Study on Risk Analysis of Railway Signal System

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Abstract:-Railway signal system requires the high level of safety in order to safeguard safe operation of the train and people's lives, so the risk analysis of railway signal system counts for much. However, due to the incomplete of the risk data, it is often impossible to obtain a satisfactory result. This article presents a comprehensive study in the risk analysis model of railway signal system on safety risks. In this methodology, evidential reasoning is employed to synthesizing the experts' opinions thus produced to determine the relative importance of the risk contributions. This allows uncertain information in the risk analysis process. Then, weighted and risk factor values are converted to the matrixes represented in numerical features via the cloud model. Finally, the risk level is obtained by using the weighted average integrated function. Also, a practical case study on risk analysis of computer interlocking system is presented to demonstrate the application of the proposed risk analysis, and the result shows that the method is not only suitable for risk analysis method, but also is able to find out the weak links in railway signal system. What is more, it provides a new foundation for the risk analysis of railway signal system.

Key-words:-Railway signal system, Risk analysis, Computer interlocking system, Evidential reasoning, Cloud model

1 Introduction

With the rapid development of the rail transportation, and the increasing improvement of running speed and density means severer requirements for the safety of railway signal system. Thus, it is of vital significance to have the risk analysis of the railway signal system safety. And so its security assessment possesses very importance significance. Computer interlocking system is the important part of the Chinese train control system, which, through analysis on it, will exert a certain positive influence on security of China's railway signal system.

At present, there are many main methods on risk analysis of complicated system, such as fault tree analysis (FTA) [1,2] , analytical hierarchy process [3], bayesian networks [4,5], fuzzy set theory [6,7], et al. The method of fault tree analysis and bayesian networks are quantitative analysis methods among these, which can calculate the risk level of the system through modeling. However, in many circumstances, the application of quantitative analysis tools may not give satisfactory results because the risk data of railway are incomplete or it is a great difficult to obtain the basic data and quantify the number of risk factors in the actual process of evaluation, in addition, the normal operations of the railway signal system is directly related to this situations that contains equipment failure, the change of natural environment, the technical level of the operating personal. The other methods of analytical hierarchy process and fuzzy set theory can transfer from the qualitative analysis to the quantitative analysis, which can integrate the quantitative analysis and the qualitative analysis. But these methods cannot systematically consider the uncertainty involved in the risk analysis, which contains fuzziness and randomness of risk, as well as the incomplete knowledge is caused by adopting the expert assessment.

As discussed above, a new method should be presented to assess the risk of railway signal system safety. As a main tool to deal with the uncertainty problem, the evidential reasoning has a prominent advantage in expression and synthesis of uncertainty information [8]. It is also used to deal with assessment problems with uncertainty, which has been developed on the basis of the Dempster-Shafer theory. Meanwhile, cloud model is an effective and simple uncertain transition model between qualitative concept and quantitative representation, further more the cloud model can realizes the transition between quality value and precise value by combining the fuzziness and randomness [9]. Considering the characteristics of methods above and the present situation in China, a risk analysis of railway signal system is established on the basis of the evidential reasoning and cloud model in this paper, which can produce an analysis results objectively and reasonablely. The presented method is not only considering the kinds of uncertainty in risk, but also carrying out the risk analysis under incomplete data effectively. In this way, the risk associated with all risk factors can be evaluated with a semi quantitative analysis method based on cloud evidential reasoning. Firstly, these uncertainty evaluations through expert remarks can be combined by using the evidential reasoning so as to produce weight value and risk assessment value of each risk factor. Secondly, the weight value and the assessment value of risk factors are expressed correspondingly in the form of cloud model. And the risk of the whole system can finally be assessed. An application shows that the proposed methodology is feasible in the practice of risk analysis of railway signal system.

