State-based risk frequency estimation of a rail traffic signal system

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Abstract

The rail traffic signal system is a safety-related system. According to the strict requirement of safety, the use of international safety standards it requires in order to carry out the systemic safety assessment. Risk frequency estimation plays a key role in the process of risk-based safety assessment. Thus in this paper, firstly, the existing risk frequency analysis methods are studied, then a state-based fault tree model based on the original fault tree model and Markov stochastic process model is proposed. After that, the state-based risk frequency estimation flow of the rail traffic signal system is summarized. Lastly, we give an example of the micro-computerized automatic block system between railway stations with the wrong cancelling block. Then the state-based fault tree model is established and its risk frequency quantitatively calculated. The method can analyse the risk frequency of rail traffic signal systems scientifically and accurately and solve the quantitative analysis issues of risk frequency in dynamic random systems effectively.

Keywords: state-based, risk frequency, rail traffic signal system, fault tree model, Markov stochastic process model.

1 Introduction

The rail traffic signal system is a safety-related system [1] and it takes charge of the safety of rail traffic system operation. The traditional method to guarantee the safety of the rail traffic signal system is based on technique specifications and safety design, which have played a positive role. However, with the development of high-speed railways and the microelectronics, computers, communications and other modern information technology that is widely used, the traditional

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method has some problems in guaranteeing the safety of the rail traffic signal system systemically and effectively. The international standard commission has made a series of safety standards (Yan and Tang [2], Gao [3]), such as IEC61508 and EN5012X. Moreover, it has formed a scientific system of safety assessment, accreditation and management, which is more systemic, comprehensive and effective than the traditional method. Nowadays, the risk-based safety assessment is one of the most important means to achieving security control in many fields, such as rail traffic, the nuclear industry, chemical industry, oil pipelines and so on, which use the systemic, comprehensive risk identification, analysis and control technology. It proves to be more scientific and effective in the protection of the safety. In terms of risk frequency estimation, it plays a key role in the process of risk-based safety assessment. Through the establishment of a safety analysis model and appropriate techniques, the risk frequency can be analyzed qualitatively or calculated quantitatively. In the field of system safety analysis, there are many techniques, tools and methods that can be applied to analyze the risk frequency (Zhang and Guo [4]), such as the expert scoring method, fault tree analysis (FTA), event tree analysis (ETA) and so on.

However, the existing risk frequency analysis methods have a common problem; they do not take the changes of system states into account carefully and cannot analyze the risk frequency of a dynamic stochastic system accurately. Specifically, in rail traffic signal systems, such as the micro-computerized automatic block system between railway stations, the system states change in real-time. Besides, the system risk is different in various working states. Thus, taking the system dynamic characteristics into account will make the risk analysis more effective and accurate. This paper proposed the state-based fault tree model based on the original fault tree model and Markov stochastic process model. Taking the micro-computerized automatic block system between railway stations with the wrong cancelling block as an example, the paper established the state-based fault tree model and calculated its risk frequency quantitatively.

2 The micro-computerized automatic block system between railway stations

The micro-computerized automatic block system between railway stations is based on axle counter technology, section block technology, a computer network and modern control technology (Zou et al. [5], Guo [6]). It integrates the separate section block equipment and the axle counter equipment into the same system to realize joint operation control of station interlocking, section block and the section occupation/clearing. The micro-computerized automatic block system between railway stations can improve transport efficiency and protect the safety of the rail traffic system further. It is important to improve the modernization and information level of China’s rail traffic signal equipment and the development direction of the single-line railway. The structure of the micro-computerized automatic block system between railway stations is shown in figure 1.

