Systems Science & Control Engineering
An Open Access Journal

ISSN: (Print) 2164-2583 (Online) Journal homepage: https://www.tandfonline.com/loi/tssc20

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To cite this article: Zixue Du, Junchao Zhou, Zhen Yang & Jin Bo (2018) The research on operational reliability evaluation of straddle-type monorail vehicle, Systems Science & Control Engineering, 6:1, 537-546, DOI: 10.1080/21642583.2018.1550690

To link to this article: https://doi.org/10.1080/21642583.2018.1550690

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Published online: 26 Nov 2018.

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SYSTEMS SCIENCE & CONTROL ENGINEERING: AN OPEN ACCESS JOURNAL
2018, VOL. 6, NO. 1, 537–546
https://doi.org/10.1080/21642583.2018.1550690

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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.

ARTICLE HISTORY
Received 26 July 2018
Accepted 17 November 2018

KEYWORDS
Straddle-type monorail vehicle; system reliability engineering; the operational evaluation; reliability; the fuzzy comprehensive evaluation method; the AHP (Analytic hierarchy process)

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

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*Zhen Yang analyzed the data; Junchao Zhou contributed analysis tools; Zixue Du wrote the paper.

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a) b)

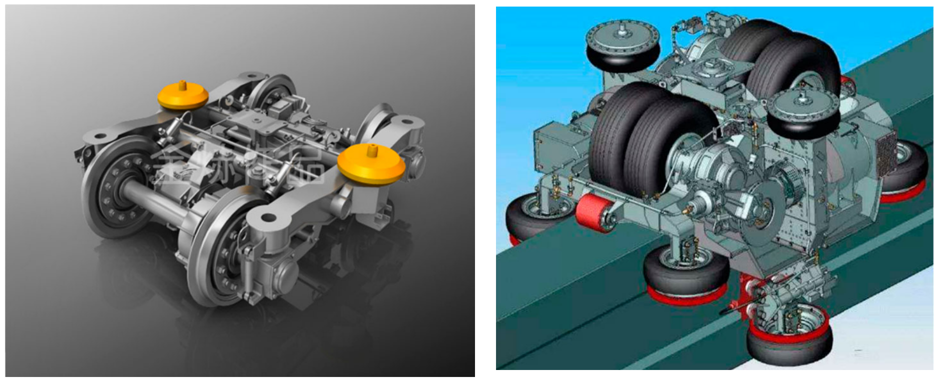

Figure 1. The contrast figure of bogie between subway vehicle and straddle-type monorail vehicle: a-bogie of subway vehicle; b- bogie of straddle-type monorail vehicle.

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 malfuction	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.

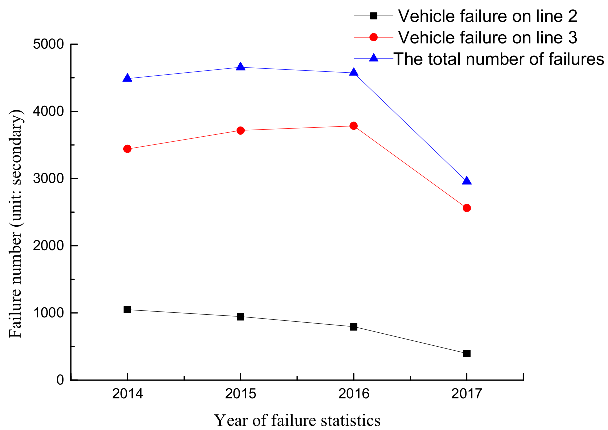

Figure 2. Straddle-type monorail vehicle annual failure trend.

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, because the vehicles on Line 2 are fewer and have been used longer than those on the No. 3, their overall performance is more stable and their yearly failures are fewer. Figure 2 shows that the total number of straddle-type monorail vehicle failures tends to decrease, in line with the practical operation: from the high failure rate in the early use of the vehicle to the occasional failure with the service time.

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 Systems, 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

