Research on Evaluation Method for Expressway E&M System Operation State Based on AHP-FCE

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Abstract. Based on an AHP-FCE model, an evaluation method for expressway E&M system operation state is proposed. The evaluation system of E&M system operation state is constructed, and three evaluation indexes, i.e. functional serviceability rate, timely repair rate and replacement repair rate, are extracted by using equipment maintenance data; the weight division of each evaluation index is completed in conjunction with AHP algorithm; an FCE model of expressway E&M system operation state is established, and the operation state evaluation is achieved finally. The analysis results show that the system state evaluation method proposed in this paper can gain an insight into the operation state of E&M system, find out systematic potential safety hazards in time, and provide theoretical support for highway maintenance work.

1. Introduction
With the gradual improvement of the expressway network in China, highway engineering construction has entered the stage of large-scale special engineering maintenance. By the end of 2019, the total mileage of expressways in China has reached 149,600km, ranking first in the world[1]. Expressway E&M equipment is the material guarantee to ensure the safe operation of highway, but the management of E&M equipment is still in an "emergent-mode" maintenance stage, the problem of giving "more priority to construction but less to maintenance" is serious[2]. There is a great number of E&M equipment of various types, and most of the equipment requires 24-hour uninterrupted operation. Due to internal quality or external environmental aspect, there are many problems such as frequent equipment failures, lagging maintenance, equipment function degradation, which make some E&M system functions unable to be effectively utilized and make it difficult for them to effectively play their functions, thus bringing potential hazards to the safe operation management of expressways[3-6].

In order to effectively learn the operation state of expressway E&M equipment, many related researches have been carried out by experts and scholars at home and abroad. Qiao Xiaoran et al. established the expressway E&M system evaluation index system according to the characteristics of expressway E&M system. By selecting evaluation indexes from equipment technology and E&M system operation effect, a multilevel fuzzy comprehensive evaluation model of expressway E&M system based on analytic hierarchy process is established to realize the comprehensive evaluation of M&E facilities[7]. Aiming at the current demand of intelligent maintenance of expressway E&M equipment, Xu Honghui et al. adopted the fault prediction and diagnosis hybrid model based on fault condition evolution to realize the fault detection of expressway E&M equipment, transmitted the detection results to E&M equipment intelligent maintenance module, and selected maintenance programs according to the corresponding types to complete the intelligent maintenance of expressway...
E&M equipment [8]. Xu Kun et al. put forward the analytic hierarchy process-based safety risk assessment model of expressway E&M system on the basis of analyzing the research in the field of information system safety risk assessment, and proposed the CAVET evaluation model by analyzing the relationship between the assets, threats, vulnerabilities and safety risks of M&E systems [9]. Chu Chengzan et al. used the comprehensive evaluation method combining analytic hierarchy process and fuzzy mathematics theory based on the combination of daily maintenance testing and special maintenance testing, and comprehensively evaluated the operation state of M&E facilities [10]. Cui et al. deduced a hierarchical standard system according to the current quality inspection and evaluation standards, and calculated the importance of each standard according to Delphi method. Through the membership function, each criterion was given a weight, and a fuzzy comprehensive evaluation model with judgment matrix was established [11]. Zhang et al. analyzed and determined the weights of influencing factors at various levels through expert consultation, and comprehensively evaluated the operation state of E&M system facilities by using five-layer analytic hierarchy process (AHP) structural model and fuzzy mathematics theory [12].

At present, in most expressway E&M equipment researches, the main operation state evaluation method of M&E system is based on the serviceability rate of the E&M system, which lacks the analysis of timely repair time and repair quality after equipment failure. Therefore, this paper puts forward an evaluation method for expressway E&M system operation state based on AHP-FCE, which, based on the maintenance data of expressway E&M equipment, extracts three indexes, i.e. functional serviceability rate, timely repair rate and replacement repair rate, and constructs an expressway E&M system operation state evaluation index system. It adopts AHP model to give weights to different indexes; and it uses FCE model to construct fuzzy matrix according to the weights of different indexes to realize the evaluation of the operation state of expressway E&M equipment.