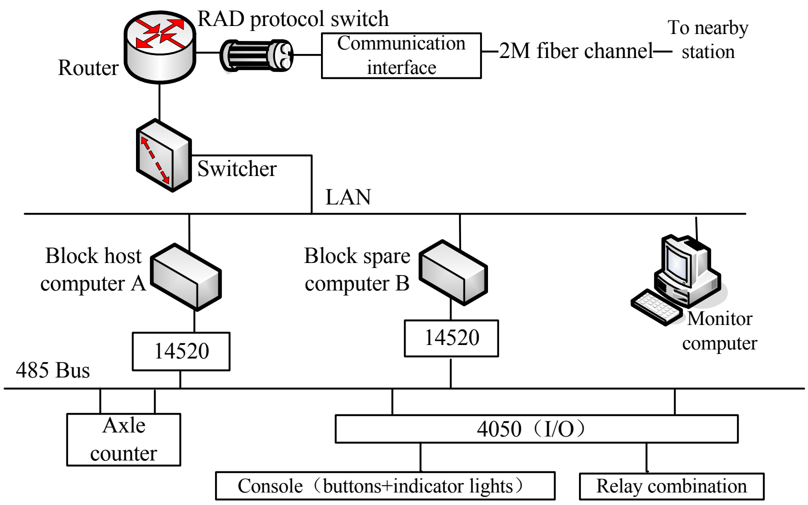

Figure 1: The structure of the micro-computerized automatic block system between railway stations.

3 Safety analysis model

3.1 Fault tree analysis (FTA)

The fault tree [7] is one important kind of graphical interpretation method for the quantitative safety analysis of complex systems and it is used to model the logical interrelationships between numbers of events that could combine in sequence to give rise to a particular undesirable outcome. FTA begins with a single undesired top event and provides a method for determining all the possible causes of that event. A correctly constructed fault tree is a graphical and logical model of the various parallel and sequential combinations of events that will result in the occurrence of the top event. The system is analyzed, from the identified top events, in the context of its hardware, software, environment, human factor and modes of operation, to find all credible causal events. The fault tree is made up of gates, which serve to permit or inhibit the flow of fault logic up the tree. The gates show the relationship of lower events – the inputs to the gate – needed for the occurrence of a higher event – the output of the gate. The fault tree is used to produce the minimal cut sets – the minimum combination of independent base events that, if they occur or exist at the same time, will cause the top event to occur. The minimal cut sets provide the basis for both the qualitative and quantitative analysis of the system. It can calculate the frequency of the top event with the minimal cut sets and the basic failure data. Taking the micro-computerized automatic block system between railway stations as an example, here the paper first uses the BlockSim 7 of the American Reliasoft company to establish the fault tree model of the wrong cancelling block without consideration of system states changing. The fault tree model is shown in figure 2.

The failure data of basic events in the fault tree model of the wrong cancelling block are shown in table 1.

It can calculate the risk frequency of the wrong cancelling block using the failure data of basic events and the fault tree model. The result is 0.91 times/y.

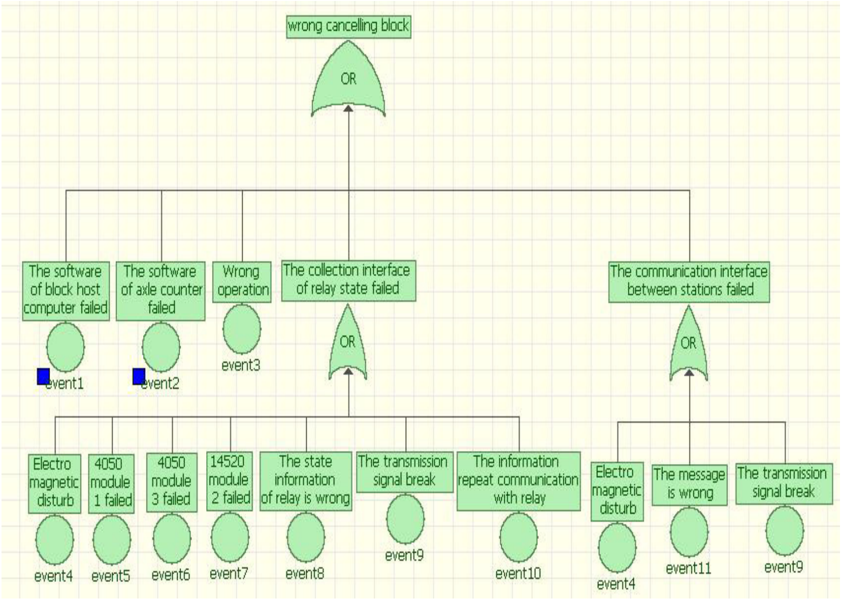

Figure 2: The fault tree model of the wrong cancelling block.

