Study on Pre-warning Model of Railway Signal System with Fuzzy Analytic Hierarchy Process

Shanpeng Zhao[1], Shaoxiang Zhao[2], Youpeng Zhang[3], Zhengjie Xu[4]
[1]School of Automation & Electrical Engineering, Lanzhou Jiaotong University, Lanzhou, China
E-mail: zsp@mail.lzjtu.cn Tel: +86-15101316773
[2]School of Automation & Electrical Engineering, Lanzhou Jiaotong University, Lanzhou, China
E-mail: 0218387@stu.lzjtu.edu.cn Tel: +86-19893172773
[3]School of Automation & Electrical Engineering, Lanzhou Jiaotong University, Lanzhou, China
E-mail: zhangyp@mail.lzjtu.cn Tel: +86-1309389565
[4]Zhuzhou CRRC Times Electric Co., LTD. Zhuzhou, China
E-mail: vivian_630520@163.com Tel: +86-18711363195

Abstract— **In order to ensure the safety of high-speed railway transportation, the command role of railway signal system should be brought into full play. By comprehensively analyzing the safety characteristics of railway signal system, a safety railway signal system pre-warning model based on fuzzy analytic hierarchy process (FAHP) was proposed. Firstly, this paper introduced the theory basis of fuzzy comprehensive evaluation method and analytic hierarchy process. Then analysed the natural geological factors, personnel factors, equipment factors and management factors of railway signal system, and studied the safety problems of "human-machine-environment" system. Finally, the feasibility and validity of the model were verified by model analysis. This pre-warning model is applied to the high-speed railway signal system, and has good reliability, high safety. It can not only discover the risk sources and hidden dangers of the railway signal system in time, but also effectively prevent accidents. It has great practical significance to guarantee the safety of railway transportation.**

Keywords — **Railway signal system; Safety pre-warning; Analytic Hierarchy Process; Fuzzy mathematics**

I. INTRODUCTION

The railway signal system is a comprehensive control system with centralized dispatching as the leader, station equipment as the basis, communication networks as the framework, train dispatching command, train operation control, equipment monitoring, disaster prevention and information management functions as a whole [1]. Intelligent construction of high-speed railway signal system is an important development direction in the future to improve transport capacity, improve service level and reduce operating costs [2]. The signal system is very important for the safe operation of high-speed railways, and Fig. 1 shows the high-speed railway in operation. Fig. 1 is high-speed railway in operation.

Fig. 1 High-speed railway in operation

Nowadays, the demand for security of railway signal system is becoming more and more severe. Many research works about railway signal system safety management are done by scholars have been greatly improved in recent years. The existing fault-tree analysis method and grey-fuzzy theory means have certain reference value for the safety risk assessment of railway signal system [3-5]. However, most of methods neglect the various uncertainties in the evaluation process. Moreover, these methods rely on a mathematical model of precise operation too much, or it is difficult to make a clear explanation of the qualitative concepts in the evaluation process by classifying the evaluation results with a threshold evaluation method. According to the overall developing level of the risk assessment methods for equipment of high-speed railway is in the empirical accident management stage and cannot meet the practical needs by enterprise production actions. It is an urgent task to break island state of security information and excavate the valuable information from the feedback data of railway system. Based on the fuzzy mathematics, this paper constructs a safety pre-warning model of railway signal system. Combining safety factors of railway signal system, the safety pre-warning model can be used to improve safety management situation of high-speed railway signal system.

The research object of this paper's security warning is the "human-machine-environment" system. Various safety-related data can be obtained and a series of activities such as evaluation, review, classification, analysis and monitoring can be carried out to obtain safety warning signals at different stages [6]. Through the timely transmission of risk signals, the safety data of the railway signal system can be obtained by using the safety pre-warning model. Compared with the risk management threshold, different control actions can be taken to avoid accidents.