2. E&M Equipment Operation State Evaluation Model
E&M system is composed of multiple subsystems, distributed in the whole expressway, involving every link from equipment to management. It is an important support for the safe operation of expressway. From the view of the overall situation of the system and the consideration of different functions of each subsystem, the operation state evaluation system and model of expressway E&M system are established through refining the operation state of the expressway E&M system to comprehensively and accurately reflect the operation state of each subsystem and the whole E&M system.

In view of the complexity of E&M system, according to the classification results of E&M system and combined with transportation industry standards, historical maintenance data and expert experience and knowledge, it is determined that the evaluation system of expressway E&M system operation state should be established first from three aspects, i.e. system, subsystem and key equipment, and the specific evaluation indexes should be selected. After induction and reorganization, the evaluation system of expressway E&M system operation state is shown in Fig. 1. The first level is evaluation objective: expressway E&M system operation state; the second level consists of six subsystems: toll collection system, monitoring system, communication system, power supply and distribution system, fire rescue system and tunnel E&M system; and the third level is the key equipment, which is the collective name of all E&M equipment with high fault rate and impact on the safe operation of expressways.
### 2.1. Evaluation index determination

The E&M system of expressway is characterized by multi-level, multi-objective and complexity, so there are many factors that affect the running state of expressway E&M system. It is necessary to consider the applicability and feasibility of specific indexes for state evaluation, construct a unified benchmark for each subsystem to obtain the real-time running state of E&M system. Therefore, this paper puts forward the evaluation indexes of functional serviceability rate, timely repair rate and replacement repair rate based on the operation and maintenance data of E&M equipment, and characterizes the operation state of E&M system through the operation of E&M equipment.

1. **Functional serviceability rate**

   Functional serviceability rate refers to the ratio of the time between failures of E&M equipment to the total running time, which can reflect the current operation state of various types of equipment in the E&M system, and its expression is
   \[
   r = \left(1 - \frac{N_f \times T_f}{N \times T}\right) \times 100\%
   \]

   Where, \( r \) is the functional serviceability rate, and the closer its value is to 1, the higher the stability of the equipment during operation; \( N \), \( N_f \) is the number of faulty equipment; \( T_f \) is the failure time; \( N \) is the total number of equipment; and \( T \) is the total running time;

2. **Timely repair rate**

   Timely repair rate refers to the ratio of the time difference between the time when the E&M equipment fails and the time when the failure is eliminated to the standard repair time of the equipment. This index reflects the maintenance efficiency when the equipment fails, and its expression is:
   \[
   p = \frac{E_d - E_r}{E} \times 100\%
   \]

   Where, \( p \) is the timely repair rate, and the smaller the value, the shorter the failure recovery time of the equipment, which indicates that it can better meet the requirements of the E&M system for uninterrupted operation of the equipment; \( E_d \) is the time of equipment failure; \( E_r \) is the time when the equipment resumes operation; \( E \) is the standard maintenance time of equipment.

3. **Replacement repair rate**

![Fig. 1 Expressway E&M System Operation State Evaluation System](image)
Replacement and repair rate refers to the ratio of the number of direct whole-piece replacements of E&M equipment to the number of trouble shootings in the process of maintenance. This index reflects the fault performance of the equipment, and its expression is

\[ s = \frac{M_l}{M} \times 100\% \]  

(3)

Where, \( s \) is the replacement repair rate, and the closer its value is to zero, the smaller the equipment maintenance cost, indicating that the fault can be eliminated by component repairing; \( M_l \) is the number of direct whole-piece replacements during maintenance; and \( M \) is the number of trouble shootings of equipment.

