Research on Human Reliability of the High-speed Railway Intelligent Dispatching Centralized Traffic Control System.

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***Abstract*—In order to effectively evaluate the human reliability of the high-speed railway intelligent dispatching Centralized Traffic Control (CTC) system. and reduce railway accidents caused by human errors of dispatchers. Based on the basic method of Cognitive Reliability and Error Analysis Method (CREAM), a human reliability evaluation model was established. The subjective and objective weights of the CPCs were obtained by the G1 method and the CRITIC method, respectively, and the combined weights of the Common Performance Conditions (CPC) were obtained on this basis. In order to make the calculation of Human Error Probability (HEP) more accurate, the Evidential Reasoning approach is used to aggregate the membership degrees of the CPCs performance effect to obtain the Context Influence Index (CII). Finally, the CII is used to evaluate the human reliability of the high-speed railway intelligent dispatching CTC system. The results show that the method can accurately calculate the HEP of the high-speed railway intelligent dispatching CTC system, and can provide a theoretical basis and reference for the personnel safety analysis of the high-speed railway intelligent dispatching CTC system.**

Keywords—intelligent dispatching CTC; CPC; human reliability; CREAM; CII; HEP

I. Introduction

As the nerve center of the high-speed railway transportation system, the Centralized Traffic Control (CTC) system is responsible for ensuring the safe, stable and reliable operation of trains[1]. With the continuous development of science and technology, high-speed railway intelligent CTC systems have emerged as the times require, using advanced technologies such as cloud computing, Internet of Things, big data and artificial intelligence. The intelligent CTC system is divided into three stages according to the level of intelligence: the intelligent CTC1.0 stage mainly realizes the functions of auxiliary adjustment of the train operation plan and the comprehensive safety card control of the train and shunting operation; the intelligent CTC2.0 stage mainly realizes the train operation Functions such as automatic plan adjustment and early and late prediction; the intelligent CTC3.0 stage mainly realizes functions such as the application of big data of train scheduling information and the intelligent adjustment of train operation plans. The official opening of the Beijing-Zhangjiakou high-speed railway at the end of 2019 marks that the CTC system has officially entered the stage of intelligent CTC 1.0. Because the intelligent CTC1.0 stage is in its infancy, its automation and intelligence level is low, and most of the operations still needs dispatchers to operate through the terminal. With the continuous advancement of science and technology, the reliability of the hardware equipment of the CTC system has been continuously improved, and the reliability of human factors has become a bottleneck restricting the reliability of the system.

Compared with domestic research in China, foreign research on human factors is earlier. In the 1950s, the Sandia National Laboratory in the United States carried out research on the Human Reliability Analysis (HRA) method. With the development of cognitive science, HRA method has also been developed rapidly. Cognitive reliability and error analysis method (CREAM) is one of the most representative classical methods in HRA methods. Because of its simplicity, science and easy operation, it has been widely used in nuclear power industry, marine transportation, aerospace, mineral mining and other fields with high safety requirements in recent years, and achieved good application results.

CREAM emphasizes that the performance output of people in production activities is not an independent random behavior, but affects people's cognitive control mode through the situational environment in which people complete tasks, that is, Common Performance Condition (CPC)[2]. Ultimately determine the person's response behavior. CREAM is divided into basic and extended methods. The basic method is relatively simple but cannot obtain relatively accurate Human Error Probability (HEP) values. Therefore, many scholars are committed to obtaining the exact value of HEP on the basis of the basic method. Marseguerr and Yang established the fuzzy evidential reasoning model based on CREAM by using the fuzzy inference method, and realized the quantitative calculation of HEP[3],[4]. In order to reduce the subjectivity of CPC performance evaluation, multi-attribute decision-making method is also introduced into CREAM[5]. In addition, Bayesian Network (BN) is also applied to CREAM. Papers[6], [7] and [8] use BN to obtain the probability distribution of control modes, and then calculate the value of HEP on this basis. Since Dr. Hollnagel, the founder of CREAM in 2012, published a disclaimer against the CREAM extension method on his personal blog, he pointed out that the extension method has some inevitable flaws. Therefore, this paper only improves the CREAM basic method.

