The research on operational reliability evaluation of straddle-type monorail vehicle*

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ABSTRACT

In order to master the main malfunction and the law of occurrence of the vehicle which affects the operational reliability of the Straddle-Type Monorail traffic, this paper, based on the structural characteristics of monorail vehicle system and the statistical data of vehicle operational malfunction, uses the analysis method of system reliability engineering to study and determine the key factors that affect the operational reliability of monorail vehicle. Then, the operational reliability evaluation index system of monorail vehicle is established based on the influencing factors. Finally, the AHP (Analytic Hierarchy Process) method is used to determine the weights of each index, and the fuzzy comprehensive evaluation method is used to evaluate the operational reliability of monorail vehicle synthetically. The evaluation results have some guidance on the development of more effective maintenance strategies for monorail vehicle maintenance departments.

1. Introduction

The Straddle-Type Monorail Vehicle is used as a carrier for the straddle-type monorail system (Timan, 2015). During the operation of the straddle-type monorail system, the vehicle failure is an important factor that affects the normal operation of the line and intuitively reflects the service quality of the rail transit operation unit (Bearfield, 2007). Vehicle reliability is the key to ensuring a safe, punctual travel and good social order. In addition, due to the straddle type monorail vehicle unique structure (Du, Wen, Zhao, Xu, & Chen, 2017; Glickenstein, 2013) (shown in Figure 1), the subway vehicle reliability research and the development of relatively is perfect (Melo & Baptista, 2017; Yin, Wang, Qin, Hua, & Jiang, 2017), but maintenance measures are not fully suitable for Straddle-Type Monorail vehicles.

Based on an urban rail transit line operational safety, the line operational safety evaluation index system of urban transit was established (Wang yanhui, 2013), in which the line operation safety index of urban rail transit was evaluated with the method of combination weights. The operative failure distribution model was established based on selected model with a large quantity of failure data for subway vehicles (Yin et al., 2017). To perform service evaluation, an integrated process combining capacity, resource usage, and system reliability, a comprehensive evaluation framework with three corresponding modules was established (Lai & Ip, 2017). Life cycle costing was a well-established method for the evaluation of alternative asset options and to produce a spend profile for an asset over its anticipated life-span, different aspects related to the failure costs within the LCCA was explored for the rail freight industry (Chile) (Parra, Crespo, Kristjanpoller, & Viveros, 2012). Both frequentist statistics and Bayesian inference techniques were employed by the parametric statistical models to combine information and contrasted to illustrate different statistical methods for combining information across multiple testing events for the Stryker family of vehicles (Steiner, Dickinson, Freeman, Simpson, & Wilson, 2015). There is fuzzy evaluation method etc in the railway vehicle operation. The fuzzy evaluation method has some failure due to that the weight of the fuzzy method is based on knowledge and experiences of the experts. So fuzzy analytical hierarchy process is proposed and it is more reasonable based the analytical hierarchy process so that it can be realistic and easy to quantify.

Therefore, by analyzing and studying the Straddle-Type Monorail vehicle fault occurrence and its causes, this paper finds out the key factors affecting the safety and
reliability of operation and comprehensive assessment of Straddle-Type Monorail vehicle safety and reliability level for the protection of Straddle-Type Monorail vehicle reliable operation, an important role in preventing various types of operational accidents, and providing a more secure and reliable way to travel. The contributions of this study are as follows: (1) Straddle-Type Monorail Vehicle operational malfunction statistical is analyzed based on a large quantity of failure data; (2) Straddle-type monorail vehicle operation reliability evaluation index system is established based on statistical analysis; (3) The fuzzy comprehensive evaluation of the operation reliability of Straddle-Type monorail vehicle is established.