Table 1: The failure data of basic events.

Number	Basic event	Failure frequency
Event1	The software of block host computer failed	SIL4
Event2	The software of axle counter failed	SIL4
Event3	Wrong operation	0.5 times/y
Event4	Electromagnetic disturb	0.1 times/y
Event5	4050 module 1 failed	0.05 times/y
Event6	4050 module 3 failed	0.05 times/y
Event7	14520 module 2 failed	0.05 times/y
Event8	The state information of relay is wrong	0.1 times/y
Event9	The transmission signal break	0.02 times/y
Event10	The information repeat communication with	0.02 times/y
Event11	The message is wrong	0.02 times/y

3.2 Markov stochastic process model

The Markov stochastic process model (Li [8]) is widely used in modern control theory. Supposing that $\{X(t), t \in T\}$ is a stochastic process and E is its states space, if for any $n \geq 1$, any $t_1 < t_2 < \ldots < t_n < t \in T$, any $x_1, x_2, \ldots, x_n, x \in E$, and it satisfies eqn (1).

$$P\left\{X(t) = x \,\middle|\, X(t_n) = x_n, \ldots, X(t_1) = i_1\right\} = P\left\{X(t) = x \,\middle|\, X(t_n) = x_n\right\} \tag{1}$$

Then $\{X(t), t \in T\}$ can be called the Markov process. The state of stochastic variable X(t) is only related with the state of $X(t_n)$ and has nothing to do with its previous state. This can be called the Markov characteristic. In the familiar stochastic process, the independent stochastic process and the independent increment stochastic process all meet the Markov characteristic. It can calculate the steady probability of system states using the Markov stochastic process model and the detailed approaches are summarized as follows.

- Define the Markov stochastic process $\{X(t), t \in T\}$ and its state space E.
- Establish the system state transition diagram.
- According to the system state transition diagram, establish the P matrix and the system state transition probability matrix A. A=P-I (I: identity matrix).
- Calculate (sI-A) and $(sI-A)^{-1}$, and establish the system initial state P(0).
- According to the P(0) and $(sI-A)^{-1}$, calculate the P(s).

$$P(s) = P(0)(sI - A)^{-1} \tag{2}$$

Then, perform the Laplace transform separately on both sides of eqn (2). This can acquire the instantaneous probability of system states. $P(t) = [P_1(t) \;\; P_2(t) \;\; P_3(t)\ldots]$.

- According to $P(t) = [P_1(t) \;\; P_2(t) \;\; P_3(t)\ldots]$, it can calculate the steady probability of system states ($t \to \infty$), $P(\infty) = [P_1(\infty) \;\; P_2(\infty) \;\; P_3(\infty)\ldots]$.

4 State-based risk frequency analysis

This analysis can establish the system Markov model and calculate the steady probability of system states through analyzing the rail traffic signal system. Based on the primary fault tree model and system states, it can establish the state-based system fault tree model. The overall flowchart of state-based risk frequency quantitative estimation is shown in figure 3.

4.1 The Markov state transition model of the micro-computerized automatic block system between railway stations

There are five kinds of states in the micro-computerized automatic block system between railway stations. The definition of system states are as follows: 0-Reset; 1-Request block; 2-Establish block; 3-Block; 4-Train arrived. Defining X(t)=j,