2.2. Weight determination

To evaluate the equipment operation state of expressway E&M system from different angles, it is necessary to analyze the correlation between various index factors and the weights of different indexes. At present, there are two commonly used weight determination methods: subjective and objective weighting methods. The subjective weighting method is to conduct subjective evaluation of each index factor based on the daily experience of experts in related fields and determine the weight subjectively according to the importance of each index. Objective weighting method is based on the differences between the indexes, using quantitative analysis method to determine the weight. Considering the diversity of the equipment maintenance data of actual E&M system and objective factors, this paper uses Delphi method to determine the weight of each E&M system. The correlation between the two indexes is determined and the importance of the two indexes is judged. Take Indexes \( a \) and \( b \) as examples, the importance of the two indexes is determined using different scales. The importance scales are shown in Table 1.

| S/N | Scale | Importance degree                  |
|-----|-------|-----------------------------------|
| 1   | 1     | \( a \) and \( b \) are equally important |
| 2   | 3     | \( a \) is slightly more important than \( b \) |
| 3   | 5     | \( a \) is more important than \( b \) |
| 4   | 7     | \( a \) is much more important than \( b \) |
| 5   | 9     | \( a \) is absolutely more important than \( b \) |
| 6   | 2, 4, 6, 8 | The importance of \( a \) and \( b \) lies between two adjacent grades |

The relative importance among the functional serviceability rate, timely repair rate and replacement repair rate of E&M equipment is scored respectively according to the Delphi method, and the discriminant matrix \( A \) for evaluating the operation state of E&M system is obtained. The expression is

\[
A = \begin{bmatrix}
a_{11} & a_{12} & \ldots & a_{1n} \\
a_{21} & a_{22} & \ldots & a_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
a_{m1} & a_{m2} & \ldots & a_{mn}
\end{bmatrix}
\]  

(4)

After obtaining the discriminant matrix \( A \) for evaluating the operation state of E&M system, the characteristic roots and characteristic vectors of the discriminant matrix are calculated, and the standardized results of the characteristic vectors are calculated as the weights of influencing factors. In the process of calculating the discriminant matrix, it is necessary to check the consistency of the discriminant matrix because there may be some conflicts between the scores of experts. If there is a consistency logic problem, it is necessary to re-adjust the importance of each evaluation index; if the logic is normal, the weight is considered as the final result.

2.3. Membership function construction

In order to get a better description of the operation state of E&M system, this paper constructs a fuzzy comprehensive model to evaluate. An operation state evaluation set \( F = \{F_1, F_2, F_3\} \) is constructed,
where $F_i$ represents the operation state evaluation index, i.e., functional serviceability rate, timely repair rate and replacement repair rate. The performance degree of E&M system operation state is taken as the evaluation result $U = \{U_1, U_2, U_3, U_4\}$, where $U_i$ represents four grades of the operation state from health to failure. According to the relationship between the index set and the result set in the fuzzy evaluation, the fuzzy membership function matrix $R$ is established, and the corresponding relationship is shown in Table 2.

### Table 2 Corresponding Relationship Between Index Set and Result Set

|                  | Healthy | Sub healthy | Deteriorated | Breakdown |
|------------------|---------|-------------|--------------|-----------|
| Functional serviceability rate | $r_{11}$ | $r_{12}$ | $r_{13}$ | $r_{14}$ |
| Timely repair rate | $r_{21}$ | $r_{22}$ | $r_{23}$ | $r_{24}$ |
| Replacement repair rate | $r_{31}$ | $r_{32}$ | $r_{33}$ | $r_{34}$ |

According to the corresponding range of each evaluation index, the membership function reasonably covers the whole range of index value. In this paper, the fuzzy relationship among evaluation grades is described by trapezoidal distribution, and the schematic diagram of membership function is shown in Fig. 2.