2. Straddle-type monorail vehicle operational malfunction statistical analysis

The Straddle-Type Monorail system includes a wide range of equipment, and the environment and the frequency of using the equipment, degree of the equipment’s failure and maintenance means are quite different, and the impact of the failure on vehicle system operations will not be the same. The reliability of the Straddle-Type Monorail vehicle is closely related to the failure level and frequency of the vehicle system. The higher the fault level of the vehicle system and the greater the frequency, the worse the safety and reliability of the Straddle-Type Monorail vehicle operation.

2.1. The classification criteria of straddle-type monorail vehicle operational malfunction

In this paper, the fault classification of GB / T 21562–2008 is used to classify and define the fault of the monorail vehicle. The detailed classification and definition of the fault grade are shown in Table 1.

The main purpose of this study is to analyze the failure of the straddle-type monorail vehicle, the trend of vehicle failure and the main factors that affect the reliability of vehicle operation, and then comprehensively evaluate the reliability of straddle vehicle operation. Therefore, a vehicle failure that has an impact on normal operation but does not cause a safety problem is listed in this paper. Combined with the classification and definition

Table 1. Straddle-type monorail vehicle failure (C) impact classification.

| Fault level classification          | Definition                                                                                                                                 |
|------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------|
| Library check malfunction          | Maintenance of effective parts during maintenance and other maintenance failures, not including adjustment, cleaning, lubrication, interchange and other maintenance. |
| Negligible failure                 | During the operation of the train, it will not affect the main functions and will not need any action. However, maintenance, adjustment, exchange and replacement after the completion of the train operations shall not include maintenance such as cleaning and lubrication. |
| Minor fault                        | During the operation of the train, the delay of the parking is less than the specified time, but the train can complete the maintenance failure after the operation. |
| Can not start a breakdown          | During the preparation for the operation of the train, before the train enters operation, the train fails and the scheduled train operation is cancelled. |
| Delay fault                        | During the operation of the train, the vehicle is stopped and lagged for more than the specified time (5 min), but the train can complete the maintenance after the day's operation. |
| Offline fault                      | Resulting in failure of the vehicle that must be replaced after the end of this operation.                                                                 |
| Passengers have fault              | During the train operation, all passengers are required to evacuate immediately or at the next station, but can return to the depot (waiting for maintenance). |
| Rescue the fault                   | During the operation of the train, the train must be towed to the depot (waiting for maintenance) by a tractor or another rescue vehicle.     |
of the fault level in Table 1, the failure of the Straddle-Type Monorail vehicle has five types which can cause the vehicle to fail to start, delay, get off the assembly line, evacuate the passengers.

2.2. Straddle-type monorail vehicle failure statistics and regular analysis

Through several investigations and researches, the records of various operational failure of Chongqing straddle-type monorail traffic on Line 2 vehicles for the four years (January 2012 ∼ December 2015) and the overall breakdown of each line are obtained as shown in Figure 2.

It can be seen from Figure 2 that the Line 3 vehicle failure increased first and then decreased, mainly because of the trial operation of the extended section at the end of 2013 during which a number of new cars are put into use in order to ensure the transport efficiency of the same year. During the run-in period, vehicle failure is an early fault and the frequency of failure is relatively high. After a year of operation of Line 3 new cars, the chance of failure is greatly reduced, so the No. 3 line vehicle failure from 2012 to 2015 first increased. Although the Line 2 also opened the extension in 2014, the number of new vehicles put into use are small. Compared to failures of all vehicles, the proportion of the new vehicle failures is too small to affect the trend. So the Line 2 vehicle failure in 2012–2015 has a decreasing trend year by year. In addition, it can be seen through the investigation that, for the vehicle management and maintenance, the company divided the vehicle subsystem failure into bogie system, the driver room equipment, traction system, monitoring systems, air conditioning systems, air brake systems, broadcasting systems, auxiliary power systems, compartments, door systems, safety aids, coupler systems, automotive signals and communication systems in accordance with the Straddle-Type Monorail vehicle structure characteristics.