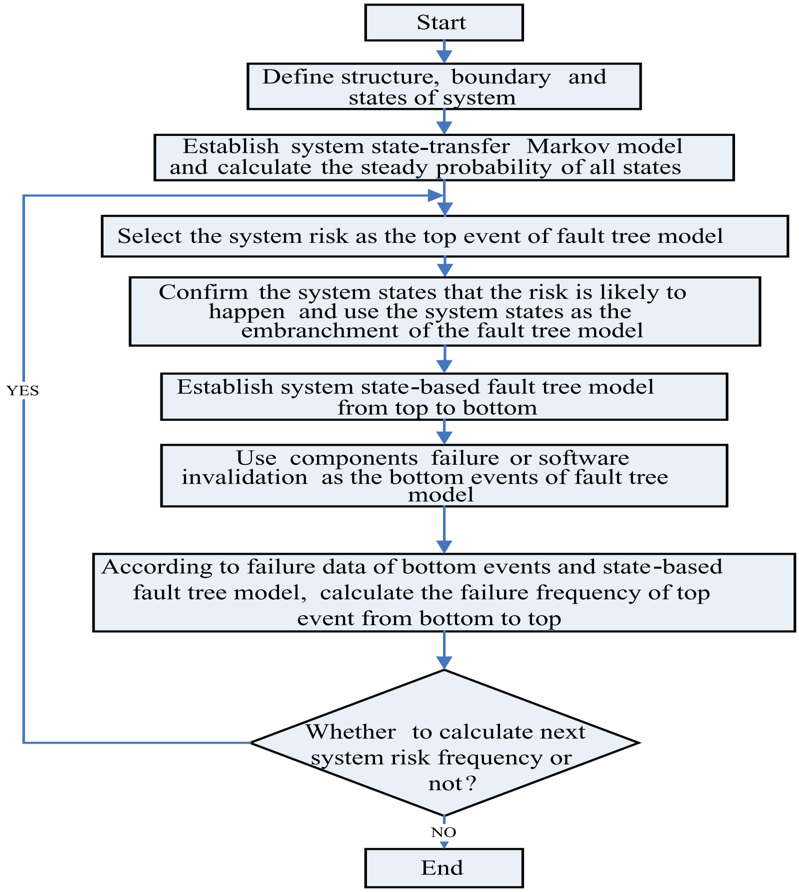

Figure 3: The flowchart of state-based risk frequency quantitative estimation.

the system is in the state j when at time t, j∈E={0,1,2,3,4}; E is the system state space. The system state transition diagram is established through analyzing the micro-computerized automatic block system between railway stations. (Suppose that the transit ability between two stations is 50 pairs one day.) The system state transition diagram is shown in figure 4.

According to the system state transition diagram, the P matrix can be calculated as

$$P = \begin{bmatrix} 0.208 & 0.792 & 0 & 0 & 0 \\ 0.026 & 0.014 & 0.96 & 0 & 0 \\ 0.046 & 0 & 0.014 & 0.94 & 0 \\ 0 & 0 & 0 & 0.556 & 0.444 \\ 0.792 & 0 & 0 & 0 & 0.208 \end{bmatrix}$$

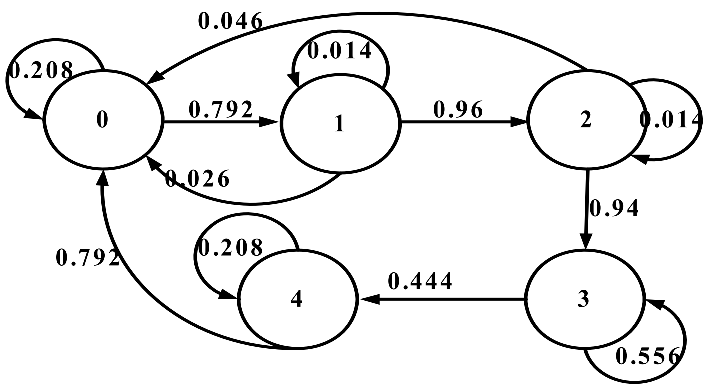

Figure 4: The state transition diagram of the micro-computerized automatic block system between railway stations.

According to the P matrix, it can calculate the system state transition probability matrix A.

$$A = P - I = \begin{bmatrix} -0.792 & 0.792 & 0 & 0 & 0 \\ 0.026 & -0.986 & 0.96 & 0 & 0 \\ 0.046 & 0 & -0.986 & 0.94 & 0 \\ 0 & 0 & 0 & -0.444 & 0.444 \\ 0.792 & 0 & 0 & 0 & -0.792 \end{bmatrix}$$

The initial state of system is reset, so P(0) = [1 0 0 0 0].