Although the above methods have achieved certain results in application. However, the existing CREAM improvement methods still have some deficiencies in the calculation of weights of CPCs and the aggregation of data, which makes the calculation accuracy of HEP low. To solve this problem, this paper proposes an improved CREAM method based on Evidential Reasoning (ER). This method first calculates the objective weight and subjective weights of CPCs through the Criteria Importance Though Intercrieria Correlation method (CRITIC) and the G1 method, then uses the combined weighting method to combine the subjective and objective weights to obtain the combined weights of the CPCs. On this basis, the ER approach is used to aggregate the datas of CPCs, and then the Context influence index (CII) value is obtained, and calculate the exact value of HEP through the CII value. Finally, the method is applied to the calculation case of the human reliability of the high-speed railway intelligent CTC system, and the case results show that the method is feasible and effective.

II. METHODOLOGY

A. CREAM

CREAM believes that there are 4 control modes, namely “scrambled mode”, “opportunistic mode”, “tactical mode” and “strategic mode”. At the same time, CREAM also gives the HEP interval under these 4 control modes[2], as shown in Table I.

TABLE I. CONTROL MODE AND PROBABILITY INTERVAL OF HEP

Control mode	Probability interval of HEP
Strategic	(0.00005，0.01)
Tactical	(0.001，0.1)
Opportunistic	(0.01，0.5)
Scrambled	(0.1，1. 0)

The above 4 control modes are determined by 9 CPCs, which are “adequacy of organization (C_1)”, “working conditions(C_2)”, “adequacy of man–machine interface and operational support(C_3)”, “availability of procedures and plans(C_4)”, “number of simultaneous goals(C_5)”, “available time(C_6)”, “time of day(C_7)”, “adequacy of training and experience(C_8)” and “ crew collaboration quality(C_9)”. According to its impact on the performance effect of human reliability, it is divided into 3 cases: positive effect “improved”, neutral effect “no significant” and negative effect “reduced”. By counting the number of “improved” and “reduced”, use the coordinate method (Σ_{improved}, Σ_{reduced}) to determine the control mode according to Figure 1. After determining the control mode, use Table 1 to determine the interval of HEP.

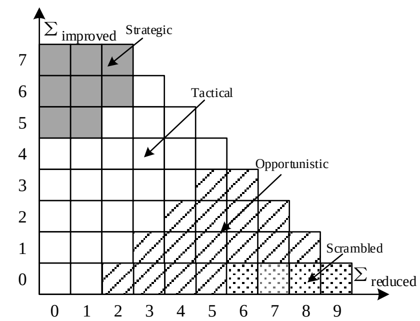

Fig. 1. Determine the diagram of the control mode.

B. Evidential Reasoning

ER approach is a multi-source information fusion algorithm based on Dempster-Shafe theory and decision theory[9]. Compared with other approach, the ER approach has a strong modeling ability for some data with fuzzy uncertainties, uncertain probability and nonlinear characteristics, which makes the results of data fusion more credible. The specific ideas are as follows:

Suppose there is a two hierarchy indicator system. The first-level indicator X and its subordinate second-level indicator $Y = \{y_i|i = 1,2,\ldots,l\}$, The weight vector of Y is $\boldsymbol{W} = \{w_i|i = 1,2,\cdots,l\}$, and $0 \leqslant w_i \leqslant 1$, $\sum_{i=1}^{l} w_i = 1$. There exists the same evaluation set $H = \{h_j|\ j = 1,2,\ldots,n\}$ for all the indicators in the two hierarchy indicator system. Without loss of generality, it is assumed that h_{j+1} is preferred to h_j. If the evaluation of the index yi can be expressed as:

$$S(y_i) = \left\{\left(h_j, \beta_{j,i}\right), i = 1,2,...,l;\ j = 1,2,...,n\right\} \tag{1}$$

where $\beta_{j,i}$ represents the belief degree that the i-th secondary indicator y_i is rated as h_j, and $\beta_{j,i} \geqslant 0$, $\sum_{j=1}^{n} \beta_{j,i} = 1$.