For a further analysis of the fault occurrence type of the monorail vehicle, the Lines 2 and 3 vehicle fault data collected through investigations and researches are analyzed statistically according to the above criteria for the fault classification of the vehicle subsystem. The vehicle subsystem failures, the yearly failures in each subsystem of the vehicle and the proportion of the number of failures in each subsystem to the total failures in the vehicle system are shown respectively in Figures 3–5.

As can be seen from Figure 3, the Line 2 subsystems with a relatively high fault rate are: broadcast system, vehicle signal and communication system, compartment equipment, cab equipment, traction system, air conditioning system, door system, air brake system, train monitoring system and auxiliary power supply system, while the Line 3 subsystems with relatively high fault rate in order are: vehicle monitoring system, bogie system and safety assist system. Although the same fault subsystems in Lines 2 and 3 vehicles are not listed in the same order, the first several vehicle failure subsystems are basically the same. It can be seen from Figure 4 that the subsystems rank nearly the same in the vehicle failure. Figure 5 indicates the proportion of the subsystem faults of the Lines 2 and 3 straddle-type monorail vehicle to the whole vehicle faults. In the order of the proportion from the highest to the lowest the subsystems are ranked as follows: the vehicle signal and communication system, the broadcasting system, the cab room equipment, the compartment equipment, the traction System, air conditioning systems, door systems, train monitoring systems, bogie systems and safety aids.

2.3. Analysis of the key subsystems related to the operating reliability of the straddle-type monorail vehicle

Through the above analysis of the 14 sub-systems of the Straddle-Type Monorail vehicle, the probability of fault occurrence of each subsystem is compared. However, the reliability of the straddle-type monorail vehicle operation is not only closely related to the probability of failure, but also to the level of the fault occurrence. For a further understanding of the impact of vehicle subsystem
failure on the reliability of Straddle-Type Monorail vehicle operation, referring to the classification and definition of the vehicle failure level in Table 1 and combined with the impact of vehicle operation failure, this study will divide the vehicle failure into the four levels like temporary repair, not being out of the maintenance works, and getting off the line and evacuation of passengers. And according to the above four fault levels, the straddle-type monorail vehicle operating failure data is accounted and the proportion of various types of failures is shown in Figure 6.

Seen from Figure 6, according to the levels of the four failures, emergency repair ranks top, failure of the library second, the off-the-line third, and evacuation of passengers fourth. But the proportion of the four levels of failures is basically the same with what the actual vehicle operation of the Lines 2 & 3 reflect.

In order to master the influence of the failure level of the sub-system components of the Straddle-Type Monorail vehicle, the failure of each fault subsystem is classified
Figure 7. Various failure statistics of straddle type monorail vehicle subsystems.

according to the four failures: temporary repair, not being out of the maintenance works, and getting off the line and evacuation of passengers. The statistics of the various types of failure of each subsystem are shown in Figure 7. Figure 7 shows the number of the failures of the fault levels for the 14 fault subsystems, and emergency repair failure on the top of the others. This level of failure does not affect the straddle-type monorail vehicle line operations, for it is negligible or minor. In addition, the comparative analysis of Figure 7 and Figures 3–5 statistical data shows:

1) Although the total number of failures in the broadcasting system, the cab equipment and the passenger compartment equipment is great, the number of serious failures which they cause, like evacuation of passengers is small;
2) The total number of failures in bogie systems, air brake systems, door systems, train monitoring systems, traction system is relatively small, but the number of serious failures is relatively great;
3) Car signal system has more failures and more serious failures like evacuation of passengers;
4) Safety auxiliary equipment, coupler system, have fewer failures, and they do not cause any failures like vehicle-off-line which impact the operation of the line.

This study focuses on subsystems with low failure levels but more failures, or with fewer failures but relatively high failure level. Through the statistical analysis of the failures of the Straddle-Type Monorail vehicle, the key subsystems which influence the reliability of the Straddle-Type Monorail vehicle operation are mainly bogie system, door system, air brake system and traction system.

