Monte Carlo analysis for safety and reliability of rail transit signal system based on Cloud Computing

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Abstract. Starting from the hot issue of introducing cloud computing into rail transit industry, this paper analyses the impact of cloud computing virtualization technology on the safety and reliability indexes of rail transit signal system, Monte Carlo method is used to model two out of 3, double two out of two and two out of two redundant structures from three main parameters of common cause failure, fault diagnosis coverage rate and dangerous failure rate, considering the uncertainty of relevant parameters. The reliability and safety indexes are calculated and simulated with MATLAB. The results show that the two out of three structure is more suitable for the rail transit signal system based on cloud computing.

1. Introduction

With the development of rail transit industry, people are increasingly dependent on rail transit for their travel. At the same time, people pay more and more attention to the performance of rail transit. Rail transit industry requires more and more computing power for its equipment. The contradiction between the demand for computing power and the limitation of equipment quantity is increasingly prominent. At the same time, cloud computing stands out from the developing information technology to solve the above contradictions because of its combination of distributed computing, grid computing, and utility computing. Therefore, the introduction of cloud computing technology into the rail transit industry, especially into the field of rail transit signal control, has become a hot issue. Due to the particularity of rail transit signal control system and its higher requirements for safety and reliability, it is necessary to further study and analyse the application of cloud computing technology in rail transit signal control system.

Firstly, the safety redundancy structure requirements of the rail transit signal control system are studied. Two out of two (1oo2 in IEC61508), two out of three (2oo3 in IEC61508) and double two out of two (2*1oo2 in IEC61508) structures are introduced. According to IEC61508 standard, considering the common cause failure and inspection and maintenance, the paper analyzes its safety and reliability calculation model, and then uses Monte Carlo method to calculate its reliability and safety index, and makes a comparative analysis. Then, in view of the influence of cloud computing technology on the reliability and safety of each safety redundant structure, the reliability and safety of each safety redundant structure and its influencing factors are analyzed through MATLAB simulation, and its comprehensive performance is evaluated.
2. Monte Carlo method
Monte Carlo method is a kind of simulation statistical method from probability theory. It is based on random experiment, using a large number of random numbers for experiment, and then using the idea of integration to process the data, so as to get the results. Also known as computer random simulation method [1-2].

In this paper, Monte Carlo method is used to analyze and verify the safety and reliability of three kinds of safety redundant structures. The basic steps include:
- According to the safety and reliability calculation model of each safety redundant structure, the specific function relationship between input and output is determined.
- The probability density function of each parameter variable in the safety and reliability calculation model is determined.
- The random number in the range of [0,1] is generated according to the random number generation function, which conforms to the uniform distribution, and a group of input parameter samples are obtained according to these random numbers.
- A group of output samples are obtained by inputting the group of input parameter samples into the safety and reliability calculation model.
- Repeat N sampling operations so that N output samples can be obtained to form a group of random samples.
- By statistical analysis of the above random samples, the probability estimates and confidence intervals of the quantitative indexes of safety and reliability for three kinds of safety redundant structures are obtained.

3. Relevant calculation model for three kinds of safety redundant structures
According to the basic steps of analysis and verification by Monte Carlo method, it is necessary to deduce the safety and reliability calculation model of two out of two, two out of three and double two out of two structures, in which the safety index is PFH and the reliability index is failure rate [5-7].

3.1. Two out of two structure
According to IEC61508 standard, two out of two structure is equivalent to its 1oo2 structure, and the calculation equation of its safety index PFH is:

\[
PFH_{1oo2} = 2(1 - \beta)\lambda_{DU}(1 - \beta)\lambda_{DU} \cdot t_{CE} + \beta \lambda_{DU}
\]

\(t_{CE}\) is the average downtime of redundant units, and its calculation equation is:

\[
t_{CE} = \frac{\lambda_{DU}(T + MRT) + \lambda_{DD} \cdot MTTR}{\lambda_{DU} + \lambda_{DD}}
\]

Among them, MTTR is the average recovery time; MRT is the average maintenance time, and T is the inspection and test interval. According to IEC61508 safety standard, MRT = MTTR.