![Fig. 2 Schematic Diagram of Membership Function](image)

The four result grades corresponding to expressway E&M system operation state are $\lambda_1$, $\lambda_2$, $\lambda_3$, and $\lambda_4$, and their expressions are as follows:

\[
\lambda_1(x) = \begin{cases} 
1 & 0 \leq x < a \\
\frac{x-b}{a-b} & a \leq x < b \\
0 & x < 0 \text{ or } b \leq x \\
\frac{x-a}{b-a} & a \leq x < b \\
1 & b \leq x < c \\
\frac{x-d}{c-d} & c \leq x < d \\
0 & x < a \text{ or } d \leq x \\
\frac{x-c}{d-c} & c \leq x < d \\
1 & d \leq x < e \\
\frac{x-f}{e-f} & e \leq x < f \\
0 & x \leq c \text{ or } f \leq x \\
\frac{x-e}{f-e} & e \leq x < f \\
1 & f \leq x 
\end{cases}
\] (5)

\[
\lambda_2(x) = \begin{cases} 
1 & 0 \leq x < a \\
\frac{x-b}{a-b} & a \leq x < b \\
0 & x < 0 \text{ or } b \leq x \\
\frac{x-a}{b-a} & a \leq x < b \\
1 & b \leq x < c \\
\frac{x-d}{c-d} & c \leq x < d \\
0 & x < a \text{ or } d \leq x \\
\frac{x-c}{d-c} & c \leq x < d \\
1 & d \leq x < e \\
\frac{x-f}{e-f} & e \leq x < f \\
0 & x \leq c \text{ or } f \leq x \\
\frac{x-e}{f-e} & e \leq x < f \\
1 & f \leq x 
\end{cases}
\] (6)

\[
\lambda_3(x) = \begin{cases} 
1 & 0 \leq x < a \\
\frac{x-b}{a-b} & a \leq x < b \\
0 & x < 0 \text{ or } b \leq x \\
\frac{x-a}{b-a} & a \leq x < b \\
1 & b \leq x < c \\
\frac{x-d}{c-d} & c \leq x < d \\
0 & x < a \text{ or } d \leq x \\
\frac{x-c}{d-c} & c \leq x < d \\
1 & d \leq x < e \\
\frac{x-f}{e-f} & e \leq x < f \\
0 & x \leq c \text{ or } f \leq x \\
\frac{x-e}{f-e} & e \leq x < f \\
1 & f \leq x 
\end{cases}
\] (7)

\[
\lambda_4(x) = \begin{cases} 
1 & 0 \leq x < e \\
\frac{x-e}{e-f} & e \leq x < f \\
0 & f \leq x 
\end{cases}
\] (8)
2.4. Establishment of evaluation model
By studying the relationship between the evaluation indexes and the evaluation result grades, the fuzzy matrix R is constructed, and its expression is

\[
R = \begin{bmatrix}
R_1 & R_2 & R_3 & R_4 \\
1 & r_{i1} & r_{i2} & r_{i3} & r_{i4} \\
2 & r_{i2} & r_{i3} & r_{i4} & \\
3 & r_{i3} & r_{i4} & & \\
4 & r_{i4} & & & \\
\end{bmatrix}
\]

According to the weight \( W \) determined by each influence index, that is, the correlation degree among the functional serviceability rate, the timely repair rate and the replacement repair rate relative to the evaluation result, the judgment result is determined as follows

\[
Y = W \cdot R = [\omega_1, \omega_2, \omega_3] \begin{bmatrix} r_{i1} & r_{i2} & r_{i3} & r_{i4} \end{bmatrix} = [y_1, y_2, y_3, y_4]
\]

The discriminant result matrix \( y_1 \sim y_4 \) represents the results of different grades respectively. According to the principle of maximum membership degree, the grade corresponding to the maximum value is selected as the final evaluation result of E&M system operation state.