Railway signal system is a multi-component and multi-link system. The components cooperate with each other to ensure the smooth operation of railway transportation. The structure of high-speed railway signal system is shown in Fig. 2. In the study of railway risk assessment, it is very difficult to quantify the risk by collecting and counting data of various fuzziness and randomness. The main activities of safety pre-warning about railway signal system include monitoring and identification of hazards, alert diagnosis and evaluation, warning decision, anticipating control and control, trend forecast and so on. These activities can be divided into two categories: pre-warning analysis and pre-warning countermeasures [7]. Firstly, according to the monitoring index system, the production process data are collected from the external environment and subsystems. Then through the analysis of monitoring information, identify pre-warning. The appropriate identification index is used to estimate the alarms that have occurred and will occur, and to diagnose and evaluate the alarms that have occurred, and to predict their development trend and harm degree. Finally, the corresponding control measures are taken.

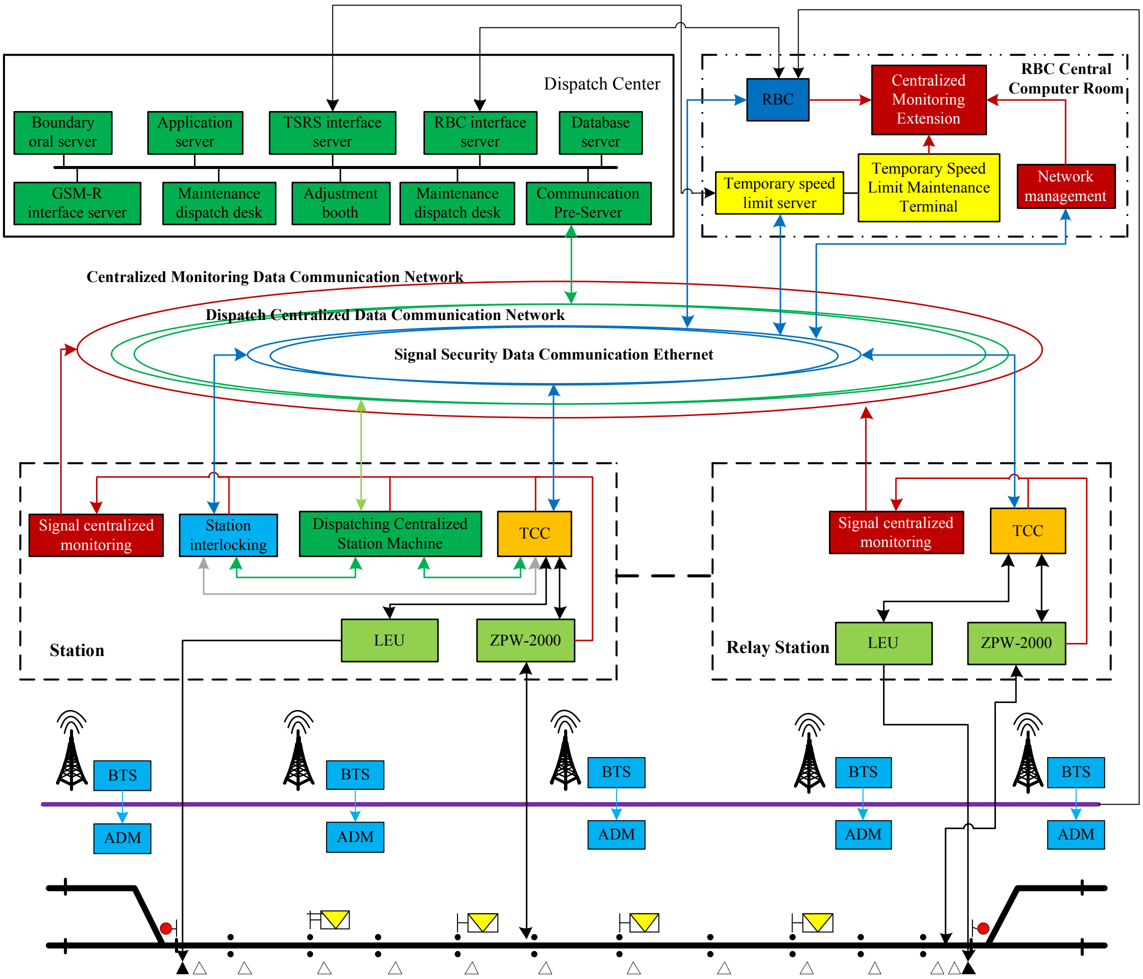

Fig. 2 Structural diagram of high-speed railway signal system

In order to measure and evaluate the risk of the railway signal system, it is necessary to select indicators that have an important impact on the system and establish a risk assessment method that can provide decision makers with the overall risk of the high-speed railway signal system. The specific risk analysis indicators have a negative impact on the system, which is not enough to draw the overall risk. It is necessary to find a relatively low risk indicator, which is beneficial for managers to develop targeted measures to increase systemic risk [8-9]. Risk warning is determined by the evaluation results to reverse the impact of system risk indicators. Based on the risk assessment index system, the fuzzy comprehensive evaluation method is used to determine the risk indicators that need to be improved, which has the effect of risk warning and is of great significance to ensure the safety of railway transportation.

II. THEORETICAL BASIS

A. *Fuzzy Comprehensive Evaluation Method*

Fuzzy comprehensive evaluation method refers to using fuzzy mathematics think to quantify the complicated systems through investigation, sampling, data accumulation and evaluation process [10-11]. The specific steps are:

(1) Determine the evaluation index and allocate the corresponding weight. The evaluation factor set $U=\{u_1,u_2,\cdots,u_m\}$ and evaluation grade standard collection $V=\{v_1,v_2,\cdots,v_n\}$ should be determined. The evaluation factor set U is a set of m factors for evaluation object, V is a collection of n evaluation ratings for each factor. Due to the influence of various factors on the evaluation is different. Analytic hierarchy process (AHP) is employed to