Let $m_{j,i}$ denote the degree to which the secondary indicator y_i supports the primary indicator X being rated as h_j, and $m_{H,i}$ denote the degree to which the primary indicator X is considered “uncertain”.

$$m_{j,i} = w_i \beta_{j,i} \tag{2}$$

$$m_{H,i} = 1 - \sum_{j=1}^{n} m_{j,i} = 1 - w_i \sum_{j=1}^{n} \beta_{j,i} \quad (3)$$

$$\bar{m}_{H,i} = 1 - w_i \quad (4)$$

$$\tilde{m}_{H,i} = w_i \left(1 - \sum_{j=1}^{n} \beta_{j,i} \right) \quad (5)$$

where $\bar{m}_{H,i}$ represents the probability function assigned by the unknown weight, $\tilde{m}_{H,i}$ represents the probability function assigned by the unknown evaluation.

$m_{j,I(i)}$, $m_{H,I(i)}$, $\bar{m}_{H,i}$ and $\tilde{m}_{H,i}$ are the mass functions obtained by the aggregation of the previous *i* secondary indicators, then the combined probability assignment function of them and the *i*+1 secondary indicator aggregation is:

$$m_{j,I(i+1)} = K_{I(i+1)} \left[m_{j,I(i)} m_{j,i+1} + m_{H,I(i)} m_{j,i+1} + m_{j,I(i)} m_{H,i+1} \right] \quad (6)$$

$$m_{H,I(i+1)} = \bar{m}_{H,I(i)} + \tilde{m}_{H,I(i)} \quad (7)$$

$$\tilde{m}_{H,I(i+1)} = K_{I(i+1)} \left[\tilde{m}_{H,I(i)} \tilde{m}_{H,i+1} + \bar{m}_{H,I(i)} \tilde{m}_{H,i+1} + \tilde{m}_{H,I(i)} \bar{m}_{H,i+1} \right] \quad (8)$$

$$\bar{m}_{H,I(i+1)} = K_{I(i+1)} \left[\bar{m}_{H,I(i)} \bar{m}_{H,i+1} \right] \quad (9)$$

$$K_{I(i+1)} = \left(1 - \sum_{t=1}^{n} \sum_{\substack{j=1 \\ j \neq t}}^{n} m_{t,I(i)} m_{j,i+1} \right)^{-1}, i = 1,2,...,l-1 \quad (10)$$

Where $K_{I(i+1)}$ is the conflict factor, indicating the degree to which different indicators support a certain evaluation level

Calculate the belief degree of the first-level indicator *X*, the formula is as follows:

$$\beta_j = \frac{m_{j,I(j)}}{\left[1 - \bar{m}_{H,I(i)} \right]} \qquad \beta_H = \frac{\tilde{m}_{H,I(j)}}{\left[1 - \bar{m}_{H,I(i)} \right]} \quad (11)$$

Where β_j represents the belief degree of the first-level indicator *X* being rated as h_j, and β_H represents the belief degree of the first-level indicator *X* being rated as "uncertain".

Since the performance effect of CPC is divided into "improved", "no significant" and "reduced", the belief degree distribution corresponding to the performance effect of the *i*-th CPC can be expressed as::

$$S(C_i) = \left\{ \left(h_1, \beta_{1,i} \right), \left(h_2, \beta_{2,i} \right), \left(h_3, \beta_{3,i} \right) \right\}, i = 1,2,...,9 \quad (12)$$

Where, h_1, h_2 and h_3 correspond to the three performance effect levels of "improved", "no significant" and "reduced", respectively.

III. IMPROVED CREAM MODEL BASED ON ER APPROACH

A. *Calculation of the CPCs Weights*

1) Objective weight

CPC is an important factor affecting the CREAM control mode. Hollnagel believes that there is a correlation between CPCs. After studying a large number of human accidents, Hollnagel gave the adjustment rules of CPC, as shown in Table II.

