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Yan-Feng LI
Jinhua MI
Hong-Zhong HUANG
Shun-Peng ZHU
Ningcong XIAO

FAULT TREE ANALYSIS OF TRAIN REAR-END COLLISION ACCIDENT CONSIDERING COMMON CAUSE FAILURE

ANALIZA DRZEWA USZKODZEŃ DLA KOLIZJI TYLNEJ CZĘŚCI SKŁADU POCIĄGU Z UWZGLĘDNIENIEM USZKODZENIA SPOWODOWANEGO WSPÓLNĄ PRZYCZYNĄ

Along with the development of modern design technology and the increasing complication of modern engineering systems, component dependency has become a universal phenomenon during the failure analysis of systems. Ignoring the dependency among the failure behaviors of system components may lead to a huge error or even yield faulty results. In this paper, three types of models and two kinds of modeling methods are introduced for solving the common cause failure issues. The fault tree model of the train rear-end collision accident has been proposed based on the explicit modeling method. The probability of occurrence of the train rear-end collision accident is calculated using the square root model. The result shows that common cause failure has significant influences on the system reliability.

Keywords*: common cause failure, train rear-end collision accident, fault tree analysis.*

Wraz z rozwojem nowoczesnych technologii projektowania i rosnącej komplikacji nowoczesnych systemów inżynierskich, zależność między komponentami stała się zjawiskiem powszechnym w analizie uszkodzeń systemów. Ignorowanie zależności między zachowaniami uszkodzeniowymi komponentów systemu może doprowadzić do ogromnego błędu, a nawet dać całkowicie błędne wyniki. W niniejszej pracy, przedstawiono trzy typy modeli i dwa rodzaje metod modelowania służących do rozwiązywania typowych problemów związanych z uszkodzeniami spowodowanymi wspólną przyczyną. Zaproponowano model drzewa uszkodzeń dla kolizji tylnej części składu pociągu w oparciu o metodę modelowania bezpośredniego. Prawdopodobieństwo wystąpienia kolizji tylnej części składu pociągu obliczono przy użyciu modelu pierwiastka kwadratowego. Wynik pokazuje, że uszkodzenie spowodowane wspólną przyczyną ma znaczący wpływ na niezawodność systemu.

Słowa kluczowe*: uszkodzenie spowodowane wspólną przyczyną, kolizjatylnej części składu pociągu, analiza drzewa uszkodzeń.*

1. Introduction

Along with the increasing complexity and redundancy of modern engineering systems, the issue of independent failure of components is dwindling while the dependent failure is becoming more pronounced. In engineering, the dependency is a general characteristic of system failures. Implementing the quantitative analysis of fault tree under the assumption of independence between basic events as well as ignoring the relationships between them generally leads to a huge uncertainty or even lead to erroneous results.

Common cause failures (CCFs) have been an important issue in reliability analysis for several decades, especially when dealing with complex systems, as CCFs often dominate random hardware failures. Systems affected by CCFs are systems in which two or more events have the potential of occurring due to the same cause. Since the 1970s, different approaches have been used to describe the CCFs, such as a β-factor model [6], basic parameter (BP) model [19], the multiple Greek letter (MGL) model [7], α-factor model [13], and square-root model [8]. However, the issues on CCFs are still the focus of much research and there does not exist a general consensus as to which method is more suitable for dealing with CCFs. Several case studies in control system, complex computer system, and transmission system have been investigated using these models in [4, 9, 10, 21–23, 26]. For the analysis of rear-end crashes, Das et al. [5] applied the genetic programming modeling approach in safety research for crash count and severity classification, which provides independence for model development without restrictions on the distribution of data. Milho et al. [12] proposed and validated a multi-body dynamics based procedure for the design of energy absorbing structures and train collision scenarios. In this methodology, the moving components of a vehicle are described as sets of rigid bodies, with their relative motion constrained by kinematic joints. In recent years, the Federal Railroad Administration has been conducting research on passenger rail equipment crash worthiness to develop technical information [14, 18]. The passenger rail equipment crash worthiness research is focused on the development of structural crash worthiness and interior occupant protection tactics, whose results have been used in the development of railroad procurement specifications [16, 17] and industry standards [1, 2]. Tyrell et al. [15] conducted a full-scale train-to-train impact test of crash energy management to establish the degree of the enhanced performance of alternative design strategies for passenger rail crashworthiness. Though most efforts have been put forward on the safety of structural crashworthiness and/or passenger rail crashworthiness, they cannot accurately be used for safety and reliability assessment

of railway vehicle, further research on the fault tree analysis of train rear-end collision accident is expected.

