to $8.8926 \times 10^{-5}$, $5.8533 \times 10^{-5}$, $4.1302 \times 10^{-4}$ and $2.9855 \times 10^{-5}$, respectively. Here, the value of failure probability, $8.8926 \times 10^{-5}$ means that the failure frequency of mobile equipment traveling one million kilometers is 8.8926. The value of failure probability $5.8533 \times 10^{-5}$ means that the mean time between failures (MTBF) of the communication signal subsystem is 17,084h. The value of failure probability $4.1302 \times 10^{-4}$ means that the MTBF of the traction power supply subsystem is 2,421h. The value of failure probability $2.9855 \times 10^{-5}$ means that the reliability index of the civil engineering subsystem is 4.0139. To compare the variation of subsystem failure probability, we intuitively show it by Figure 10.

By comparison, it can be seen that the failure probability of each subsystem needs to be adjusted, where the traction power supply subsystem has the largest failure probability adjustment. Simultaneously, the failure probability adjustment amount of each subsystem is negative, indicating that each subsystem needs to improve its reliability to meet the specified railway system reliability requirements.

Since then, this numerical example has achieved the reliability calculation of the railway system and the reliability allocation from the railway system layer to the subsystem layer. In practical applications, interested scholars can further study the reliability allocation from the subsystem layer to the component layer and the part layer.

Note that most of the existing studies calculate the failure probability of top-level events based on constructed fault trees and then evaluate the reliability of systems or subsystems. Or carry out reliability allocation for a certain subsystem or a key component. And these two parts are independently researched. This paper combines the two parts of research content for the first time, achieving bottom-up system reliability calculation and top-down reliability allocation.

**Table 2.** The reliability allocation results of the railway system

| Notation | Event | The current subsystem failure probability | The target subsystem failure probability |
|---|---|---|---|
| *P*1 | The mobile equipment subsystem failure | $1.2 \times 10^{-4}$ | $8.8926 \times 10^{-5}$ |
| *P*2 | The communication signal subsystem failure | $8.9606 \times 10^{-5}$ | $5.8533 \times 10^{-5}$ |
| *P*3 | The traction power supply subsystem failure | $4.6822 \times 10^{-4}$ | $4.1302 \times 10^{-4}$ |
| *P*4 | The civil engineering subsystem failure | $3.6805 \times 10^{-5}$ | $2.9855 \times 10^{-5}$ |

**Source(s):** Authors' own work

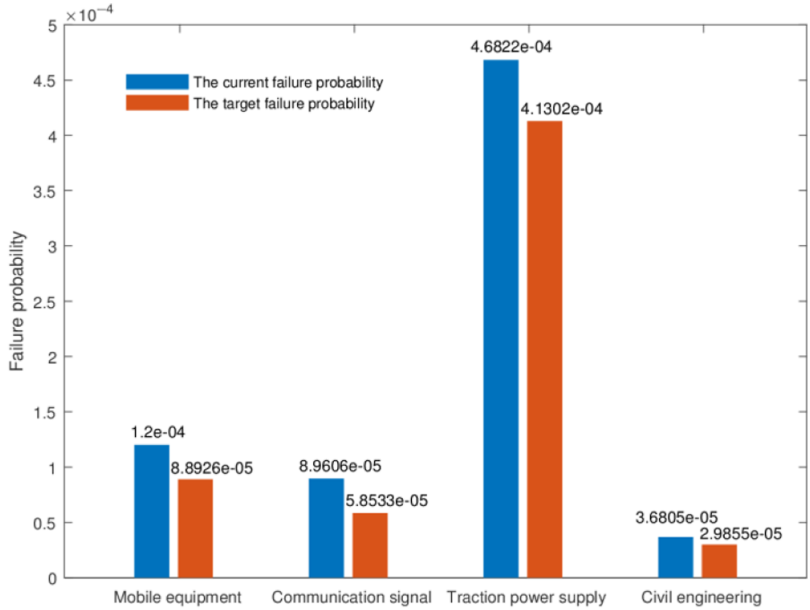


**Figure 10.** The variation of subsystem failure probability. Source: Authors' own work

This two-way closed-loop analysis framework enables the overall coordination of system reliability requirements, thereby providing a basis for the reliability design of railway systems.

## 6. Conclusions

As a complex system, this paper firstly discussed the composition structure of the railway system and analyzed the dynamic interactions between subsystems via their interfaces. To ensure the safe and reliable operation of a railway, a fault tree is constructed based on its components. Then, based on the fault tree, this paper introduced the reliability allocation method into the railway system for the first time, achieving the overall allocation of the reliability of each subsystem at the system level and meeting the specified railway system reliability requirements. Here, in view of the failure probability is the most direct evaluation index of the subsystem, the failure probability is selected as the allocation index. Finally, through giving the target system failure probability, we allocated the reliability index to each subsystem. The results showed that each subsystem needs to improve its reliability to meet the specified railway system reliability requirements and the traction power supply system is the most important subsystem, which is the most efficient in improving the reliability of the railway system.

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**Corresponding author**
Jiaxu Chen can be contacted at: chenjiaxu168@163.com

**Jiaxu Chen** serves as an Assistant Researcher at the China Academy of Railway Sciences Corporation Limited. His primary focus is on research concerning railway system safety risk analysis and evaluation, integrated design, analysis, and modeling of railway RAMS (Reliability, Availability, Maintainability, and Safety), as well as railway system integration and comprehensive support technologies. He has been awarded the First Prize of the Science and Technology Award from the China Academy of Railway Sciences Corporation Limited and the 8th National Railway Youth Science and Technology Innovation Award.