TABLE II. RULES FOR ADJUSTING CPCS

Adjusted CPCs	Dependent CPCs					Threshold
C_2	C_1	C_3	C_6	C_7	C_8	4
C_5	C_2	C_3	C_4	-	-	2
C_6	C_2	C_3	C_4	C_5	C_7	4
C_9	C_1	C_8	-	-	-	2

According to Table II, taking C_9 as an example to illustrate the adjustment rules, if the performance effect of C_9 is "no significant" and the performance effects of C_1 and C_8 are "improved", then the performance effect of C_9 is adjusted from "no significant" to "improved". It can be seen that there is still coupling between CPCs, The adjustment rules of the other three CPCs are similar and will not be repeated here.

For the weight calculation of CPC, most of the improved models of CREAM use the Analytic Hierarchy Process(AHP). It can be seen from Table 4 that there is a correlation between CPC. From the perspective of information theory, if the correlation between a CPC and other CPC is smaller, the information provided by it is more differentiated and the amount of information is larger, so the CPC is more important and the weight assigned to it should be larger. It can be seen that it is reasonable to assign weights according to the relevance of CPC.

Different from the entropy weight method and the standard deviation method, when calculating the weight, the CRITIC method not only considers the influence of variation on CPCs, but also considers the influence of correlation on CPCs, so the obtained weight is more credible. The basic steps of the CRITIC method are as follows:

First, calculate the standard deviation of each CPC. The standard deviation σ_i is calculated as follows:

$$\sigma_i = \sqrt{\frac{1}{m-1} \sum_{q=1}^{m} \left(y_{q,i} - \bar{y}_i \right)^2} \quad i = 1,2,...,9 \quad (13)$$

where $y_{q,i}$ is the value of C_i in the *q*-th(q=1,2,…,m) task, and $\bar{y}_i$ is the mean value of C_i in *m* tasks.

Second, the conflict between CPCs is calculated. The conflict between C_i and other CPCs is calculated as follows:

$$p_i = \sum_{j=1}^{n} \left(1 - \frac{Cov(i,j)}{\sigma_i \sigma_j} \right) \quad i = 1,2,...,9 \quad (14)$$

where $Cov(i,j)$ represents the covariance of C_i and C_j, and σ_i and σ_j represent the standard deviation of C_i and C_j, respectively.

Finally, the objective weight is calculated. The objective weight of C_i is calculated as follows:

$$\omega_i = \frac{\sigma_i p_i}{\sum_{i=1}^{n} \sigma_i p_i} \quad i = 1,2,...,9 \tag{15}$$

2) Subjective weight

G1 method is an improved subjective weighting method of AHP. Compared with AHP, it does not need to construct judgment matrix and consistency test, and its calculation is simple and effective[10]. The specific calculation steps are as follows:

Determine the most significant CPC in the CPCs, denoted as x_1, then filter the second most significant index as x_2, and so on, until all CPCs are sorted by significance, denoted as $X=\{x_1,x_2,\ldots,x_9\}$.

Judging the significance of CPC in Table III, the ratio of the significance of x_{i-1} to x_i is r_i:

$$r_i = \frac{\lambda_{i-1}}{\lambda_i} \qquad i = 2,3,...,9 \tag{16}$$

where λ_i is the weight of the i-th CPC.

TABLE III. SIGNIFICANCE JUDGMENT CRITERIA

r_i	Significance statement
1.0	x_{i-1} and x_i Equally Significant
1.2	x_{i-1} is slightly more significant than x_i
1.4	x_{i-1} is relatively more significant than x_i
1.6	x_{i-1} is quite more significant than x_i
1.8	x_{i-1} is extremely more significant than x_i

Using the r_i value, calculate the weight value of the 9-th CPC

$$\lambda_9 = \left(1 + \sum_{i=2}^{9} \prod_{k=i}^{n} r_k\right)^{-1} \tag{17}$$

The weights of other CPCs are calculated as follows:

$$\lambda_{i-1} = r_i \lambda_i \qquad i = 2,3,...,9 \tag{18}$$

3) Combined weight

In order to obtain the weight of CPCs, both subjectivity and objectivity can be considered. Then the difference between the subjective weight and the objective weight to the combined weight should be smaller, and the following objective function M1 is established for this purpose.

$$\text{M1}: \begin{cases} \min(w) = \sum_{i=1}^{9} \left(w_i \ln \frac{w_i}{\omega_i} + w_i \ln \frac{w_i}{\lambda_i} \right) \\ s.t. \ \sum_{i=1}^{9} w_i = 1, \ w_i \ge 0, \quad i = 1,2,...,9 \end{cases} \tag{19}$$

Solve M1 to get the combined weights:

$$w_i = \frac{\sqrt{\omega_i \times \lambda_i}}{\sum_{i=1}^{9} \sqrt{\omega_i \times \lambda_i}} \quad i = 1,2,...,9 \tag{20}$$

Where λ_i is the subjective weight and ω_i is the objective weight.