Thus, the purpose of this paper is to incorporate common-cause failures into the fault tree analysis of train rear-end collision accident. It attempts to offer a basis for safety and reliability assessment of railway vehicle. This paper consists of 5 sections. In the rest sections, the existing models for CCF modeling are briefly introduced in Section 2. Two CCF modeling methods are presented in Section 3. Fault tree analysis of train rear-end collision accident considering CCF has been put forward in Section 4 and it is followed by a brief conclusion in Section 5.

2. Existing models for CCF modeling

2.1. Basic parameter model

Supposing a system is comprised of three components: A, B, and C. The total failure probability of component A includes the probability of independent failure of component A and the failure probability of dependent component B or C or both B and C while component A fails. Let A_I, B_I and C_I denote the independent failure events of components A, B and C, respectively. $P(A_I)$, $P(B_I)$ and $P(C_I)$ represent the failure probability of A_I, B_I and C_I . Thus, the total failure probability of A, B and C can be calculated respectively as follows.

$$P(A)=P(A_I)+P(AB)+P(AC)+P(ABC) \tag{1}$$

$$P(B)=P(B_I)+P(AB)+P(BC)+P(ABC) \tag{2}$$

$$P(C)=P(C_I)+P(AC)+P(BC)+P(ABC) \tag{3}$$

For the common cause component group composed of A, B and C, supposing that the components are statistically identical, the failure probability of any components can be expressed as:

$$Q_I=\sum_{k=1}^{3}\binom{3-1}{k-1}Q_k \tag{4}$$

where Q_k denotes the simultaneous failure probability of any k components.

Similarly, for a system composed of m components, the total failure probability of the system can be obtained as:

$$Q_I=\sum_{k=1}^{m}\binom{m-1}{k-1}Q_k \tag{5}$$

where Q_I denotes the failure probability of the system which composed of m components, Q_k represents the simultaneous failure probability of any k components.

2.2. The β-factor model

The β-factor Model is one of the most commonly used CCF models, which was originally proposed by Fleming [6]. It assumes that a certain percentage of all failures are CCFs. The strength of common cause failure in this model is quantified by β factor. The β-factor model is initially targeted for two-component parallel system. Two categories of failure are taken into account within the CCF model, that is, the independent failure of a certain component itself and the common cause failure. The total failure probability of a component is composed of two parts, the probability of independent failure denoted by Q_1, and the common cause failure denoted by Q_2. Then the common cause factor β is the fraction of the total failure probability attributable to dependent failures [3]:

$$\beta=\frac{Q_2}{Q}=\frac{Q_2}{Q_1+Q_2} \tag{6}$$

The value β can also be obtained by the conditional probability that there is a CCF given that there is a failure, which is expressed as:

$$\beta=P\left(\mathrm{CCF}\middle|\mathrm{Failure}\right) \tag{7}$$

This model is commonly used for its easy comprehension. The parameter value is based on engineering experience and the published statistics of CCF, and the range of β-factor is from 0 to 0.25 [3].

2.3. The Square-Root model

The square-root method is a simple bounding technique used to estimate the effect of CCFs on a system [8]. Consider a parallel system consisting of two components A and B. A_F, B_F, $A_F \cap B_F$ are the failure events of components A, B and the system, respectively. Then the unavailability of the system is defined as

$$P(A_F \cap B_F)\le P(A_F),\ P(A_F \cap B_F)\le P(B_F) \tag{8}$$

which also can be expressed as $P(A_F \cap B_F)\le \min\{P(A_F), P(B_F)\}$.