2 The risk analysis process based on cloud evidential reasoning

According to the theory above, a comprehensive risk analysis of railway signal system based on cloud evidential reasoning was presented and developed, which can calculate the final risk level, and then the result was expressed in the form of cloud droplets. In proceeding with our research, first of all, risk analysis begins with problem definition which includes identifying the need for safety, e.g., the risk factors setting, and that of the evaluation criteria. Secondly, all of the experts' judgments of system risk were synthesized by applying evidential reasoning which is a rational way to attain the weight value and risk assessment value. Then, the weight value and the risk assessment value are expressed in the form of cloud model, and we can obtain the evaluation result through the comprehensive assessment between the weight value and the risk assessment value, which can finally be expressed by a floating cloud model, and we would like the floating cloud to compare with the standard cloud model when determining the final risk grades. The analysis flow of system risk based on cloud evidential reasoning is shown in Figure 1.

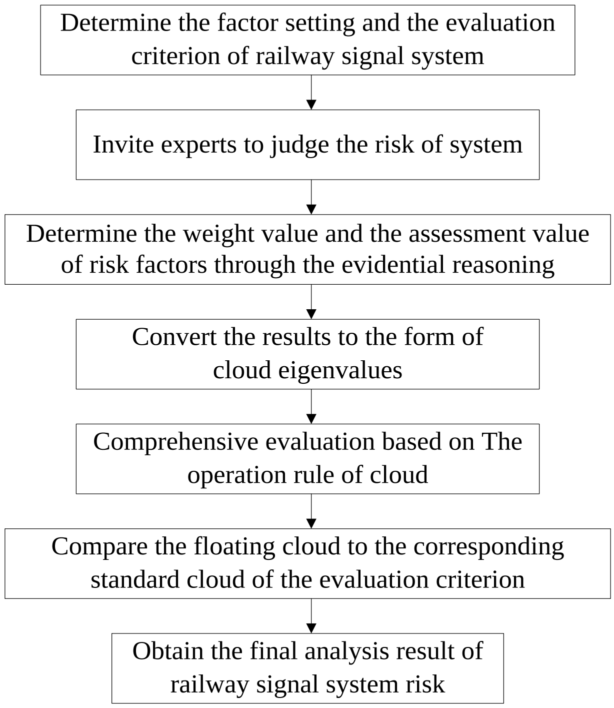

Fig.1 The analysis flow of system risk based on cloud evidential reasoning

3 Risk analysis model of railway signal system

3.1The risk factors setting and the evaluation criterion

The purpose of risk identification is to systematically identify all potential hazardous events associated with a railway signal system. First of all, the risk factors setting of the assessment system can be determined by risk identification. Suppose there are n risk factors, which can be expressed in the risk factors setting $\boldsymbol{U}=\{u_1,u_2,\cdots,u_n\}$. In addition, according to the European railway safety standards, the evaluation criterion is divided into four levels which consists of 'negligible', 'tolerable', 'undesirable', 'intolerable'. Then the setting $\boldsymbol{V}=\{v1,v2,v3,v4\}$={negligible, tolerable, undesirable, intolerable} is used to express the four levels, and each risk level is realized with the cloud model. The qualitative remarks of each factor in the assessment system given in this paper all have bilateral constraints, for the factor remark that has bilateral constraints [Cmin,Cmax]. Its cloud processing can use the intermediate value of constraints as the expectation to approximate the remark, and then the eigenvalues of the cloud can be calculated , which is shown in Equation(1) as follows:

$$\begin{cases} \mathrm{Ex} = (\mathrm{C}_{\min} + \mathrm{C}_{\max}) / 2 \\ \mathrm{En} = (\mathrm{C}_{\max} - \mathrm{C}_{\min}) / 6 \\ \mathrm{He} = \lambda \end{cases} \quad (1)$$

where λ is a constant that can be adjusted according to the fuzziness and randomness in risk factors.

3.2 Calculate the weight factors

Once the factors setting and the risk level setting are established, the risk analysis moves from the risk identification to the data and information collection. Because the contribution of each risk factor to the system is different, the weight of the contribution of each risk factor should be taken into consideration in order to represent its relative contribution to the risk of a railway signal system. In this study, five important degrees are used to describe that how important about risk factor, which is represented by the setting $\boldsymbol{S}$, and it is served as a frame of discernment in evidential reasoning. Therefore, the weight state setting of risk factors is $\boldsymbol{S}=\{s_1,s_2,s_3,s_4,s_5\}$={very important, more important, important, less important, not important}. Considering the statistic data does not exist, expert judgments should be applied. Then, we need to ask for the experts to apply their wealth of experience to give the assessment for the weight degree of each risk factor. Suppose $m_{u_1 r}$ is a degree of contribution of risk factor of u_1, which is according to the expert of r, $m_{u_1 r}$ is defined by:

$$\begin{cases} m_{u_1 r}(s_1) = x_1 \\ \quad\vdots \\ m_{u_1 r}(s_5) = x_1 \\ \sum m_{u_1 r} = 1 \end{cases}$$

where $m_{u_1 r}$ is referred to as a basic probability assignments. $m_{u_1 r}(s_1)$ represents the extent to which the obtained weight evaluation by the rth expert of the risk factor of u_1 belongs to a weight level of S_1defined weight state.

However, the different evidences are synthesized by the classical evidential theory tool may not give reasonable results due to the high conflict between bodies of evidences. In order to solve this problem above, the discounting evidence combination rule is used to improve the classical evidential reasoning in this study. Before the information fusion of evidence, we give a discount coefficient for each evidence according to certain rules to reduce the degree of conflict between the evidence information, then, evidential reasoning is used to synthesize the evidence information.

Suppose there are m experts to assess the weight of risk factor, then, we can construct m evidences of E_1, $E_2 \cdots E_m$, the basic probability assignments is corresponding to each evidence is m_1, $m_2 \cdots m_m$. In this paper, the distance of evidences might be taken into account to determine the discount coefficient. And then, the distance between E_1 and E_2 is defined as follows [10]:

$$d_{ij} = \sqrt{\frac{1}{2}(\boldsymbol{m}_i - \boldsymbol{m}_j)^{\mathrm{T}} \boldsymbol{D}(\boldsymbol{m}_i - \boldsymbol{m}_j)} \quad (2)$$

where

i,j=1,2,⋯, m. $\boldsymbol{D} = \frac{|A \cap B|}{|A \cup B|}, A, B \in R(S)$, $d_{ij} \in [0,1]$.

The distance of evidences can describe the degree of confidence between bodies of evidences which is obtained by the difference of evidence. When d_{ij} =0, it represents that the two pieces of evidence are exactly the same, and they have greatest similarity. When d_{ij} is more large, it shows that there are larger conflict between the two pieces of evidence, the similarity is more little. According to Equation (2) to calculate the distance of evidences, and the similarity of evidences can be defined by:

$$s_{ij} = 1 - d_{ij} \quad (3)$$

then, the obtained similarity between any two evidences can be expressed to a similarity matrix as follows:

$$S=\begin{bmatrix} 1 & s_{12} & \cdots & s_{1n} \\ s_{21} & 1 & \cdots & s_{2n} \\ \vdots & \vdots & & \vdots \\ s_{n1} & s_{n2} & \cdots & 1 \end{bmatrix} \quad (4)$$

If the degree of a single piece of evidence provided by an expert is highly supported by the other evidences, showing that the evidence is more similar with other evidences, and so the discount coefficient of the evidence should be larger. On the contrary, the lower degree of support, the little corresponding discount coefficient is. Therefore, the degree of evidence of E_i is supported by other evidences can be calculated as follows:

$$\mathrm{Sup}(E_i) = \sum_{j=1, j\neq i}^{n} s_{ij} \quad i, j = 1, 2, \cdots, n \quad (5)$$

In this paper, we serve the highest degree of support among n evidences as the key evidence. We can compare the degree of support of E_i to the key evidence, and then the discount coefficient of E_i can be defined as follows,

$$\beta_i = \frac{\mathrm{Sup}(E_i)}{\max\limits_{1\le r\le n}\{\mathrm{Sup}(E_r)\}} \quad i = 1, 2, \cdots, n \quad (6)$$

Thus the obtained basic probability assignments of each evidence above can be amended according to the obtained discount coefficient as follows:

$$\begin{cases} m'(s_k) = \beta m(s_k) & s_k \neq S \\ m'(S) = 1 - \sum m'(s_k) \end{cases} \quad (7)$$