B. Calculation of HEP value

For CREAM, there are three reasonable assumptions[11],[12]:

- The control mode space is continuous.
- HEP varies with the context exponentially
- If the maximum Σ_{improved} and the minimum Σ_{reduced} are reached at the same time, namely, (Σ_{improved}, Σ_{reduced})=(7, 0), the context is in the most supportive state and HEP is at its minimum. On the contrary, if (Σ_{improved}, Σ_{reduced}) = (0, 9), the highest value of HEP is reached.

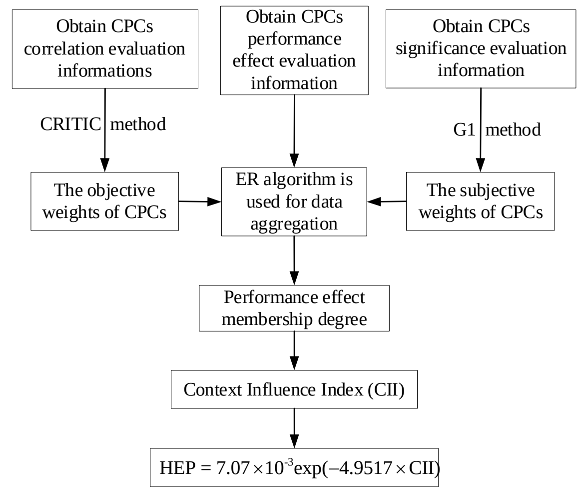

Fig. 2. Human Reliability Evaluation Process of High-speed Railway Intelligent Dispatching CTC System.

On this basis, Sun[12] uses the Context influence index (CII) to calculate the HEP. and define the CII formula as：

$$CII = \frac{\Sigma_{\text{improved}}}{7} - \frac{\Sigma_{\text{reduced}}}{9} \tag{21}$$

Then establish the function correspondence between HEP and CII[12]:

$$HEP = \text{HEP}_0 \times \exp(\varphi \times CII) \tag{22}$$

Where HEP_0 is the basic failure probability, i.e. the HEP value when (Σ_{improved}, Σ_{reduced}) = (0, 0), φ is the undetermined coefficient.

According to Assumption 3, we have:

$$\begin{aligned} \text{HEP}_{\min} &= \text{HEP}_0 \times \exp(\varphi) \\ \text{HEP}_{\max} &= \text{HEP}_0 \times \exp(-\varphi) \end{aligned} \tag{23}$$

It is known from Table I that $\text{HEP}_{\max}$=1, $\text{HEP}_{\min}$=0.0005, and substituting them into Eq. (23) can be obtained:

$$\text{HEP}_0 = 7.07 \times 10^{-3}; \varphi = -4.9517 \tag{24}$$

The HEP can be calculate by Eq. (24):

$$HEP = 7.07 \times 10^{-3} \exp(-4.9517 \times CII) \tag{25}$$

Drawing on the ideas of paper [12], this paper defines CII as follows:

$$CII = \beta_1 - \beta_3 \tag{26}$$

Where β_1 and β_3 are “improved” and “reduced” membership degrees, respectively. The neutral effect “not significant” is not considered in CII, because no matter in the traditional CREAM or the improved CREAM, the “not significant” effect is 0, although there is literature [7] that the neutral effect "not significant" should be equivalently assigned to positive and negative effects, even with this view, the results of CII remain unchanged [14].

Therefore, in summary, the human reliability evaluation process of the high-speed railway intelligent dispatching CTC system constructed in this paper is shown in Figure 2.