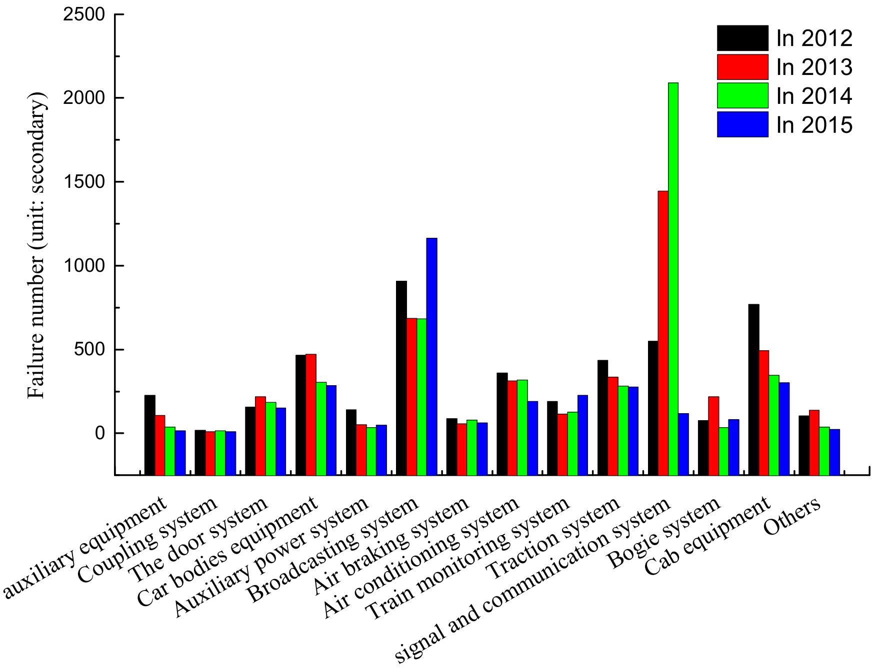

Figure 3. Chongqing rail transit lines 2 & 3 vehicle subsystem failure situation.

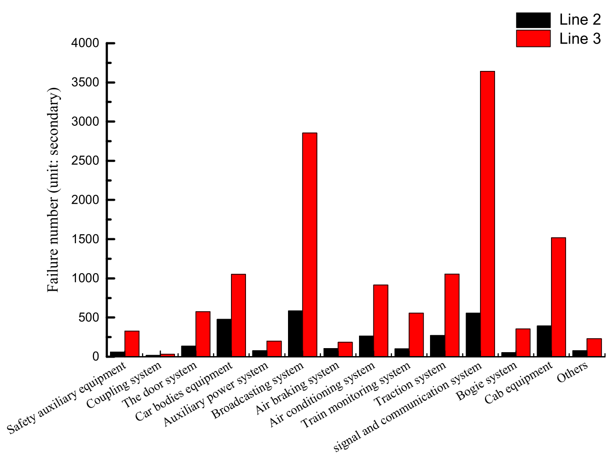

Figure 4. Straddle-type monorail vehicle subsystem's annual failure situation.

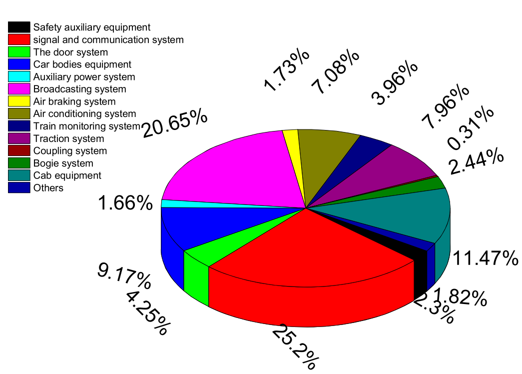

Figure 5. Straddle-type monorail of the failure of the subsystem share.

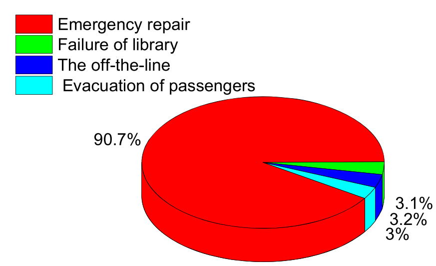

Figure 6. Straddle monorail vehicle rating ratio.