3. Straddle-type monorail vehicle operation reliability evaluation index system

3.1. Reliability evaluation index establishment

Straddle-type monorail vehicles as a complex large system, have many factors affecting operational reliability. In the evaluation of operational reliability, according to the principle of index system construction and combined with the structural characteristics of the Straddle-Type Monorail vehicle system, 17 indicators of operational reliability evaluation are put forward from the four key subsystems which affect the reliability of the vehicle operation.

According to the obtained index, a reliability evaluation model (as shown in Figure 8) of the straddle-type monorail vehicle operation with hierarchical structure is established. The model is the target layer $M$, the criterion layer $Z_i$ and the index layer $P_{ij}$ from top to bottom:

1) The target layer $M$. This paper is about the safety and reliability of the straddle type monorail vehicle operation.
2) The criteria layer $Z_i$. This paper has the standard selection of the door system $Z_1$, bogie system $Z_2$, traction system $Z_3$ and air brake system $Z_4$ four indicators.
Figure 8. Cross-seat monorail vehicle comprehensive evaluation index system.

(3) The index layer $P_{ij}, Z_1$ includes the door plank $P_{11}$, the drive guide $P_{12}$, gantry $P_{13}$, motor $P_{14}$; $Z_2$ includes six indicators: a rubber tire pressure monitoring device $P_{21}$, a central pulling device $P_{22}$, an air spring $P_{23}$, a frame $P_{24}$, a driving device $P_{25}$, a basic braking device $P_{26}$; $Z_3$ includes three indicators: the brake valve and piping system $P_{31}$, wind source system $P_{32}$, brake control unit (BCU) $P_{33}$; $Z_4$ includes four indicators: pantograph device $P_{41}$, current transformer Device $P_{42}$, the controller $P_{43}$, traction motor $P_{44}$.

As the role of each indicator element in the reliability evaluation model of the straddle-type monorail vehicle operation shown in Figure 8 is different, the relative weight of each index needs to be determined. In order to scientifically determine the weight of the indicators in the index system throughout the index system, we discussed with the person in charge of operations, monorail vehicle technology and maintenance personnel and relevant experts. The value of each element based on the frequency of occurrence and the seriousness of the consequences, in the judgment matrix (Wang, Wang, & Qi, 2016) is determined, the scale of evaluation is shown in Table 2, and the scale of the elements in the judgment matrix is as follows:

### Table 2. Comparison of the importance of the degree of scale table.

| Standard scale | Importance level |
|----------------|------------------|
| 1              | $B_i, B_j$ two factors equally important |
| 3              | $B_i$ factor is slightly more important than the $B_j$ factor |
| 5              | $B_i$ factor is more important than the $B_j$ factor |
| 7              | $B_i$ factors are strongly important than $B_j$ factors |
| 9              | $B_i$ factors are extremely important than $B_j$ factors |
| 2, 4, 6, 8     | Said $B_i, B_j$ two factors, Between the adjacent judgments reciprocal Shows the result of comparison between factor $B_j$ and $B_i$ |

### Table 3. Judgment matrix M-Z.

| M   | $Z_1$ | $Z_2$ | $Z_3$ | $Z_4$ |
|-----|-------|-------|-------|-------|
| $Z_1$ | 1     | 1/4   | 5     | 3     |
| $Z_2$ | 4     | 1     | 6     | 4     |
| $Z_3$ | 1/5   | 1/6   | 1     | 1/3   |
| $Z_4$ | 1/3   | 1/4   | 3     | 1     |

### Table 4. Judgment matrix Z1-P.

| $P_{11}$ | $P_{12}$ | $P_{13}$ | $P_{14}$ |
|----------|----------|----------|----------|
| $P_{11}$ | 1        | 1/7      | 1/5      | 1/4      |
| $P_{12}$ | 7        | 1        | 4        | 5        |
| $P_{13}$ | 5        | 1/4      | 1        | 3        |
| $P_{14}$ | 4        | 1/5      | 1/3      | 1        |