IV. An Illustrative Example

A. Description of the Example

In order to improve safety management and reduce the occurrence of accidents, a railway Group Co Ltd conducts human reliability assessment on the intelligent CTC system of the lines under the jurisdiction of the railway Group Co Ltd. There are 3 tasks to be evaluated, namely “manually handling the train arrive route” (Task#1), “issuing a construction scheduling order” (Task#2), and “setting a temporary speed limit” (Task#3). The performance effects of CPC for the 3 tasks are shown in Table IV.

TABLE IV. CPCs performance effects for 3 tasks

TASK	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
#1	1	1	0	1	−1	-1	0	0	1
#2	1	1	0	0	−1	0	-1	1	-1
#3	1	1	0	−1	0	-1	0	-1	1

Where 1 means “improved”, 0 means “not significant”, −1 means “reduced”

B. Identify the Headings

Use Eq. (15), (18) and (20) to calculate the subjective and objective weights and combined weights of CPC, respectively. Table V shows the weights of CPCs

TABLE V. CPCs performance effects for 3 tasks

CPCs	**subjective**	**objective**	**combined**
C_1	0.094	0.137	0.114
C_2	0.106	0.108	0.108
C_3	0.128	0.155	0.142
C_4	0.114	0.098	0.107
C_5	0.121	0.068	0.092
C_6	0.086	0.117	0.101
C_7	0.077	0.059	0.068
C_8	0.143	0.127	0.136
C_9	0.131	0.131	0.132

C. Calculation of HEP

After obtaining the weights of the CPCs, the ER approach is used to aggregate the CPC data of the 3 tasks to obtain the membership degrees of different performance effects, Details are shown in Table VI.

TABLE VI. Membership of performance effects

TASK	**Improved (β_1)**	**Not Significant (β_2)**	**Reduced (β_3)**
#1	0.4847	0.3429	0.1725
#2	0.3636	0.3536	0.2828
#3	0.3585	0.2955	0.3460

According to Eq. (25), calculate the HEP of the 3 tasks respectively

$$HEP_1 = 7.07\times10^{-3}\exp(-4.9517\times0.3122) = 0.001507$$
$$HEP_2 = 7.07\times10^{-3}\exp(-4.9517\times0.0808) = 0.004739$$
$$HEP_3 = 7.07\times10^{-3}\exp(-4.9517\times0.3122) = 0.006646$$

It can be seen that the human error probability of “setting a temporary speed limit” (Task#3) is the highest, “issuing a construction scheduling order” (Task#2) is the second, and “manually handling the train arrive route” (Task#1) is the lowest. This is because the process of task#3 is the most complex, so the probability of errors is the highest, which is also very consistent with the results of the on-site investigation, which shows the accuracy of this method from the side.

D. Discussion

It can be seen that ($\Sigma_{improved}$, $\Sigma_{reduced}$) = (4, 2) of task#1, ($\Sigma_{improved}$, $\Sigma_{reduced}$) = (3, 3) of task#2 and task#3. According to the basic CREAM theory, its control modes are “Tactical mode”, so the HEP interval of the 3 tasks are all (0.001, 0.1). The HEP values of the 3 tasks calculated in this paper are all between (0.001, 0.1), which also shows the effectiveness of the calculation method. But compared with the basic cream, the HEP value obtained in this paper is an accurate value, not a rough interval value.

V. Conclusions

The focus of this paper is based on the CREAM basic method, using various methods to improve it, and using the improved method to evaluate the human reliability of the high-speed railway intelligent CTC system. Because the basic method of cream does not take into account the calculation of the weight, the improved method uses the CRITIC method and the G1 method to combine the weights of the CPCs, which makes the weight acquisition more accurate. On the basis of obtaining the weights, ER approach was used to carry out weighted aggregation of CPC to get CII value. Finally, the HEP value of the high-speed railway intelligent dispatching CTC system is obtained by calculating the CII value. The improved method can quantify the HEP of the CTC system more accurately, and has higher precision compared with the traditional CREAM basic method. However, the method in this paper also has some shortcomings. For example, the performance effect evaluation of CPC mainly relies on the on-site observation of experts or professionals to obtain it. In the future, it is necessary to optimize the method of obtaining the performance effect of CPC. Simulation for reliability is also the focus of further research

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