If A and B are dependent, we can get

$$P(A_F \cap B_F)=P(A_F|B_F)P(B_F)\ge P(A_F)P(B_F) \tag{9}$$

Let $a= P(A_F)P(B_F)$ and $b= \min\{P(A_F), P(B_F)\}$, the square-root CCF model is then approximated using the geometric mean of a and b as follows

$$P(A_F \cap B_F)=\sqrt{ab} \tag{10}$$

Similarly, for a n-component parallel system, the upper and lower limit of the unavailability can be obtained by

$$a=\prod_{i=1}^{n}P(A_i),\ b=\min\left\{P(A_1),P(A_2),\cdots,P(A_n)\right\} \tag{11}$$

In this paper, the square-root model is used to analyze the impact of CCF on the train rear-end collision accident.

3. Common cause failure modeling method

When dealing with the common cause failure, there are mainly two kinds of modeling methods for fault tree analysis with CCF, namely, implicit modeling and explicit modeling [25]. A fault tree is a well-arranged method of modeling the failure of a top event. The failure of a top event depends on other basic components. The dependencies between the components are modeled in a tree structure using AND- or OR-gates. The CCF part is not considered during the process of system reliability analysis only after it to get the probability of occurrence of the top event for the implicit method, while within it for the explicit method.

3.1. Implicit modeling for CCF

The implicit CCF model of a parallel system with 3 units (A, B and C) can be depicted as shown in Fig. 1. Using T represents the event "system failure", and "T_1" is the intermediate event that means "System failure without considering the impact of CCF".

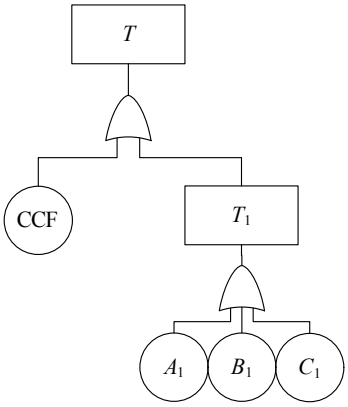

Fig. 1. Implicit model of CCF

Where the failure of each system unit is composed of its internal failure of a component (denoted as A1, B1 and C1) and CCF.

3.2. Explicit modeling of CCF

Suppose that the failure of each system unit is composed of its internal failure of a component (denoted as A_1, B_1 and C_1) and the common cause failure (A_2, B_2 and C_2), T is the event of "system failure". The explicit model of a parallel system with 3 units (A, B and C) can be depicted as shown in Fig. 2.

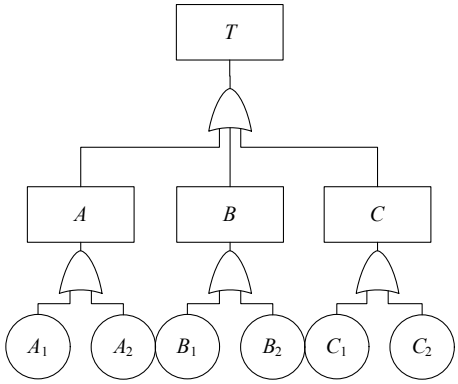

Fig. 2. Explicit modeling of CCF

From Fig.2, the system failure is directly caused by individual component failures, and the difference of explicit method and implicit method is the former considering the CCF in component failure event and the latter in whole system.

4. Fault tree analysis of train rear-end collision accident considering CCF

4.1. Fault tree modeling of train rear-end collision accident

On condition that the single-track has only one railway, and assuming that the collision avoidance systems, such as a signal lamp control system, distance control system, train state communication and control system as well as the dispatching center danger warning systems, are put into use [11]. Fault tree analysis is one of the most important logic and probabilistic techniques used in system reliability assessment [24]. The faults can be events that are associated with component hardware failures, human errors, software errors, or any other pertinent events. A fault tree depicts the logical interrelationships of basic events that lead to the top event of the fault tree. The top event of the fault tree is the event for which the failure causes will be resolved and the failure probability determined. It defines the failure mode of the system that will be analyzed. A fault tree analysis (FTA) should be carried out through the following steps [20]: 1) identify the objective for the FTA; 2) define the top event, scope, resolution, ground rules of the fault tree; 3) construct and evaluate the fault tree; 4) interpret and present the results. The fault trees of train rear-end collision accident are shown in Fig. 3 – Fig. 5 and the codes and names of basic events are showed in Table 1.