### Table 5. Judgment matrix Z2-P.

| $P_{14}$ | $P_{22}$ | $P_{23}$ | $P_{24}$ | $P_{25}$ | $P_{26}$ |
|----------|----------|----------|----------|----------|----------|
| $P_{14}$ | 1        | 5        | 4        | 3        | 6        | 8        |
| $P_{22}$ | 1/5      | 1        | 1/4      | 1/3      | 4        | 5        |
| $P_{23}$ | 1/4      | 4        | 1        | 1/2      | 5        | 6        |
| $P_{24}$ | 1/3      | 3        | 2        | 1        | 4        | 7        |
| $P_{25}$ | 1/6      | 1/4      | 1/5      | 1/6      | 1        | 4        |
| $P_{26}$ | 1/8      | 1/5      | 1/6      | 1/7      | 1/4      | 1        |

### Table 6. Judgment matrix Z3-P.

| $P_{31}$ | $P_{32}$ | $P_{33}$ |
|----------|----------|----------|
| $P_{31}$ | 1        | 3        | 5        |
| $P_{32}$ | 1/3      | 1        | 4        |
| $P_{33}$ | 1/5      | 1/4      | 1        |

### 3.2. Structure judgment matrix

The judgment matrix shown in Tables 3–7 can be established according to the hierarchical structure shown in Figure 8 for the relative importance of the safety reliability evaluation index of the Straddle-Type Monorail vehicle operation.

### 3.3. Single-level order, and for consistency test

The single order of the hierarchy can be summed up as the problem of the eigenvalues and eigenvectors of the
judgment matrix. The set of values obtained by the normalization of the eigenvectors of the judgment matrix is the weight of the lower indexes associated with the upper element. In order to examine whether the judgment matrix is consistent with the importance of each element, it is necessary to perform a consistency check in each sort. In order to measure whether the order of judgment matrix is satisfactory, it is necessary to introduce the IR value of the judgment matrix as shown in Table 8. When the random consistency ratio $RC < 0.1$, the judgment matrix is satisfied with the consistency, otherwise you need to adjust the judgment matrix, until the test passed.

In this study, we use the square root method for the judgment matrix shown in Tables 3–7 to find the eigenvalues and the corresponding eigenvectors, and perform the consistency test. The results are as follows: where $W_i$ represents the lower elements belonging to the $i$ element Relative to the right of $i$, $\lambda_{\text{max}}$ denotes the largest eigenvalue of the judgment matrix, and $I^c$ denotes the hierarchical general ranking consistency index.

For M-Z matrices:

$$W_M = (0.2488, 0.5698, 0.0577, 0.1237)$$  \hspace{1cm} (1)

$\lambda_{\text{max}} = 4.2200$, $I^c_M = 0.0742$, $R_M^C = 0.0825 < 0.1$, Through the consistency test.

For $Z_1$-P matrix:

$$Wz_1 = (0.0501, 0.5904, 0.2367, 0.1228)$$  \hspace{1cm} (2)

$\lambda_{\text{max}} = 4.2381$, $I^c_1 = 0.0794$, $R_1^C = 0.0882 < 0.1$, Through the consistency test.

For the $Z_2$-P matrix:

$$Wz_2 = (0.4294, 0.0969, 0.1829, 0.2145, 0.0497, 0.0266)$$  \hspace{1cm} (3)

$\lambda_{\text{max}} = 6.5204$, $I^c_2 = 0.1041$, $R_2^C = 0.0839 < 0.1$, Through the consistency test.

For the $Z_3$-P matrix:

$$Wz_3 = (0.6267, 0.2797, 0.0936)$$  \hspace{1cm} (4)

$\lambda_{\text{max}} = 3.0858$, $I^c_3 = 0.0429$, $R_3^C = 0.0739 < 0.1$, Through the consistency test.