\(\beta\) is a common cause failure factor and \(\beta_D\) is a common cause failure factor of measurable dangerous failure. Both of them meet the requirement of \(\beta_D = 0.5\beta\), the calculation equation of \(\beta\) is:

\[
\beta = \frac{\lambda^{CCF}}{\lambda} = \frac{\lambda^{CCF}}{\lambda^{ind} + \lambda^{CCF}}
\]

Among them, \(\lambda^{ind}\) is the independent failure rate and \(\lambda^{CCF}\) is the common cause failure rate.

\(\lambda_D\) is the dangerous failure rate, \(\lambda_{DD}\) is the measurable dangerous failure rate, and the calculation equation is:
\[ \lambda_{DD} = \lambda_{D} \cdot DC \]  

(4)  

\[ \lambda_{DU} \] is the failure rate of unmeasurable danger, and the calculation equation is:

\[ \lambda_{DU} = \lambda_{D} - \lambda_{DD} = \lambda_{D}(1 - DC) \]  

(5)

For the failure rate of the system, it can be calculated according to the conditional probability. Assuming that the dangerous failure rate of each redundant unit in the two out of two redundant structure is \( \lambda_{D} \), then according to the relationship between the failure rate \( \lambda \) given in IEC61508 and the dangerous failure rate \( \lambda_{D} \), it can be concluded that the failure rate of the redundant unit \( \lambda = 2 \lambda_{D} \). In terms of safety, the whole structure will fail if any element of the two out of two structure fails, so the reliability index of the two out of two structure can be calculated. Therefore, the calculation equation of \( \lambda_{1oo2} \):

\[ \lambda_{1oo2} = C_{2}^{1} \lambda \]  

(6)

3.2. **Two out of three structure**

According to IEC61508 standard, the calculation equation of safety index PFH of two out of three structure is:

\[ PFH_{2oo3} = 6((1 - \beta_{D})\lambda_{DD} + (1 - \beta)\lambda_{DU})(1 - \beta)\lambda_{DU} \cdot t_{CE} + \beta \lambda_{DU} \]  

(7)

At the same time, the independent failure rate \( \lambda_{ind} = (1 - \beta)\lambda \) and common cause failure \( \lambda_{CCF} = \beta\lambda \) can be calculated according to the calculation equation of \( \beta \), Considering the factors of common cause failure, any two or more units in the two out of three structure will fail, so according to the conditional probability, the independent failure part of the two out of three structure includes the probability that any two redundant units will fail independently and the third redundant unit will not fail and the probability that all three redundant units will fail independently; According to the common cause failure described in IEC61508, i.e. all redundant units in the structure fail, the common cause efficiency of the two out of three structure is also \( \lambda_{CCF} \), so the calculation equation of reliability index \( \lambda_{2oo3} \) of the two out of three structure is:

\[ \lambda_{2oo3} = C_{3}^{2} \lambda_{ind} \cdot \lambda_{ind} \cdot (1 - \lambda) + \lambda_{ind} \cdot \lambda_{ind} \cdot \lambda_{ind} \cdot \lambda + \lambda_{CCF} \]  

(8)

3.3. **Double two out of two structure**

According to its principle, the double two out of two structure can be regarded as a two system parallel structure which is composed of two out of two structures in the way of 1oo2D of IEC61508 standard.