allocate corresponding weight to each factor. Weight indicators $W=\{w_1,w_2,\cdots,w_m\}$ of m factors satisfy the relational expression:

$$\sum_{i=1}^{m} w_i = 1 \tag{1}$$

(2) Fuzzy comprehensive evaluation. Comprehensive evaluation is in accordance with various factors of the category. The lines of evaluation matrix are evaluation grade standard of each factors, and columns of evaluation matrix are each factor, evaluation matrix R can be obtained by:

$$R=\begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix} \tag{2}$$

Weighted sets $W=\{w_1,w_2,\cdots,w_m\}$ is obtained by AHP, fuzzy comprehensive evaluation set of such factors is defined as:

$$\boldsymbol{B}=\boldsymbol{W}\circ\boldsymbol{R}=(b_1,b_2,\cdots,b_n) \tag{3}$$

Where $b_j=\min\left\{1,\sum_{i=1}^{m}(a_i\wedge r_{ij})\right\},(j=1,2,\cdots,n)$, which takes all the factors into account at the same time and makes full use of information of R, the level of comprehensive evaluation is strong, so the choice of this model is to evaluate each evaluation rating $v_j\ (j=1,2,\cdots,n)$ considering various factors at the same time.

B. *Analytic Hierarchy Process*

The AHP is a structured technique for helping people deal with complex decisions. It can help us deal with qualitative problems with quantitative analysis method. Firstly, each index in system should be resolved into several levels. Every index at the same level is subject to the upper index and governs the lower index. Then a hierarchical structure model about the problem can be constructed. Secondly, the relationship of indexes in system should be analyzed. With a rule, one index should be compared with another index at the same level about the importance to the upper index. Then a comparison matrix about the comparison process can be got. Lastly, the weight of every index can be got with the comparison matrix based on the rule and the consistency of comparison matrix should be tested. Using weight indexes, total arrangement weight of level to system can be got [12].

In this paper, the process of AHP is as follows:

(1) First, criteria are compared pair-wise with respect to the goal. A judgmental matrix, denoted as A, will be formed using the comparisons. Each entry a_{ij} of the judgmental matrix is formed comparing the row element A_i with the column element A_j :

$$A=(a_{ij})\ \ (i,j=1,2,\ldots,\text{the number of criteria}) \tag{4}$$

The use of a Point 9 scale to transform the verbal judgments into numerical quantities representing the values of a_{ij} The scale is explained in Table I.