### Table 7. Judgment matrix $Z_4$-P.

| Z4    | P41 | P42 | P43 | P44 |
|-------|-----|-----|-----|-----|
| P41   | 1   | 3   | 1/4 | 4   |
| P42   | 1/3 | 1   | 1/5 | 1/2 |
| P43   | 4   | 5   | 1   | 6   |
| P44   | 1/4 | 2   | 1/6 | 1   |

### Table 8. Random consistency index $I^R$ table.

| Order | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|-------|---|---|---|---|---|---|---|---|---|
| $I^R$ | 0 | 0 | 0.58 | 0.90 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 |

3.4. Thetotal ranking and consistency of the test

Using the results of single ordering at all levels in the same hierarchy, the weighted sum is merged and the final ranking of the index layer relative to the target layer is obtained. The consistency check of the hierarchical total ranking is also carried out from top to bottom, and also need to be consistent in the total order of the test, and when $RC < 0.1$, that the total ranking of the results of the results of satisfactory consistency. The total sorting results of the judgment matrices shown in Tables 3–7 are shown in Table 9.

| Rule layer | Index layer | Combination weights |
|------------|-------------|---------------------|
| Door system Z1 | door plank P11 (0.0501) | 0.0125 |
|             | (0.5904) | 0.1469 |
|             | Gantry P13 (0.2367) | 0.0589 |
|             | motor P14 (0.1228) | 0.0306 |
| Bogie system Z2 | pressure monitoring device P21 (0.4294) | 0.2535 |
|             | Central traction device P22 (0.0969) | 0.0572 |
|             | Air spring P23 (0.2145) | 0.108 |
|             | Architecture P24(0.2145) | 0.1266 |
|             | Drive device P25 (0.0497) | 0.0293 |
|             | Basic brake device P26 (0.0266) | 0.0157 |
| Air brake system Z3 | Brake valve and piping system P31 (0.6267) | 0.0362 |
|             | Wind source system P32 (0.2797) | 0.0161 |
|             | Brake control unit (BCU) | 0.0054 |
|             | P33 (0.0936) | 0.0292 |
| Electric traction system Z4 | Pantograph P41 (0.2364) | 0.0094 |
|             | Variable flow device P42 (0.0761) | 0.0731 |
|             | Controller P43 (0.5912) | 0.0731 |
|             | Traction motor P44 (0.0962) | 0.0119 |

For $Z_4$-P matrices:

$$Wz_4 = (0.2364, 0.0761, 0.5912, 0.0962)$$  \hspace{1cm} (5)

$$\lambda_{\text{max}} = 4.2200$$, $I^c_4 = 0.0733$, $R_4^C = 0.0815 < 0.1$, Through the consistency test.

It can be seen that the overall order of the hierarchy is satisfactory, that is, the judgment matrix shown in Tables 3–7, which are based on data and expert experience, is reasonable.
4. The fuzzy comprehensive evaluation of the operation reliability of straddle-type monorail vehicle

Based on the application of AHP method to determine the reliability index of Chongqing straddle-type monorail vehicle operation, the fuzzy comprehensive evaluation method is used to evaluate the reliability of Chongqing Straddle-Type monorail vehicle. Based on the principle of fuzzy transformation and the principle of maximum membership, the author makes a comprehensive evaluation of the factors related to the evaluated objects (Jia, Zhang, & Xi, 2009). The main steps are:

4.1. Establishment of evaluation factors set

In the comprehensive evaluation of the reliability of the straddle-type monorail vehicle operation, the set of factors that have been determined, that is, the index system of the evaluation object, is divided into two layers. The first layer is the total target factor set \( M = \{Z_1, Z_2, Z_3, Z_4\} \). The second layer is the sub-target factor set:

\[
Z_1 = \{P_{11}, P_{12}, P_{13}, P_{14}\}, \quad Z_2 = \{P_{21}, P_{22}, P_{23}, P_{24}, P_{25}, P_{26}\}, \quad Z_3 = \{P_{31}, P_{32}, P_{33}\}, \quad Z_4 = \{P_{41}, P_{42}, P_{43}, P_{44}\}. 
\]