According to IEC61508 safety standard, the PFH of redundant unit can be regarded as its unmeasurable dangerous failure rate, i.e. \( PFH = \lambda_{DU} \), so the safety index \( PFH_{1oo2D} \) of dual system parallel structure can be obtained:

\[ PFH_{1oo2D} = 2(1 - \beta)\lambda_{DU}((1 - \beta D)\lambda_{DD} + (1 - \beta)\lambda_{DU} + \lambda_{SD})t_{CE} + 2(1 - K)\lambda_{DD} + \beta \lambda_{DU} \]  

(9)

Among them, \( K \) is the switching success rate, the recommended value of IEC61508 safety standard is 0.98, and \( \lambda_{SD} \) is the measurable safety failure rate. The calculation equation is:

\[ \lambda_{SD} = \frac{\lambda}{2} DC \]  

(10)

\( t_{CE} \) is the average downtime, and its calculation equation is:
The PFH of the double two out of two structure can be obtained by taking the unmeasurable dangerous failure rate of $\lambda_{DU_{1oo2}}$, the measurable dangerous failure rate of $\lambda_{DD_{1oo2}}$ and the measurable safety failure rate of $\lambda_{SD_{1oo2}}$ into the calculation equation;

$$PFH_{2*1oo2} = 2(1-\beta)\lambda_{DU_{1oo2}}(1-\beta)\lambda_{DD_{1oo2}} + (1-\beta)\lambda_{DU_{1oo2}} + \lambda_{SD_{1oo2}})I_{CE_{1oo2}} + 2(1-K)\lambda_{DD_{1oo2}} + \beta\lambda_{DU_{1oo2}}$$

(12)

In the same way, according to the structural characteristics of double two out of two structure, if each two out of two structure is regarded as a "redundant unit", then its failure rate is $\lambda_{1oo2}$, then its independent failure rate is $\lambda_{ind_{1oo2}} = (1-\beta)\lambda_{1oo2}$ and its common cause failure rate is $\lambda_{CCF_{1oo2}} = \beta\lambda_{1oo2}$. Then the calculation of the failure rate of double two out of two structure can be regarded as the calculation of the failure rate of 1oo2D structure with the redundant unit failure rate of $\lambda_{1oo2}$. According to the characteristics of the 1oo2D structure, if both redundant structures fail or one fails to switch, the system fails. Therefore, according to the conditional probability, the independent failure part of the double two out of two structure consists of two "redundant units" that have independent failure at the same time and the probability of switching failure after the independent failure of the main unit. The common failure rate of two "redundant units" is $\lambda^{CCF}_{1oo2}$, so the reliability index of double two out of two structure is $\lambda_{2*1oo2}$.

$$\lambda_{2*1oo2} = C^2_2\lambda^{ind}_{1oo2} \cdot \lambda^{ind}_{1oo2} + (1-K)\lambda^{ind}_{1oo2} \cdot (1-\lambda) + \lambda^{CCF}_{1oo2}$$

(13)

4. The influence of redundant structure of cloud computing technology

If the cloud computing technology is introduced into the rail transit industry, the train control equipment of each station is integrated, and the computing function is undertaken, for the safety computer, its traditional redundant units will be replaced by independent virtual cloud platforms. Due to some characteristics of cloud computing technology, some main parameters of above computing model will be affected, including common cause failure factors $\beta$ and failure rate $\lambda$, etc.

The main reason is that the core technology of cloud computing is virtualization. At present, there are two main virtualization technologies applied: Docker container technology and virtual machine technology. Docker technology can effectively improve the utilization rate of computers, although virtual machine technology supports different operating systems, at the same time, because of the single operating system, it will greatly increase the common cause failure factors. However, the utilization ratio of virtual machine technology to computing power is poor, so more servers may be needed under the same demand of computing power, which will increase the failure rate of the system [8-12]. Due to the lack of corresponding data support, the impact of cloud computing equipment on $\beta$ and $\lambda$ cannot be quantified, so only qualitative analysis can be made. The values of $\beta$ and $\lambda$ below are based on the following assumptions:

- The computing power of a server adopting Docker technology is the same as that of k (k > 1, k is integer) servers adopting virtual machine technology.
- The failure rate of each server is the same, and its common cause failure rate is recommended in IEC61508 safety standard. At the same time, it is considered that all servers will fail in case of common cause failure.
• A server adopting Docker technology can complete the calculation requirements of redundant units of a safety computer platform, while a server adopting virtual machine technology needs k servers.