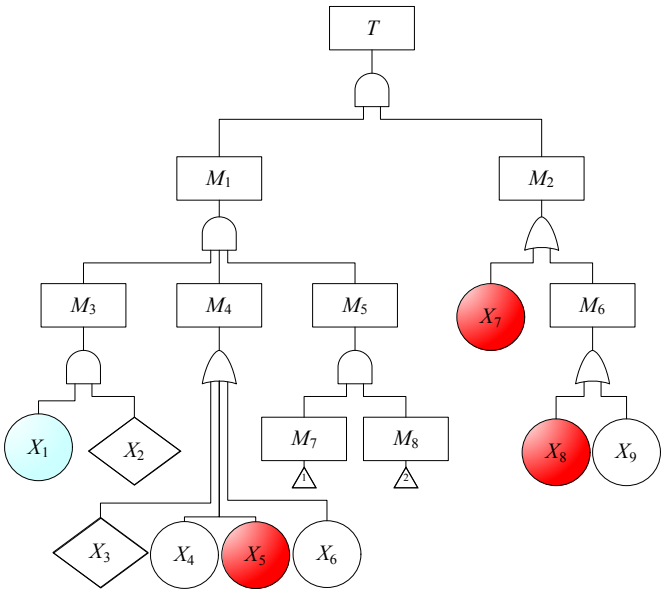

Fig. 3. The fault tree of train rear-end collision accident

4.2. Qualitative analysis

According to Fig. 3 – Fig. 5, the structure function of fault tree for the train rear-end collision accident can be obtained as follows:

$$\Phi(X) = X_1 \cdot X_2 \cdot (X_3 + X_4 + X_5 + X_6) \cdot (X_{10} + X_{11} + X_{12} + X_{13} + X_{14}) \cdot (X_{15} + X_{16} + X_{17} + X_{18} + X_{19}) \cdot (X_{20} + X_{21} + X_{22} + X_{23} + X_{24}) \cdot ((X_{28} + X_{29} + X_{30} + X_{31}) \cdot (X_{33} + X_{34} + X_{35}) + X_{32} + X_{25} + X_{26} + X_{27}) \cdot (X_7 + X_8 + X_9) \quad (12)$$

From Eq. (12), the train rear-end collision event has totally 1×1×4×5×5×5×(4×3+4)×3=24000 failure modes, and there are 192

Table 1. The codes and names of basic events

Code	Event name	Code	Event name	Code	Event name
T	Train rear-end accident	X_1	Two trains are assigned on the same railway interval	X_{19}	Distance decision and control of back-train failure
M_1	Condition of rear-end existing	X_2	Only one rail on the same direction in this interval	X_{20}	Missing or error of Front-train state signal
M_2	Driver cannot avoid by braking	X_3	Dispatch order error	X_{21}	Human decision and control failure
M_3	Two trains on the same rail	X_4	Front-train stopped or crawling	X_{22}	Back-train did not receive the exact signal of front-train
M_4	Back-train faster than Front-Train	X_5	Driver break the order	X_{23}	Train state communicate and control error by environment
M_5	Collision avoidance system failure	X_6	Brake system abnormal	X_{24}	Back-train state decision and control failure
M_6	Driver brake fails	X_7	Driver unnoticed the danger	X_{25}	Too late to dispose the danger
M_7	Collision avoidance system failure	X_8	Too late to brake on visual distance	X_{26}	Improper disposition of danger
M_8	Manual intervention fails	X_9	Brake system failure	X_{27}	Dispatcher off-site
M_9	Signal lamp failure	X_{10}	Data acquisition of location error	X_{28}	Danger warning system has been closed
M_{10}	Distance control system failure	X_{11}	Error signal caused by human	X_{29}	Danger warning system did not get the accuracy data
M_{11}	Communicate and control system failure	X_{12}	Data acquisition logical error	X_{30}	The defect of danger distinguish software
M_{12}	Dispatcher is not aware of the danger	X_{13}	Error signal by environment	X_{31}	The irrational of the danger warning pattern
M_{13}	Dispatcher on-site but unwitnessed the danger	X_{14}	Signal output error	X_{32}	Abstracted of dispatcher
M_{14}	Danger warning measures failure	X_{15}	Mistake get target location	X_{33}	Information overload, task complicated
M_{15}	Human monitoring undetected the danger	X_{16}	Control order did not carry out exactly	X_{34}	Lack of experience
M_{16}	Danger warning system undetected the danger	X_{17}	Distance computing error	X_{35}	Unreasonable human-computer interface
M_{17}	Unnoticed the warn of the danger warning system	X_{18}	Distance control error by environment		