Table I The fundamental scale

Intensity of importance	Explanation
1	Two activities contribute equally to the objective, elements A_i and A_j are equally important
3	Experience and judgment slightly favor A_i over A_j
5	Experience and judgment strongly favor A_i over A_j
7	A_i is favored very strongly over A_j; its dominance demonstrated in practice
9	The evidence favoring A_i over A_j is of the highest possible order of affirmation
2、4、6、8	Sometimes one needs to interpolate a compromise judgment numerically because there is no good word to describe it
Reciprocals of above	If A_i has one of the above judgments assigned to it when compared with A_j, then A_j has the reciprocal value when compared with A_i

(2) Once the judgmental matrix of comparisons of criteria with respect to the goal is available, the local priorities of criteria is obtained and the consistency of the judgments is determined. It has been generally agreed that priorities of criteria can be estimated by finding the principal eigenvector ω of the matrix A, That is:

$$Aw=\lambda_{max}\omega \tag{5}$$

When the vector ω is normalized, it becomes the vector of priorities of the criteria with respect to the goal. λ_{nax} is the largest eigenvalue of the matrix A and the corresponding eigenvector ω contains only positive entries. The consistency of the judgmental matrix can be determined by a measure called the consistency ratio (*CR*), defined as:

$$CR=\frac{CI}{RI} \tag{6}$$

Where *CI* is called the consistency index and *RI*, and the random index *CI* is defined as:

$$CI=\frac{(\lambda_{\max}-n)}{(n-1)} \tag{7}$$

RI is the consistency index of a randomly generated reciprocal matrix from the Point 9 scale, with reciprocals forced. The *RI* values for matrices of different sizes are shown in Table II.

Table II Average consistencies of random matrices

Size	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

If *CR* of the matrix is higher, it means that the input judgments are not consistent, and hence are not reliable. In general, a consistency ratio of 0.10 or less is considered acceptable. If the value is higher, the judgments may not be reliable and have to be elicited again.

C. Pre-warning Method of High-speed Railway Signal System

For the pre-warning method of high-speed railway signal system, the risk level of system is reflected by layered warning light signals. Pre-warning signal is divided into four levels: green signal means the risk level of the system is acceptable, which need to maintain the status quo. Blue signal means the risk level of the system is conditional acceptable, which need to attract the attention of managers. Yellow signal means the risk level of the system is undesired, which can result in system failure and delay. Red signal means the risk level of the system is unacceptable, which may cause an accident, and the managers must take timely measures to control the risk.

According to the fuzzy comprehensive evaluation method to determine the four evaluation levels, assuming that the evaluation results of the acceptable risk level correspond to the green signal.

The evaluation results of the conditional acceptable risk level correspond to the blue signal; the evaluation results of the undesired risk level correspond to the yellow signal; the evaluation results of the unacceptable risk level correspond to the red signal. The risk pre-warning of the system and subsystem can be getting by the results of fuzzy comprehensive evaluation, for each subsystem of the evaluation index system of the single parameter and the subjection degree can be used on the basis of numerical pre-warning and risk pre-warning signals. Risk pre-warning level index are shown in Table III.

Table III Risk pre-warning level index table

Pre-warning level		Level I Green signal (Acceptable)	Level II Blue signal (Conditional acceptable)	Level III Yellow signal (Undesired)	Level V Red signal (Unacceptable)
Comprehensive index	Fuzzy comprehensive evaluation result of system B_i	$i \le 1$	$i = 3$	$i = 4$	$i \ge 5$
	Fuzzy comprehensive evaluation result of sub-system b_i	$i \le 2$	$i = 3$	$i = 4$	$i \ge 5$
	Subjection degree $r_{ij}(u_i)$	$i \le 2$	$i = 3$	$i = 4$	$i \ge 5$

III. CONSTRUCTION OF EARLY WARNING MODEL OF HIGH-SPEED RAILWAY SIGNAL SYSTEM

The risk monitoring and pre-warning technology in the high-speed railway signal system lead to finding accident potential and all kinds of risk, and giving the pre-warning suggestion to the relevant personnel in time. Accurately, the scientific method is adopted to carry on the control and management of the risk, to reduce the accident risk effectively and guarantee the safety [13].