• If k servers are used to complete the computing requirements of the safety computer platform, the failure rate of each safety redundant unit is considered to be increased by k times.

• When Docker technology is adopted, the common cause failure factor is considered to be larger than the recommended range of IEC61508 standard. When virtual technology is adopted, the common cause failure factor is considered to be within the recommended range of IEC61508 standard.

5. Value of each parameter

When using the Monte Carlo method, it needs some parameter distribution functions in addition to the calculation model, so it is necessary to determine the value of the parameters in the calculation model.

5.1. Mean recovery time (MTTR)

According to the research of relevant literature, in the maintenance process of safety related systems, the average recovery time presents a skewed distribution, in which lognormal distribution is the most widely used distribution function. According to the literature [4] and [8] and the historical statistics of MTTR, 0.5h-24h is selected as the value range of MTTR. It can be calculated that the distribution function of MTTR is $\ln N(1.242, 0.998)$.

5.2. Dangerous failure rate ($\lambda_D$)

$\lambda_D$ can choose to obey the triangle distribution, according to the recommended value range given in IEC61508 safety standard, and the reference value given in reference [4]. The recommended value interval in IEC61508 can be taken as the value interval of $\lambda_D$ and the recommended value in reference [4] can be taken as the mode. The fitting $\lambda_D$ obeys the triangle distribution $T(5E-8, 1E-6, 2.5E-5)$, and the distribution can be taken as the $\lambda_D$ of the redundant unit in Docker technology. According to the above assumptions, the $\lambda_D = k\lambda_D$ of the redundant unit in virtual machine technology can be calculated.

5.3. Common cause failure factor ($\beta$)

There are recommended values of common cause failure factor in IEC61508, the recommended values are (2%, 10%, 20%). Many existing studies show that it is very difficult to fit the distribution function of common cause failure factor. According to the literature [9], common cause failure factor has a great impact on the calculation of reliability and safety index. At the same time, due to the impact of cloud computing, common cause failure factor will increase significantly. Therefore, in the absence of historical statistical data support, a large value distribution [4] [8] should be selected. At the same time, according to the above assumptions, the ranges (20% ~ 99%) and (2%-20%) should be taken respectively to the uniform distribution, i.e. $\beta \sim U(0.2, 0.99)$ and $\beta \sim U(0.02, 0.2)$.

5.4. Fault diagnosis coverage rate (DC)

According to IEC61508, there are two ranges of DC values, 60% - 90% and 90% - 99%. According to literature [4], the diagnosis coverage rate of safety related systems in rail transit industry is between 90% and 99%. Therefore, the value range of DC is defined as the uniform distribution within the range of 90% ~ 99%, i.e. $DC \sim U(0.9, 0.99)$.

5.5. Inspection and test interval (T)

According to the requirements of TG /XH102-2015 High speed railway signal maintenance rules (business management part), the centralized maintenance cycle of safety critical system applied in train operation control system is once a year, i.e. 8760h. Therefore, when calculating the safety and
reliability indexes, the inspection and test interval T is fixed value 8760h.

6. Analysis of simulation results

Based on the above parameters, we can calculate the safety and reliability index of each safety redundant structure, and get the result by MATLAB simulation.

6.1. Safety analysis

6.1.1. Test 1.

The parameter values of MTTR, DC and T have been given above. The dangerous failure rate $\lambda_D$ selects the triangle distribution of $\lambda_D \sim T(a, c, b) \sim T(5E - 8,1E - 6,2.5E - 5)$. The common cause failure factors $\beta$ are $\beta \sim U(0.2,0.99)$ and $\beta \sim U(0.02,0.2)$ respectively. The number of tests is 100000, so as to simulate the impact on safety index of Docker technology. The comparison diagram of cumulative distribution function (CDF) on PFH of three structures is shown in figure 1 and figure 2.