3. Case Analysis

3.1. Extraction of evaluation indexes
Based on the investigation of the troubleshooting details and warehouse-in/out data of the expressway E&M system management platform of the city, the functional serviceability rate, timely repair rate and replacement repair rate of key equipment are calculated. Taking the barriers, cameras, optical line terminals, UPS power supplies, alarms and lighting equipment as examples, some results are shown in Table 3.

| Evaluation index       | Functional serviceability rate | Timely repair rate | Replacement repair rate |
|------------------------|--------------------------------|-------------------|------------------------|
| Barrier                | 93.28%                         | 24.00%            | 38.09%                 |
| Camera                 | 86.35%                         | 59.62%            | 6.25%                  |
| Optical line terminal  | 95.23%                         | 75.28%            | 40.00%                 |
| UPS power supply       | 72.31%                         | 45.33%            | 81.81%                 |
| Alarm                  | 90.36%                         | 15.73%            | 28.57%                 |
| Lamp                   | 86.31%                         | 52.56%            | 47.63%                 |

3.2. Implementation of evaluation model
After extracting the relevant evaluation indexes of expressway E&M system, the importance among evaluation indexes is scored with expert scoring method, and the weight of functional serviceability rate, timely repair rate and replacement repair rate of key equipment are obtained by analytic hierarchy process as follows:

\[
W = (\omega_1, \omega_2, \omega_3) = (0.4267, 0.2174, 0.3559)
\]

Meanwhile, the discriminant matrices of different levels are obtained according to the scoring results, where the matrices \( A \) and \( B_i \) are the discriminant matrices of the first level and the second level respectively, and their expressions are as follows:

\[
A = \{0.067, 0.1342, 0.1356, 0.3441, 0.1965, 0.1226\}
\]

\[
B_1 = \{0.6667, 0.3333\}
\]

\[
B_2 = \{0.25, 0.75\}
\]

\[
B_3 = \{0.6667, 0.3333\}
\]
Since different indexes are used in the evaluation of expressway E&M system, the evaluation results are different. Therefore, the membership function \( R \) for evaluating the running state of expressway E&M system is constructed according to the relationship among different evaluation indexes and evaluation results, and the arithmetic average of each index is calculated as the index result of the system according to the weight result \( B_i \) of different M&E system equipment, and the fuzzy membership function \( R_i \) is constructed as shown in Table 4.

### Table 4 Results of Fuzzy Membership Function

| E&M subsystem                        | Evaluation of membership function |
|--------------------------------------|-----------------------------------|
| Toll collection subsystem            | \( R = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0.643 & 0.357 \\ 0 & 0 & 0 & 1 \end{bmatrix} \) |
| Monitoring subsystem                 | \( R = \begin{bmatrix} 0 & 0 & 0.74 & 0.26 \\ 0 & 0 & 0.25 & 0.75 \end{bmatrix} \) |
| Power supply and distribution subsystem | \( R = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0.103 & 0.897 \end{bmatrix} \) |

According to the different weights of equipment evaluation indexes in each expressway E&M system, combined with the evaluation membership function, the evaluation results of different subsystems are obtained. Because different E&M subsystems have different weights in E&M system, the final evaluation result matrix \( B \) is obtained through weight distribution, and its expression is

\[
B = A_i \cdot W \cdot R
\]  

Substituting the data into the above formula, the final matrix \( B \) is \([0.064, 0.127, 0.376, 0.433]\).

According to the principle of maximum membership degree, the maximum membership degree of 0.433 in matrix \( B \) is selected as an important basis for evaluating the operation health status of expressway E&M system. From this, it can be seen that the operation state of the expressway E&M system is healthy.

### 4. Conclusions

Considering the influence of timely repair and maintenance quality of E&M equipment failures on E&M system running state, and combining with the study on evaluation method of expressway E&M system operation state based on equipment serviceability rate, the evaluation results can reflect the operation situation of expressway and discover the potential safety hazards of M&E system in time. In this paper, based on AHP-FCE method, the operation state evaluation method of expressway E&M system is constructed, and the operation state is divided into different grades, which can effectively evaluate the operation state of expressway E&M system and provide data support for intelligent maintenance of expressway.

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