The safety pre-warning model of high-speed railway signal system includes many indexes. Each index includes many related factors. To these factors, some can be quantitative expression and some can only be qualitative expression. We can combine analytic hierarchy process with fuzzy comprehensive evaluation approach to get the safety pre-warning model of high-speed railway signal system.

The multi-grade fuzzy comprehensive evaluation about quantitative index together with qualitative index can be achieved. There are three key factors of this method: factor set (U), weight set (W) and evaluation set (V).

A. Determining the Factor Set and Evaluation Set

$U = \{u_1, u_2, \cdots, u_m\}$ is evaluation factor set, that is the evaluation index system $u_i (i = 1, 2, \cdots, m)$ shows the i factor which is influential to evaluation objects. The establishment of index system must follow the principles: systematic, scientific comparability and feasibility. After Delphi questionnaires repeatedly surveys, index system is divided into a number of levels according to their attributes. In general, the levels can be classified into three categories.

The highest level: only one factor in this level, which is usually the intended target or desired results in analyzing problems, so, also known as the target layer.

The middle level: this level includes intermediate links used for the realization of target level. It can be composed of a number of levels, including the criteria and the sub-criteria, thus, also known as criteria level.

The lowest level: this level includes a variety of measures and decision-making schemes for achieving the target, thus, also known as scheme level.

Evaluation grade standard collection $V = \{v_1, v_2, \cdots, v_n\}$

should be determined. The evaluation factor set U is a set of m factors for evaluation object, V is a collection of n evaluation ratings for each factor. The influence of various factors on the evaluation is different [14-15].

B. Determining the Weight Set

The weight set is based on the expert investigation, all of the weight subsets are expressed using qualitative language, which are transformed into normal cloud. The degree of the importance can be expressed using different normal cloud digital characters. The weight set can be expressed as $W=\{w_1, w_2, \cdots, w_m\}$. Normally, the grade of the weight factor subsets is not less than 3 and not more than 9.

C. Risk Matrix Rating Standard

The basic idea of security risk classification is based on the theory of risk of mathematical relationship, risk = risk probability × risk severity degree. The risk rating can be obtained according to the degree of risk levels. In the actual process of risk management, it is hard to calculate the risk accurately and quantitatively, so qualitative or half quantitative methods commonly are used in the risk level classification.

In the process of the risk assessment of railway signal system, expert assignment or index can be used to express the likelihood and the severity of the accident. Risk matrix rating table is presented in Table IV.

Table IV Risk matrix rating table

Risk probability	Risk severity degree				
	Level V (Negligible)	Level IV (Mild)	Level III (Moderate)	Level II (Serious)	Level I (Disaster)
Frequent	6	6	7	8	8
Sometimes	4	5	6	7	8
Occasional	2	4	5	7	7
Rare	1	2	4	6	7
Remote	1	1	3	5	6

Evaluation criterion can be defined as four levels in this paper, acceptable, conditional acceptable, don't want to, unacceptable [14], the value range of these four levels are defined as: [0, 3), [3, 5), [5, 7) and [7, 8], use these evaluation criterions to describe the evaluation results.

IV. MODEL APPLICATION

A. Construction of "Human-machine-environment" Multiple Risk Factors

High-speed railway signal system is related to railway corporation management, line operation, supervision, organization and personnel. Involving the signal system equipment, maintenance of equipment and all kinds of complicated environment.

These large "human-machine-environment" multiple risk factors, in which each part is risk factor, risk involved in the whole process of the train operation, unsafe failure and accident is the result of multiple factors interaction.