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

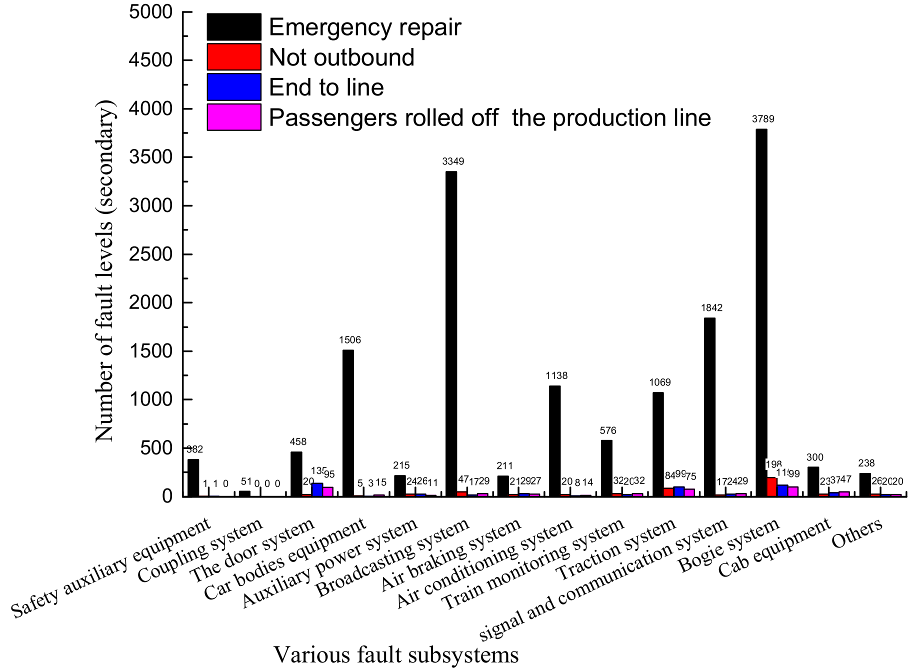

Figure 7. Various failure statistics of straddle type monorail vehicle subsystems.

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.

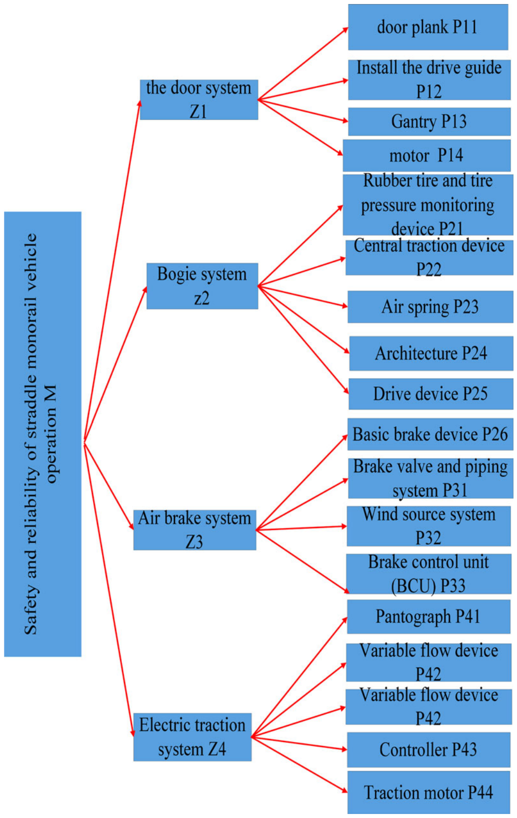

Figure 8. Cross-seat monorail vehicle comprehensive evaluation index system.

(3) The index layer P_{ij}. Z_1 includes the door plank P_{11}, the drive guideP_{12}, gantyP_{13},motorP_{14}; Z_2 includes six indicators: a rubber tire pressure monitoring device $P21$, a central pulling device P22, an air spring P23, a frame P24, a driving device P25, a basic braking device P26; Z3 includes three indicators: the brake valve and piping system P31, wind source system P32, brake control unit (BCU) P32; Z4 includes four indicators: pantograph device P41, current transformer Device P42, the controller P43, traction motor P44.

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. Comparison of the importance of the degree of scale table.

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

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.

Z_2	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.

Z_2	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.

Z_3	P_{31}	P_{32}	P_{33}
P_{31}	1	3	5
P_{32}	1/3	1	4
P_{33}	1/5	1/4	1

Table 2, and the scale of the elements in the judgment matrix is as follows:

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

Table 7. Judgment matrix Z4-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

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 < 0.10, 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, $\lambda_{\max}$denotes the largest eigenvalue of the judgment matrix, and I^c denotes the hierarchical general ranking consistency index.

For M-Z matrices:

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

$\lambda_1\max = 4.2226$, $I_M^C = 0.0742$, $R_M^C = 0.0825 < 0.1$, Through the consistency test.

For Z_1-P matrix:

$$Wz_1 = (0.0501, 0.5904, 0.2367, 0.1228) \tag{2}$$

$\lambda_2\max = 4.2381$, $I_1^C = 0.0794$, $R_1^C = 0.0882 < 0.1$, Through the consistency test.

For the Z_2-P matrix:

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

$\lambda_3\max = 6.5204$, $I_2^C = 0.1041$, $R_2^C = 0.0839 < 0.1$, Through the consistency test.

For Z_3-P matrices:

$$Wz_3 = (0.6267, 0.2797, 0.0936) \tag{4}$$

$\lambda_{\max} = 3.0858$, $I_3^C = 0.0429$, $R_3^C = 0.0739 < 0.1$, Through the consistency test.