![Figure 1. PFH comparison of three structures ($\beta \sim U(0.2,0.99)$).](image1)

![Figure 2. PFH comparison of three structures ($\beta \sim U(0.02,0.2)$).](image2)
In the CDF curve figure, the slope of the curve is larger, the reliability performance is better. For test 1, it can be seen from figure 1 that when $\beta$ is taken as $\beta \sim U(0.2,0.99)$, the safety index of the three structures is close. The safety index of double two out of two structure and the two out of two structure is better than that of the two out of three structure. In general, the safety of the two out of two structure is better than that of the double two out of two structure, but the probability of the PFH of the double two out of two structure is less than $3.07E-7$ is higher than that of the two out of two structure. At the same time, by comparing Fig. 1 and Fig. 2, it can be found that $\beta$ has a great influence on the safety of the double two out of two structure, When $\beta$ is increased, the safety of the double two out of two structure may be lower than that of the other two redundant structures. In order to further study the influence of $\beta$ on the safety of the three redundant structures, $\lambda_D$ is taken as $1E-6$, DC is taken as 0.9 and 0.99 respectively, and $\beta$ is taken as $[0, 1]$, the step size is 0.01, the MTTR is 8h, and other conditions are the same as above. When DC is 0.9 and 0.99, the PFH values of three structures are compared, as shown in figure 3 and figure 4.

![Figure 3. PFH comparison of three structures (DC = 0.9).](image)

![Figure 4. PFH comparison of three structures (DC = 0.99).](image)
From figure 3, it can be seen that the safety of the double two out of two structure is greatly affected by the common cause failure rate $\beta$. When $\beta$ is large enough, the safety of the double two out of two structure is significantly lower than the other two structures. Under the condition of figure 4, the threshold value is about 0.82. At the same time, compared with Fig. 3 and Fig. 4, it can be seen that DC also has a huge impact on the safety of the double two out of two structure. When the DC is large enough, the safety of the double two out of two structure is always lower than that of the structure of two out of three and two out of two, and the safety of two out of two structure is always better than that two out of three structure. In order to specifically analyze the impact of DC on the safety index of the three structures, the value of $\beta$ is 0.2, and the value of DC is $[0.9, 0.99]$ and the step size is 0.01, as shown in figure 5.

![PFH comparison of three structures (DC = 0.9 ~ 0.99)](image)

It can be seen that the larger the DC, the better the safety of the system. When the DC is large enough, the safety of the double two out of two structure is lower than the other two structures. At the same time, it can be seen that the safety of the two out of two structure is slightly better than the two out of three structure.

Therefore, it can be concluded from test 1 that the increase of common cause failure factor $\beta$ of the system will have an impact on three redundant structures, and will have the greatest impact on the double two out of two structure. For cloud computing technology, if Docker technology is adopted and the above assumptions are met, because a single operating system and all redundant units virtualized on the same server, the common cause failure factor $\beta$ will be very high, If the fault detection rate DC is also very high at this time, it is not recommended to use double two out of two structure for safety redundancy structure only from the perspective of safety, and it is recommended to choose two out of two and two out of three structures.

6.1.2. Test 2.

The parameter values of MTTR, DC and T have been given above. The dangerous failure rate $\lambda_D$ selects the triangle distribution of $\lambda_D \sim k \times T(a, c, b) \sim k \times T(5E-8, 6E-6, 2.5E-5)$ where k is taken as 2 and 4, the common cause failure factor $\beta$ is taken as $\beta \sim U(0.02, 0.2)$, and the number of
tests is 100000, so as to simulate the impact on the safety index of virtual machine technology. The CDF comparison diagram of three PFH structures is shown in figure 3 and figure 4.