The occurrence of each risk factor could cause new risks, which needs us to research the interaction relationship between the "human-machine-environment" multiple risk factors. "Human-machine-environment" multiple risk factors for the index system of high-speed railway signal system risk model established by collecting relevant information and consulting expert experience, as shown in Fig. 3.

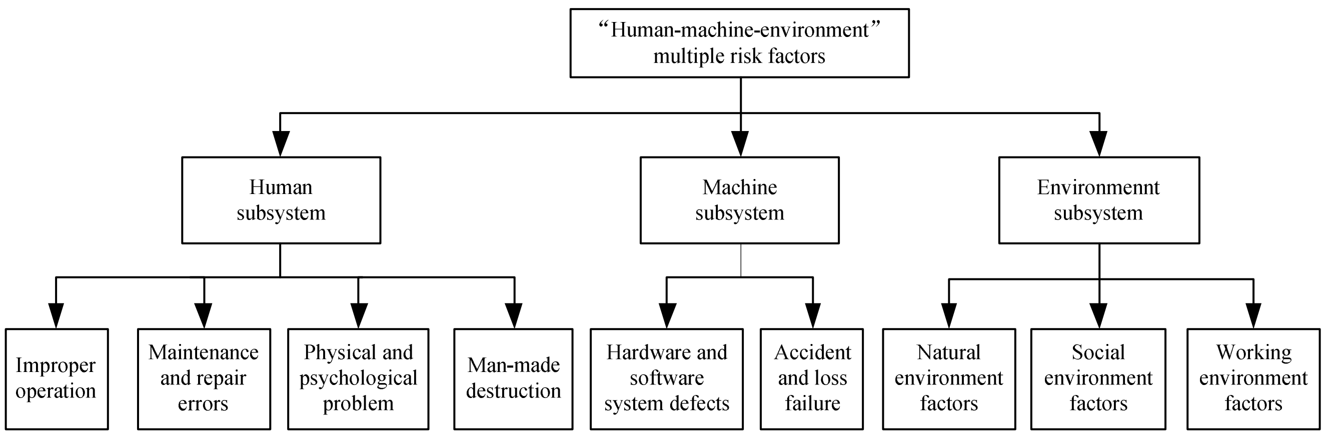

Fig. 3 Construction of "human-machine-environment" multiple risk factors

In Fig. 3, first layer is "human-machine-environment" multiple risk factors. Second layer indicators are human subsystem, machine subsystem and the environment subsystem; Secondary indexes in human subsystem indicators including improper operation, maintenance and repair errors, physical, psychological problems and man-made destruction;

Machine subsystem indicators including hardware and software system defects and accident and loss failure; Environment subsystems including natural environment, social environment and working environment factors .

B. Risk Comprehensive Analysis of High-speed Railway Signal System

The risk comprehensive analysis of high-speed railway signal system is constructed by a detailed survey get the data to evaluation system to support the data. Risk level obtained by collecting the data, the applications described earlier risk calculation model for high-speed railway signal system risk analysis of three factors subsystems, one is obtained by fuzzy comprehensive evaluation method of human risk assessment, machine risk assessment and environmental risk assessment results as follows:

$$\psi_h = \omega_h \times R_h = (b_1, b_2, b_3, b_4)$$

$$\psi_m = \omega_m \times R_m = (b_1, b_2, b_3, b_4)$$

$$\psi_e = \omega_e \times R_e = (b_1, b_2, b_3, b_4)$$

According to the results of evaluation subsystem, we can get the overall risk of the system, assuming R_s is the membership degree of fuzzy matrix for high-speed railway signal system: $R_s = (\psi_h\ \psi_m\ \psi_e)'$. Each subsystem's risk influence to the system weights determined by analytic hierarchy process: $\omega_s = (0.635\ \ 0.259\ \ 0.106)$. Assuming the risk for high-speed railway signal system is $\psi_s = \omega_s \circ R_s = (B_1, B_2, B_3, B_4)$. Based on the principle of maximum membership degree, $\text{Max}(B_1, B_2, B_3, B_4)$ is the corresponding evaluation, risk assessment of the value is high-speed railway signal system, so we got the risk level of high-speed railway signal system as a whole.