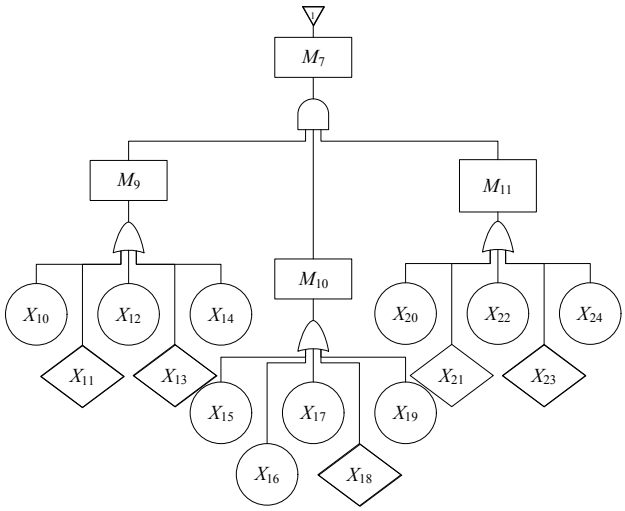

Fig. 4. Fault tree of the event "collision avoidance system failure"

failure modes even without subdividing the collision avoidance system. The level of detail FTA has direct influence on the quantity of these failure modes.

Due to the long event chain of the train rear-end collision accident, Eq. (12) shows that each failure mode occurs only when there

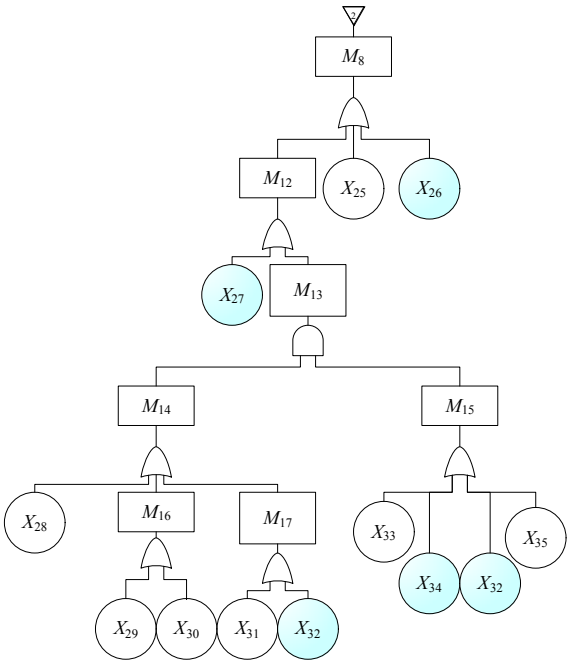

Fig. 5. The fault tree of "manual intervention fail"

are at least eight events occur at the same time. The probability of occurrence of a train rear-end collision event will be extremely low if all the basic events are independent, but as a result of the common cause failure, the probability of accident occurrence will be higher. In the following figures, the common cause failures caused by different reasons have been labeled by different colors.

4.3. Quantitative analysis

For the train rear-end collision accident, we assume that the failure probabilities of bottom events are known as listed in Table 2.

Table 2. The probability of bottom events

Code	Probability	Code	Probability	Code	Probability
X_{27}	0.020	X_{30}	0.002	X_{33}	0.001
X_{28}	0.001	X_{31}	0.005	X_{34}	0.020
X_{29}	0.001	X_{32}	0.020	X_{35}	0.001

The structure function of intermediate event "dispatcher is not aware of the danger" can be expressed as follows:

$$\Phi(X)=\left((X_{28}+X_{29}+X_{30}+X_{31})\cdot(X_{33}+X_{34}+X_{35})+X_{32}+X_{27}\right) \quad (13)$$