The purpose of the amendment of the basic probability assignments is to reduce the degree of conflict among evidences, and then the judgments of each expert can be synthesized by using the evidential reasoning algorithm. The synthesis rule of evidential reasoning can be stated as follows:

$$m(A) = \begin{cases} \dfrac{1}{1-K} \sum\limits_{A_i \cap B_j = A} m_1(A_i) m_2(B_j) & A \neq \varnothing \\ 0 & A = \varnothing \end{cases} \quad (8)$$

Consequently, the basic probability assignments of risk factors can be calculated through the Equation (8). And the weight processing can use the largest credibility value as the final weight value of the risk factor, which is represented by w^{u_i} . And then we can turn the each weight level into the cloud model $(\mathrm{Ex}^{w_{u_i}}, \mathrm{En}^{w_{u_i}}, \mathrm{He}^{w_{u_i}})$, as is shown in Table 1.

Table 1 Definitions of the weight cloud

The weight state	very important	more important	important	less important	not important
Ex	1.000	0.750	0.500	0.250	0
En	0.085	0.085	0.085	0.085	0.085
He	0.002	0.005	0.005	0.005	0.002

At this stage, according to the operational rule of cloud [11], let the weight factors that is expressed as cloud model be the normalized relative weight of risk factors $W=\{w_1,w_2, \cdots ,w_n\}$. This can be represented by using Equation (9):

$$w_i = \frac{w_{u_i}}{\sum\limits_{i=1}^{n} w_{u_i}} = \frac{(\mathrm{Ex}^{w_{u_i}}, \mathrm{En}^{w_{u_i}}, \mathrm{He}^{w_{u_i}})}{\sum\limits_{i=1}^{n} (\mathrm{Ex}^{w_{u_i}}, \mathrm{En}^{w_{u_i}}, \mathrm{He}^{w_{u_i}})}$$
$$= \left(\frac{\mathrm{Ex}^{w_{u_i}}}{\sum\limits_{i=1}^{n}\mathrm{Ex}^{w_{u_i}}}, \left|\frac{\mathrm{Ex}^{w_{u_i}}}{\sum\limits_{i=1}^{n}\mathrm{Ex}^{w_{u_i}}}\right| \sqrt{\left(\frac{\mathrm{En}^{w_{u_i}}}{\mathrm{Ex}^{w_{u_i}}}\right)^2 + \left(\frac{\sum\limits_{i=1}^{n}\mathrm{En}^{w_{u_i}}}{\sum\limits_{i=1}^{n}\mathrm{Ex}^{w_{u_i}}}\right)^2}, \left|\frac{\mathrm{Ex}^{w_{u_i}}}{\sum\limits_{i=1}^{n}\mathrm{Ex}^{w_{u_i}}}\right| \sqrt{\left(\frac{\mathrm{He}^{w_{u_i}}}{\mathrm{Ex}^{w_{u_i}}}\right)^2 + \left(\frac{\sum\limits_{i=1}^{n}\mathrm{He}^{w_{u_i}}}{\sum\limits_{i=1}^{n}\mathrm{Ex}^{w_{u_i}}}\right)^2} \right)$$
$$= (\mathrm{Ex}_{w_1}, \mathrm{En}_{w_1}, \mathrm{He}_{w_1}) \quad (9)$$

3.3Determine the assessment value of risk factors

The method of determining the evaluation value of risk factors is the same as the weight factors determination method. In a similar way, firstly, we have invited a group of experts to give the evaluation of each risk factor according to the four risk levels that are defined by section 3.1. Then, after determining the discount coefficient, we can calculate the final assessment result m_{u_i} through synthesizing the amended value by using the evidential reasoning, and then the final result is expressed as cloud model.

3.4 The result of risk analysis

After all risk factors' weight value and assessment value are calculated, the comprehensive assessment result can be obtained through combining the two important value by using fuzzy operation. The comprehensive result of assessment system is $F=\sum_{i=1}^{n} w_i m_{u_i}$=(Ex,En,He) , and the corresponding floating cloud can be obtained through the Forward Cloud Generator. Then, we compare the floating cloud with the standard cloud model to determine the final risk grades. In other words, the final comprehensive result is decided by the distance between the floating cloud and the standard cloud model, the distance is shorter, the greatest impact on floating cloud.