C. Pre-warning Process of High-speed Railway Signal System

In order to get the risk pre-warning results of the high-speed railway signal system, firstly, we should analyze the risk of each subsystem, then the overall risk of system is analyzed, the risk assessment for grading index membership degree is identified as the pre-warning indicators. The pre-warning process is: $Max(B_i)\ i \in (1,2,3,4)$ is maximum membership degree principle, which is determined according to the fuzzy comprehensive evaluation. When $i \geq 3$ the system risk status need to attract the attention of managers, and the larger the value of i , the lower the risk of system. After the system raise warning alarm, the risk level $Max(b_i)\ i \in (1,2,3,4)$ of each subsystem can be traced to analyze, the corresponding value of i is maximum, the risk level of the subsystem is the lowest. Subsystem with low risk level, we need to further explore the influencing factors of risk subsystem. It must be traced back to the index of subsystem layer. It is necessary to analyze the membership degree of each index, and identify the bottleneck of system. Pre-warning process is shown in Fig. 4.

Combining with the above analysis of the high-speed railway system after absorbing fuzzy evaluation result of three subsystems, we have calculated the fuzzy risk level of the whole system, and conducted the pre-warning.

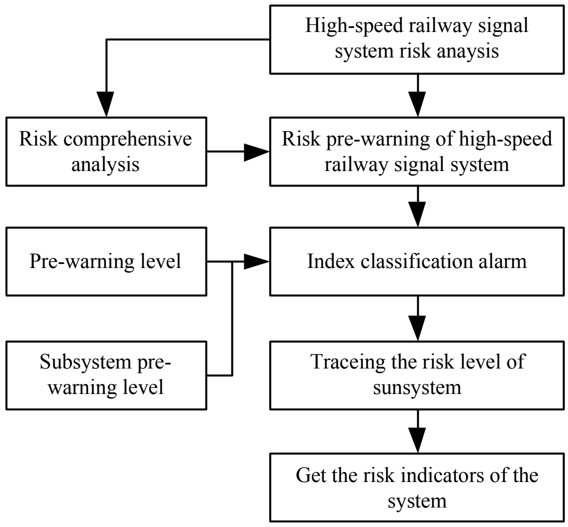

Fig. 4 The procedure of the pre-warning

In this paper, we get the subordinate vector of the three subsystems as follows:

$$\psi_h = \omega_h \times R_h = (0.9293, 0.0707, 0.0363, 0)$$

$$\psi_m = \omega_m \times R_m = (0.0587, 0.1403, 0.4773, 0)$$

$$\psi_e = \omega_e \times R_e = (0.9567, 0.0433, 0.0217, 0)$$

Fuzzy comprehensive evaluation matrix is obtained as:

$$R_s = \left(\psi_h \quad \psi_m \quad \psi_e\right) = \begin{pmatrix} 0.9293 & 0.0707 & 0 \\ 0.0587 & 0.1403 & 0 \\ 0.9567 & 0.0433 & 0 \end{pmatrix}$$

The overall fuzzy reliability of systems is obtained as:

$$\psi_s = \omega_s \circ R_s = (0.7067, 0.0858, 0.1490, 0)$$

According to maximum membership degree principle, the fuzzy risk level of the high-speed railway signal system is acceptable if the pre-warning signal is green. The risk level of corresponding system in a good condition. In the three subsystems, the risk level of human subsystem and environment subsystem is acceptable.

The risk level of machine subsystem is conditional acceptance by analyzing the membership degree of index of machines in the system. The risk level of equipment and operating units are blue alert signal, and the risk of operating unit level is lower than the risk of unit level. The risk of this machine subsystem level is acceptable, but it needs to attract the attention of managers, so the management department should take reasonable measures to improve the risk level of the each subsystems.