Presume that the bottom events are independent, the probability of the event "dispatcher is not aware of the danger" can be calculated:

$$P(M_{12})=0.0398 \quad (14)$$

The occurrence of events "lack of experience" and "abstracted of dispatcher" are inter-actionable, thus, the common cause failures need to be considered. From Fig. 5 and engineering experience, the event "dispatcher off-site" is mutual exclusion with the event "dispatcher on-site but unwitnessed the danger", and the events "danger warning system being closed", "danger warning system undetected the danger" and "unnoticed the warn of the danger warning system" are mutual exclusion to each other. Therefore, the structure function of sub-tree M_{12} can be formulated as follows:

$$\begin{aligned}P(M_{12})&=P\left((X_{28}+X_{29}+X_{30}+X_{31})\cdot(X_{33}+X_{34}+X_{35})+X_{32}+X_{27}\right)\\&=P\left((X_{28}+X_{29}+X_{30}+X_{31})\cdot(X_{33}+X_{34}+X_{35})+X_{32}\right)+P(X_{27})\end{aligned} \quad (15)$$

Let $X_a=X_{28}+X_{29}+X_{30}+X_{31}$ and $X_b=X_{33}+X_{35}$, this yields

$$\begin{aligned}P(X_a)&=P(X_{28}+X_{29}+X_{30}+X_{31})\\&=P(X_{28})+P(X_{29}+X_{30})+P(X_{31})\\&=0.001+(1-(1-0.001)(1-0.002))+0.005\approx 0.009\end{aligned} \quad (16)$$

$$P(X_b)=P(X_{33}+X_{35})=1-(1-0.001)(1-0.001)\approx 0.002 \quad (17)$$

Based on the analysis, Eq. (15) can be further simplified as:

$$\begin{aligned}P(M_{12})&=P(X_aX_b+X_aX_{34}+X_{32})+P(X_{27})\\&=P(X_a)P(X_b)+P(X_a)P(X_{34})+P(X_{32})-\\&\quad P(X_a)P(X_b)P(X_{34})-P(X_a)P(X_b)P(X_{32})-\\&\quad P(X_a)P(X_{34}X_{32})+P(X_a)P(X_b)P(X_{34}X_{32})+P(X_{27})\end{aligned} \quad (18)$$

According to the square root model introduced in section 2.2, we can get the following expression.

$$\begin{aligned}P(X_{34}X_{32})&=\sqrt{ab}=\sqrt{P(X_{34})P(X_{32})\min\left\{P(X_{34}),P(X_{32})\right\}}\\&=\sqrt{0.020\times 0.020\times\min\left\{0.020,0.020\right\}}=0.0028\end{aligned} \quad (19)$$

$$P(M_{12})=0.0402 \quad (20)$$

Compare with the probability without considering the CCF, the relative error for the probability of occurrence of top event considering CCF is:

$$\eta=\frac{0.0402-0.0398}{0.0402}\times 100\%=1.01\% \quad (21)$$

From Eq. (21), it should be noted that the result without considering common cause failure lead to a huge deviation. It can be observed from the results that CCF has a remarkable effect on the reliability analysis of train rear-end collision accidents.

5. Conclusion

In this paper, common-cause failure modes have been incorporated into the fault tree analysis of train rear-end collision accident using the explicit fault tree modeling method and the square root mode. The probability of occurrence of the event "dispatcher is unaware of the danger" is $P(M_{12})$=0.0402. Under the assumptions that bottom events are independent, it is worth noting that the assessment without considering common cause failure shows a huge deviation. It demonstrated that CCF has a significant effect on the probability of occurrence of train rear-end collision accident, which offers a basis for safety and reliability assessment of railway vehicle.

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Yan-Feng LI, Ph.D. candidate
Jinhua MI, Ph.D. candidate
Prof. Hong-Zhong HUANG, Ph.D.
Shun-Peng ZHU, Ph.D.
Ningcong XIAO, Ph.D.
School of Mechanical, Electronic, and Industrial Engineering
University of Electronic Science and Technology of China
No. 2006, Xiyuan Avenue, West Hi-Tech Zone
Chengdu, Sichuan, P. R. China, 611731
E-mail: hzhuang@uestc.edu.cn