![PFH comparison of three structures (k=2)](image)

**Figure 6.** PFH comparison of three structures (k = 2).

![PFH comparison of three structures (k=4)](image)

**Figure 7.** PFH comparison of three structures (k = 4).

For test 2, by comparing Fig.6 and Fig.7, it can be found that if the above assumption is satisfied, the multiplication of dangerous failure rate has little effect on the safety index of the three structures. Therefore, it can be concluded that if the virtual machine technology meets the above assumption, the safety redundant structure is recommended to adopt double two out of two structure only from the safety point of view.
6.2. Reliability analysis

6.2.1. Test 3.
The parameter values of MTTR, DC and T have been given above. The triangle distribution of
dangerous failure rate $\lambda_D$ select $\lambda_D \sim T(a,c,b) \sim T(5E-8,1E-6,2.5E5)$, the common cause failure
factor $\beta$ takes $\beta \sim U(0.2,0.99)$ and $\beta \sim U(0.02,0.2)$ respectively, and the number of tests is 100000,
so as to simulate the influence on the reliability index of Docker technology. The CDF comparison
diagram of the failure rate on three structures is shown in figure 8 and figure 9.

![Figure 8](image_url1)
Figure 8. Comparison of failure rates of three structures ($\beta \sim U(0.02,0.2)$).

![Figure 9](image_url2)
Figure 9. Comparison of failure rates of three structures ($\beta \sim U(0.2,0.99)$).
According to Fig. 8 and Fig. 9 from test 3, it can be seen that the increase of common cause failure factor $\beta$ will have a negative impact on the reliability of the three structures, but it has little impact on the reliability comparison of the three structures. The reliability is always two out of three > double two out of two > two out of two.

6.2.2. Test 4.
The parameter values of MTTR, DC and T have been given above. The triangle distribution of the dangerous failure rate $\lambda_D$ selects $\lambda_D \sim k \times T(a, c, b) \sim k \times T(5E-8, 1E-6, 2.5E-5)$, in which $K$ is taken as 2 and 4, the common cause failure factor $\beta$ is taken as $\beta \sim U(0.02, 0.2)$, and the number of tests is 100000. In order to simulate the impact on the reliability index of virtual machine technology, the failure rate comparison diagram of three structures is obtained as shown in figure 10 and figure 11.

Figure 10. Comparison on failure rate of three structures (k = 2).

Figure 11. Comparison on failure rates of three structures (k = 4).
In the same way, comparison on figure 10 and 11 from test 4 can find that the multiplication of dangerous failure rate will have a negative impact on the reliability of the three structures, but has a little impact on the reliability comparison relationship, so it can be concluded that the same conclusion can be drawn with test 3, and the reliability is always two out of three > double two out of two > two out of two.

Combining test 3 and test 4, it can be found that no matter Docker technology or virtual machine technology is used, its reliability is always 2oo3 > 2*1oo2 > 1oo2. Therefore, from the perspective of reliability alone, two out of three structure is recommended for safety redundancy structure.

7. Conclusion
This paper mainly studies the safety and reliability of three redundant structure, including two out of two, two out of three, and double two out of two redundant structure, and makes a series of qualitative analysis and assumptions on the impact of cloud computing technology on the redundant structures. The influence of Docker technology and virtual machine technology on the safety and reliability of redundant structure is simulated, and the Monte Carlo method is used to analyze. The conclusion is as follows:

- Under the influence of Docker technology, the common cause failure factor β increases, which has the greatest impact on the double two out of two structure. At this time, it is suggested to adopt the two out of three structure in terms of safety and the two out of three structure in terms of reliability.
- Under the influence of virtual technology, the dangerous failure rate λD increases, this has little influence on the three structures. In this case, it is suggested to adopt the double two out of two structure from the safety aspect and the two out of three structure from the reliability aspect.

To sum up, it can be found that the safety and reliability of the two out of three structure are less affected by common cause failure factors and dangerous failure rates, and the comprehensive performance based on the cloud computing technology can be better than the double two out of two structure and two out of two structure.

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