The detailed approaches to calculate the system states steady probability are summarized as section 3.2 and it can use MATLAB to calculate. The steady probabilities of system states are: $P_0(\infty)$=0.194, $P_1(\infty)$=0.155, $P_2(\infty)$=0.151, $P_3(\infty)$=0.321, $P_4(\infty)$=0.179.

4.2 State-based fault tree model

In order to analyze the risk frequency of the dynamic stochastic system more scientifically and accurately, one can combine the primary fault tree model and the system states to establish the state-based fault tree model. Taking the micro-computerized automatic block system between railway stations as an example, here the paper uses the BlockSim 7 of American Reliasoft company to establish the state-based fault tree model of the wrong cancelling block. The fault tree model is shown in figure 5.

The failure data of basic events in the state-based fault tree model are the same as table 1. According to the failure data of basic events, the steady probability of system states and the state-based fault tree model of the wrong cancelling block, it can calculate the risk frequency of the wrong cancelling block. The result is 0.455 times/y.

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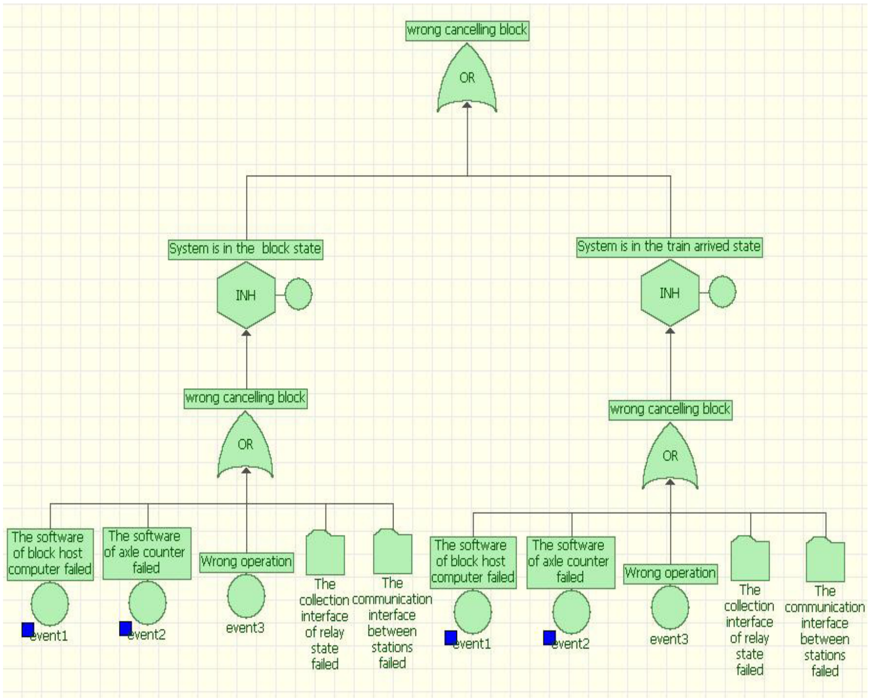

Figure 5: The state-based fault tree model of the wrong cancelling block.

Comparing the state-based fault tree model with the primary fault tree model, it can be seen that the state-based fault tree model is more scientific and accurate than the primary fault tree model in analyzing the risk frequency of the dynamic stochastic system.

5 Conclusions

Through studying the risk-based safety assessment theory and technology in the field of rail traffic signal systems, this paper proposed the state-based fault tree model to calculate the risk frequency based on the primary fault tree model and Markov model. In addition, taking the micro-computerized automatic block system between railway stations as an example, the paper established the primary fault tree model and state-based fault tree model of the wrong cancelling block. Comparing the state-based fault tree model and the primary fault tree model, it can be seen that the state-based fault tree model is more scientific and accurate than the primary fault tree model in analyzing the risk frequency of the dynamic stochastic system. In addition, it can guarantee the safety of the rail traffic signal system more effectively by adopting the state-based fault tree model.

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