V. Conclusions

According to the safety characteristics of high-speed railway signal system, the risk factors of railway signal system were analyzed. The safety problem of "human-machine-environment" system was studied, and the pre-warning mechanism was introduced into the safety management of high-speed railway. The safety index system of the railway signal system and the multi-risk factors of the "human-machine-environment" were established. The application results show that the pre-warning model can not only classify the evaluation results, but also analyze the uncertainty of the evaluation objects, and provide more abundant reference information for risk assessment, effectively preventing the occurrence of railway transportation accidents. Railway signal system risk monitoring and pre-warning technology is a comprehensive risk management system, which can significantly improve the risk management level. With the support of fuzzy analytic hierarchy process, the system has improved the safety production level, improved the overall management level of the system, and ensured the safety of high-speed railway transportation.

Acknowledgment

This artical is support by China Railway Corporation Science and Technology Research and Development Plan Project (2017J005-A).

References

[1] Youpeng Zhang, Zhengjie Xu, and Hongsheng Su, "Risk assessment on railway signal system based on fuzzy-FMECA method," in *Sensor & Transducers*, vol. 165, no. 09, pp. 203-210, September 2013.

[2] Youpeng Zhang, Zhengjie Xu, and Hongsheng Su, "Risk evaluation and application on fuzzy-FMECA method using cloud model," in *TELKOMNIKA Indonesian Journal of Electrical Engineering*, vol.12, no. 02, pp. 1509-1518, February 2014.

[3] Dechao Liu. "Research on safety and risk warning of the high-speed railway signal system." *Beijing Jiaotong University*, Beijing, 2019.

[4] C.K. Kwong, H. Bai, "Determining the importance weights for the customer requirements in QFD using a fuzzy AHP with an extent analysis approach," in *IIE Transactions*, vol. 35, no. 7, pp. 619-626, October 2010.

[5] Felix T.S. Chan, Niraj Kumar, "Global supplier development considering risk factors using fuzzy extended AHP-based approach," in *Omega*, vol. 35, no. 4, pp. 417-431, August 2007.

[6] Chuanchun Fu. "Research on network security risk assessment method for high-speed railway signal system." *Xinan Jiaotong University*, Chengdu, 2017.

[7] Yanxia Ma, Yunshui Zheng, Bing Ma, et al, "Safety analysis of railway Signal systems based on extension." in *Control Engineering of China*, vol. 26, no. 03, pp. 525-531, March 2019.

[8] Guangde Li. "The railway train safety early warning system based on information fusion technology research." *Chongqing Jiaotong University*, Chongqing, 2016.

[9] Zhengjie Xu, Youpeng Zhang, and Hongsheng Su, "Application of risk assessment on fuzzy comprehensive evaluation method based on the cloud model," in *Journal of Safety and Environment*, 14, no. 02, pp. 69-72, April 2014.

[10] Zhenguo Yu. "Research of rail safety risk early warning system & key technology." *China Academy of Railway Sciences*, Beijing, 2017.

[11] Zhida Jiao, Rui Song, and Shengbo Cheng, "Research on early warning model for railway operation safety," in *Journal of Dalian Jiaotong University*, vol. 36, no. 04, pp. 74-79, August 2015.

[12] Zhenzhen Luo. "Research on information security situation assessment method of railway signal system." *Beijing Jiaotong University*, Beijing, 2018.

[13] M. Rezvani, V. Sekulic, A. Ignjatovic, et al, "Interdependent security risk analysis of hosts and flows," in *IEEE Transactions on Information Forensics and Security*, vol. 10, no. 11, pp. 2325-2339, November 2015.

[14] Chichun Lo, Jiawan Chen, "A hybrid information security risk assessment procedure considering interdependences between controls," in *Expert System with Application*, vol. 30, no. 01, pp. 247-257, January 2012.

[15] K. M. Carter, N. Idika and W. W. Streilein, "Probabilistic threat propagation for network security," in *IEEE Transactions on Information Forensics and Security*, vol. 9, no. 9, pp. 1394-1405, September 2014.