4.2. Determination of the evaluation set

Suppose \( v = \{v_1, v_2, \ldots, v_m\} \), the level set. Each level can correspond to a fuzzy subset. In the evaluation of the reliability level of the straddle type monorail car, you can take the evaluation set, \( v = \) {excellent, good, qualified, Worse, poor}, so the evaluation is divided into five grades, using the full score 5 points, as Table 10 shows.

4.3. The establishment of fuzzy relations matrix

The single factor fuzzy evaluation of the reliability level of the Straddle-Type Monorail vehicle operation is to judge from the single factor of the factor set \( U \) to determine the membership degree of the evaluation object to the elements of the evaluation set. When the evaluation object is judged by the factor \( i \), the membership degree of the \( j \)-th element \( v_{ij} \) is \( r_{ij} \), then the evaluation set of the \( i \)-th single factor is \( R_i = \{r_{i1}, r_{i2}, \ldots, r_{im}\} \), the evaluation set of \( n \) factors is composed of a single factor fuzzy relation matrix \( R = (R_i | U) \), through the Chongqing monorail vehicle operation and management unit research and consultation with a number of industry experts to get the results, The fuzzy relation matrix of sub-target factors is:

(1) The fuzzy evaluation matrix for the door system is:

\[
R_1 = \begin{bmatrix}
0 & 0.2 & 0.55 & 0.2 & 0.05 \\
0.35 & 0.5 & 0.1 & 0.05 & 0 \\
0.3 & 0.45 & 0.2 & 0.05 & 0 \\
0.1 & 0.5 & 0.35 & 0.05 & 0 
\end{bmatrix}
\]

(2) The fuzzy evaluation matrix for the bogie system is:

\[
R_2 = \begin{bmatrix}
0.1 & 0.65 & 0.2 & 0.05 & 0 \\
0.3 & 0.5 & 0.15 & 0.05 & 0 \\
0.4 & 0.45 & 0.1 & 0.05 & 0 \\
0.3 & 0.5 & 0.5 & 0.1 & 0 \\
0.2 & 0.45 & 0.3 & 0.05 & 0 
\end{bmatrix}
\]

(3) The fuzzy evaluation matrix for the air brake system is:

\[
R_3 = \begin{bmatrix}
0.2 & 0.6 & 0.15 & 0.05 & 0 \\
0.15 & 0.55 & 0.25 & 0.05 & 0 \\
0.3 & 0.65 & 0.01 & 0 & 0 
\end{bmatrix}
\]

(4) The fuzzy evaluation matrix for the electric traction system is:

\[
R_4 = \begin{bmatrix}
0.2 & 0.4 & 0.3 & 0.05 & 0.05 \\
0.3 & 0.4 & 0.2 & 0.2 & 0.1 \\
0.25 & 0.5 & 0.15 & 0.05 & 0.05 \\
0.15 & 0.65 & 0.15 & 0.05 & 0 
\end{bmatrix}
\]

Table 10. Security level weighting and standard scores.

| The safety status grade evaluative | Excellent | Good | Qualified | Worse | Poor |
|-----------------------------------|-----------|------|-----------|-------|------|
| Weighted value \( k \)            | 1         | 2    | 3         | 4     | 5    |
| The standard score                | < 1       | 1-1.9| 2-2.9     | 3-3.9 | 4-5  |

4.4. Synthetic fuzzy comprehensive evaluation vector

The fuzzy comprehensive evaluation result vector \( w_{zi} \) of each evaluation target is obtained by synthesizing the evaluation target weight vector and the fuzzy matrix \( R_i \) of the evaluation target by using Formula 11.