4 A case study

Computer interlocking system is one of the new technologies of railway signal system, and its main function is to guarantee the safety, reliability of the high-speed train. In this section, a case example on risk analysis of computer interlocking system is used to demonstrate the proposed risk analysis methodology. The risk level is divided according to the definition of risk of EN50126 which is the European Railway safety standard [12]. Then, we have set up the risks factors setting of the system through learning system structure, function requirements and the actual situation. And the risk factors setting of computer interlocking system is described by U={u_1,u_2,u_3,u_4}={switch operations and collection fault, electrical shock of interlocking equipment, signal control fault, interlocking equipment misfire}, which involves four risk factors resulting in failure of computer interlocking system.

4.1 Establish the evaluation criterion of cloud model

Firstly, the qualitative descriptors of risk level are defined as 'negligible', 'tolerable', 'undesirable' and 'intolerable', it is also expressed by the setting $\boldsymbol{V}$={v_1,v_2,v_3,v_4}={negligible, tolerable, undesirable, intolerable}, and the corresponding evaluation value ranges are $[0,3)$, $[3,5)$, $[5,7)$ and $[7,8)$. According to the formula (1) and the method mentioned in section 3.1, we can calculate the assessment value of the risk standards expressed in the form of the eigenvalues of the cloud model, and then we can obtain the risk evaluation criterion based on the cloud model. The evaluation criterion based on cloud model is shown in Table 2.

Table2 Evaluation criterion based on cloud model

risk level	negligible	tolerable	undesirable	intolerable
evaluation criterion	(1.5,0.5,0.05)	(4,0.33,0.05)	(6,0.33,0.05)	(7.5,0.167,0.05)

4.2 Calculate the weights and assessment value

In this study, we should work out the weight value of each risk factor because the contribution of each risk factor to the computer interlocking system is different. The weight factors can be obtained according to the method described in section 3.2. The risk factor of u_1 serves as an example to explain the step. The basic probability assignments of risk factors of u_1 can be obtained by adopting the evaluation of five experts who are invited to assess the weight level. The basic probability assignments of u_1 is shown in Table 3.

Table 3 the BPA of switch operations and collection fault

weight state	expert 1	expert 2	expert 3	expert 4	expert 5
s_1	0.7	0.6	0	0.2	0.6
s_2	0.2	0.3	0.4	0.4	0.4
s_3	0.1	0.1	0.5	0.4	0
s_4	0	0	0.1	0	0

s_5	0	0	0	0	0

The similarity between evidences can be calculated by the preceding Equation (2) and Equation (3), Then, we can obtain a similar matrix:

$$S=\begin{bmatrix} 1 & 0.9000 & 0.4084 & 0.5641 & 0.8268 \\ 0.9000 & 1 & 0.4804 & 0.6394 & 0.9000 \\ 0.4084 & 0.4804 & 1 & 0.8268 & 0.4432 \\ 0.5641 & 0.6394 & 0.8268 & 1 & 0.6000 \\ 0.8268 & 0.9000 & 0.4432 & 0.6000 & 1 \end{bmatrix}$$

And then, the discount coefficient can be calculated by the Equation (5) and Equation (6), the result is shown as follows:

$$\beta=(0.9245,1,0.7394,0.9008,0.9487)$$

According to the discount coefficient above, the obtained basic probability assignments of u_1 shown in Table 3 be amended by using Equation (7). then the evaluation result of risk factor of u_1 can be acquired by synthesizing the information through the synthesis rule of evidential reasoning, and the evaluation results is shown in Table 4. The largest credibility of weight value of w_1 is served as the final evaluation result of the weight factor. In other words, the weight value of switch operations and collection fault is 'very important', and it is expressed by cloud model as (1.000,0.085,0.002).

Table 4 The weight evaluation result of switch operations and collection fault

risk factor	s_1	s_2	s_3	s_4	s_5	S
u_1	0.6888	0.3025	0.0087	0	0	0

In a similar way, the weight value of the other risk factors and the corresponding cloud model can be obtained. Then, the weight of risk factors can be normalized by using the Equation (9), and we also can obtain the result expressed by cloud model, the result is shown in Table 5.