Table 9. Overall sorting and weight.

Rule layer	Index layer	Combination weights
The door system Z1	door plank P11 (0.0501)	0.0125
	Install the drive guide P12 (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) P33(0.0936)	0.0054
Electric traction system Z4	Pantograph P41(0.2364)	0.0292
	Variable flow device P42(0.0761)	0.0094
	Controller P43(0.5912)	0.0731
	Traction motor P44(0.0962)	0.0119

For Z_4-P matrices:

$$Wz_4 = (0.2364, 0.0761, 0.5912, 0.0962) \tag{5}$$

$\Lambda_{\max} = 4.2200$, $I_4^C = 0.0733$, $R_4^C = 0.0815 < 0.1$, Through the consistency test.

3.4. The total 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 < 0.10, 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.

The overall consistency check is:

$$R_0{}^c = \frac{I^C}{R^C} = \frac{\begin{array}{c}0.2488 \times 0.0794 + 0.5698 \times 0.1041 + \\ 0.0577 \times 0.0429 + 0.1237 \times 0.0733\end{array}}{\begin{array}{c}0.2488 \times 0.9 + 0.5698 \times 1.24 + \\ 0.0577 \times 0.58 + 0.1237 \times 0.9\end{array}} = 0.0843 < 0.1 \tag{6}$$

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:

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

4.2. Determination of the evaluation set

Suppose $v = \{v1, v2 \ldots v_m\}$, 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 $R_i = \{ri1, ri2, \ldots, Rim\}$, the evaluation set of n factors is composed of a single factor fuzzy relation matrix $R = (R|\ U_i)$, 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:

$$R_1 = \begin{bmatrix} 0 & 0.2 & 0.55 & 0.2 & 0.05 \\ 0.35 & 0.5 & 0.1 & 0.05 & 0 \\ 0.3 & 0.45 & 0.2 & 0.05 & 0 \\ 0.1 & 0.5 & 0.35 & 0.05 & 0 \end{bmatrix} \quad (7)$$

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

$$R_2 = \begin{bmatrix} 0.1 & 0.65 & 0.2 & 0.05 & 0 \\ 0.3 & 0.5 & 0.15 & 0.05 & 0 \\ 0.4 & 0.45 & 0.1 & 0.05 & 0 \\ 0.3 & 0.45 & 0.1 & 0.05 & 0.05 \\ 0.3 & 0.5 & 0.5 & 0.1 & 0 \\ 0.2 & 0.45 & 0.3 & 0.05 & 0 \end{bmatrix} \quad (8)$$

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

$$R_3 = \begin{bmatrix} 0.2 & 0.6 & 0.15 & 0.05 & 0 \\ 0.15 & 0.55 & 0.25 & 0.05 & 0 \\ 0.3 & 0.65 & 0.01 & 0 & 0 \end{bmatrix} \quad (9)$$

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

$$R_4 = \begin{bmatrix} 0.2 & 0.4 & 0.3 & 0.05 & 0.05 \\ 0.3 & 0.4 & 0.2 & 0.2 & 0.1 \\ 0.25 & 0.5 & 0.15 & 0.05 & 0.05 \\ 0.15 & 0.65 & 0.15 & 0.05 & 0 \end{bmatrix} \quad (10)$$

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.

$$z_i = W_{z_i} * R_i = (b_1 \quad b_2 \quad b_3 \quad b_4 \quad b_5) \quad (11)$$

In the formula 11, bi 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:

$$Z1 = (0.2899, \quad 0.4731, \quad 0.1769, \quad 0.0575, \quad 0.0025)$$

$$Z2 = (0.2405, \quad 0.5432, \quad 0.1581, \quad 0.0525, \quad 0.0107)$$

$$Z3 = (0.1954, \quad 0.5907, \quad 0.1686, \quad 0.0453, \quad 0)$$

$$Z4 = (0.2323, \quad 0.4831, \quad 0.1893, \quad 0.0538, \quad 0.0414)$$

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

4.5. 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: $Z_1* = 1.8651, Z_2* = 1.9291, Z_3* = 1.9865, Z_4* = 1.9780$ that is 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.

Acknowledgements

The part of the paper has been presented before by Zixue Du in a conference the proceedings of monorail 2017.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the National Natural Science Foundation of China under [grant number 51475062]; the Artificial Intelligence Key Laboratory of Sichuan Province under [grant number 2017RYY04]; Sichuan Provincial Key Lab of Process Equipment and Control under [grant number GK201806]; Project of Sichuan Provincial Department of Education under [grant number 18ZB0423]; Talent Project of Sichuan University of Science and Engineering under [grant number 2017RCL42].

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