\[
z_i = W_z \ast R_i = (b_1 \ b_2 \ b_3 \ b_4 \ b_5)
\]

In the formula 11, \( b_i \) indicates the degree of membership of the evaluation target from the fuzzy level of the \( vi \) level. According to the formula 11, the fuzzy comprehensive evaluation results vector for the door system, the bogie system, the air brake system and the electric traction system are as follows:

\[
\begin{align*}
Z_1 &= (0.2899, \ 0.4731, \ 0.1769, \ 0.0575, \ 0.0025) \\
Z_2 &= (0.2405, \ 0.5432, \ 0.1581, \ 0.0525, \ 0.0107) \\
Z_3 &= (0.1954, \ 0.5907, \ 0.1686, \ 0.0453, \ 0) \\
Z_4 &= (0.2323, \ 0.4831, \ 0.1893, \ 0.0538, \ 0.0414)
\end{align*}
\]
4.5. The vector analysis of fuzzy comprehensive evaluation results

In the actual analysis, the maximum membership principle is used to analyze the results, but in some cases, it narrowly obtains a reasonable evaluation result. This paper uses the weighted average principle to analyze the results of fuzzy evaluation (Gu, Chen, & Yang, 2008; Wei, Luo, Li, Zhang, & Xu, 2015). The weighted average formula is as follows:

\[ Z_i^* = \frac{\sum_{k=1}^{m} b_k^2 \times k}{\sum_{k=1}^{m} b_k^2} \]  \tag{12}

From the formula 12 can get the weighted average: \( Z_1^* = 1.8651, Z_2^* = 1.9291, Z_3^* = 1.9865, Z_4^* = 1.9780 \). Thus, the Straddle-Type Monorail vehicle operation, the door system, bogie system, air brake system and power traction system four aspects of the security status level are 'good'.

According to the above \( Z_1, Z_2, Z_3 \) and \( Z_4 \), let the target factor fuzzy relation matrix \( R = (Z_1, Z_2, Z_3, Z_4)^T \), combined with the weight vector \( W_M \) of the total target elements, The results of the fuzzy comprehensive evaluation of the reliability of monorail vehicle operation are as follows:

\[ M = W_M \times R = (0.2492, 0.5211, 0.1672, 0.0535, 0.0118) \]  \tag{13}

Similarly, the weighted average \( M^* = 1.9233 \) can be obtained, that is, the overall safety and reliability evaluation results of Chongqing Straddle-Type Monorail vehicle are 'good'.

5. Conclusion

Based on the analysis of operational failure data of Chongqing Straddle-Type Monorail Lines 2 and 3 vehicles, the fault occurrence law is obtained, and the main subsystems which influence the operational reliability of straddle-type monorail vehicle is determined. Then, an index system and evaluation model for the reliability of Straddle-Type Monorail vehicle operation are established. The fuzzy comprehensive evaluation method is used to analyze and evaluate the four aspects which are closely related to operational reliability: the door system, the bogie system, the air brake system and the electric traction system of the Straddle-Type Monorail vehicle system. The results show that the overall security status of the four subsystems is GOOD, and the actual situation is the same. It indicates the correctness and rationality of the assessment model.

The AHP method is used to analyze the relative importance of each index of the reliability of the straddle-type monorail. The results show that the factors that affect the safety and reliability of the straddle-type monorail vehicle operation are rubber tires and tire pressure, followed by the monitoring device, the drive guide and the frame.

In the primary index, the bogie system has the greatest impact on the safety and reliability of the Straddle-Type Monorail vehicle operation. Among the indicators in the first level, the bogie system has the greatest impact on the security of the vehicle operation. The overall ranking in the first and second level is in line with the actual situation in the operation process. The evaluation conclusion is in agreement with the actual operation. The evaluation results can be provided for the operating units to make the more effective measures and to reasonably purchase spare parts.

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