Table 5 The weight value of risk factors based on cloud model

risk factor	weight state	cloud model expression	The normalized cloud model
u_1	very important	(1.000,0.085,0.002)	(0.308,0.031,0.001)
u_2	more important	(0.750,0.085,0.005)	(0.230,0.023,0.001)
u_3	very important	(1.000,0.085,0.002)	(0.308,0.031,0.001)
u_4	important	(0.500,0.085,0.005)	(0.154,0.015,0.001)

We have carried out the evaluation of the risk level of each risk factor. The method to determine the risk assessment value is similar to the method of the determination of the weight factors. The evaluation result of risk is shown in Table 6.

Table 6 The result of risk analysis

risk factor	risk level	Cloud model expression
u_1	negligible	(1.5,0.5,0.05)
u_2	tolerable	(4,0.33,0.05)
u_3	negligible	(1.5,0.5,0.05)
u_4	tolerable	(4,0.33,0.05)

4.3 The evaluation result of risk analysis

According to the weight value of each risk factor described in Table 5 and the evaluation result of risk factors described in Table 6, the final evaluation result $F=\sum_{i=1}^{n} w_i m_{u_i}$ =(2.460,0.269,0.026) can be calculated by using the weighted average integrated function. Then, the corresponding floating cloud can be obtained through the forward cloud generator, and the final risk grades can be obtained on the basis of comparing the floating cloud with the standard cloud model. From the above result described in Figure 2, it is obvious that the floating cloud is located between the negligible cloud and the tolerable cloud, and it is closer to the negligible cloud, Therefore, the final risk analysis result of computer interlocking system can be though as 'negligible'.

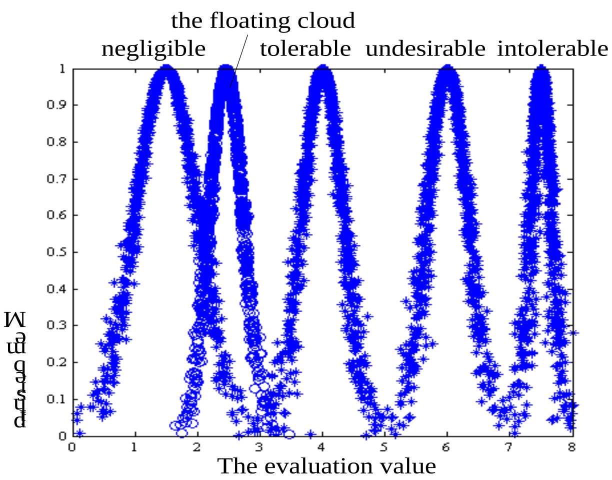

Fig.2 The analysis result of computer interlocking system risk

In general, the safety of computer interlocking system is conformed to the international safety standards. The assessment result is consistent with the actual situation. Meanwhile, according to the evaluation result, we can obtain the weak link which consists of two risk factors, namely electric shock of interlocking equipment and system misfire. Therefore, we have to adopt a certain measures against the two 'tolerable' level of the electric shock of interlocking equipment and system misfire. For example, the cable insulation distance between equipment shall be designed in accordance with international standard to prevent electric shock, and considering the problem that cooling system completely, the fire accident can be prevented by using the fire materials. Furthermore, we have to strengthen the security of computer interlocking system to avoid unnecessary accidents.

5 Conclusions

In order to solve the problem of railway signal system safety risk analysis, and combining with the actual situation of China railway, the paper proposes a new semi quantitative methodology for railway signal system based on the evidential reasoning and cloud model. In this methodology, the evaluation of the risk of a computer interlocking system is carried out by using an evidential reasoning approach, which provides the risk analysis with a rational tool to make full use of the experts' judgment, and reduces the uncertainty in risk. The improved evidential reasoning is well suited for handling the conflict problem between evidences, and making the result more objectively and effectively. The cloud model combines the fuzziness and randomness of risk and realizes the transition between quality and quantity, and it can make the evaluation result be reflected intuitively. The comprehensive risk analysis of computer interlocking system based on cloud evidential reasoning has shown to be quite reasonable and effective in practice. The proposed methodology will provide the basis for risk management decision, furthermore, it also provides a reference for risk analysis of railway signal system.

Acknowledgements

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