Identification of key subsystems for urban rail vehicles based on fuzzy comprehensive evaluation

Zongyi Xing[1]*, Lingli Mao[2], Limin Jia[3], Yong Qin[3]

[1]*School of Automation, Nanjing University of Science and Technology, Nanjing 210094, China*

[2]*School of Mechanical Engineering, Nanjing University of Science and Technology, Nanjing 210094, China*

[3]*State Key Laboratory of Rail Traffic Control and Safety, Beijing Jiaotong University, Beijing 100044, China*

Received 6 May 2014, www.tsi.lv

Abstract

Identification of key subsystems for urban rail vehicles is important for the selection of maintenance strategy. The fuzzy comprehensive evaluation technique is applied to determine the key subsystems of urban rail vehicles. Firstly, the vehicle is divided into nine subsystems according to the module partition method. Then, the degrees of occurrence, severity, detection and maintenance cost are chosen as the evaluation factors that are quantified based on fuzzy theory and collected historical data. Finally, the calculation model of critical degree is established based on the fuzzy comprehensive evaluation method. The proposed approaches are applied to Guangzhou Metro Corporation, and five key subsystems are selected. The experiment results, which are consistent with those of most knowledgeable engineers and experts, indicate the validity of the proposed method.

Keywords: key subsystem, urban rail vehicle, fuzzy comprehensive evaluation

1 Introduction

Urban rail vehicles served as efficient tools for transporting large volumes of passengers often operate in a closed environment, which may cause great inconvenience to passengers and lead to personal injury or property loss when a traffic accident occurs. With the increase in rail lines and vehicle complexity, vehicle maintenance is more challenging and complicated, so it is essential to determine a valid and effective method to identify the key subsystems of urban rail, which ensures the reliability and operational safety of urban rail vehicles under existing resources.

The most commonly-used methods to identify key subsystems or components are as follows: importance degree evaluation, risk priority number assessment, and etc. Birnbaum [1] proposed an importance degree-based method to identify the most important components by quantifying their contribution to the performance of the whole system. The risk priority number method [2] classifies and scores the severity, occurrence, and detection of failure modes according to on-site experience, and then the key subsystems are identified by those three factors. Zhike [3] proposed that the particular set of kinetic parameter values of the model closely approximates the corresponding biological system, and globally identified the key components and steps in signal transduction networks at a systems level by applying multi-parametric sensitivity analysis. Pan [4] used the fault numbers as evaluation criteria to determine the important subsystems of urban rail vehicles. In the paper, fuzzy comprehensive evaluation method was put forward to analyse the key subsystems of urban rail vehicles.

In next section, we summarize the evaluation factors and main identification methods of the key subsystems. Section 3 discusses a case study, in which the door subsystem was chosen as an illustration example to calculate the key degree, and then key subsystems of urban rail vehicles are constructed. Finally, conclusions are offered in Section 4.

2 Identification of key subsystems based on fuzzy comprehensive evaluation

There are two fundamental principles of fuzzy comprehensive evaluation [5] as follows: fuzzy linear transformation and maximum membership degree, which quantify the related various factors of the evaluated object and judge the allocation weights of the factors according to their impact on the object to make a reasonable comprehensive evaluation. With the introduction of fuzzy math into evaluation process, the complex uncertain problem can be solved better and evaluation results are more objective and accurate.

2.1 EVALUATION FACTORS OF IDENTIFICATION OF CRITICAL SYSTEM

The occurrence, severity, detection, and maintenance cost of failure modes are combined to confirm a key subsystem based on deterministic calculation and uncertainty evaluation using fuzzy sets.

* ***Corresponding author*** e-mail: xingzongyi@163.com

The failure occurrence degree λ_i of the subsystem S_i is represented as

$$\lambda_i = n_i / N \,, \tag{1}$$

where n_i is the fault number of subsystem S_i, and N is the fault number of the whole urban rail vehicle.

The j-th failure mode probability of the subsystem S_i is written as

$$\alpha_{ij} = n_j / n_i \,, \tag{2}$$

where n_j is the appearance number of the failure mode M_j and n_i is the fault number of subsystem S_i.

The failure occurrence degree λ_i and failure mode probability α_{ij} can be quantified based on the collected historical data.

The severity, detection and maintenance costs are evaluated comprehensively based on fuzzy theory [6]. The severity s_{ij} is determined according to the failure mode's influence on the normal operation of the vehicle and its damage to the vehicle's functions. The detection d_{ij} indicates the degree that the failure mode can be detected in advance. The maintenance costs c_{ij} contain the human and material costs. From relevant literatures [7,8] and on-site practical experience, the evaluation criteria and membership functions about severity, detection, and maintenance costs are detailed in Tables 1-3.

TABLE 1 Rating scales of severity

Severity s_{ij}	**Membership function**
Inevitably having a huge impact on normal operation of vehicles, resulting in casualties (A)	[0.8 0.9 0.95 1.0]
Probably having a large impact on normal operation of vehicles, causing a great damage to the functional realization of the vehicles (B)	[0.6 0.75 0.8 0.85]
Probably having an impact on the normal operation of vehicles, causing damage to the functional realization of the vehicles (C)	[0.35 0.4 0.5 0.65]
Having no impact on the normal operation of vehicles, causing damage to the functional realization of the vehicles (D)	[0.2 0.25 0.3 0.4]
Having little/ no impact on the normal operation of vehicles and functional realization of the vehicles (E)	[0 0.05 0.15 0.25]

TABLE 2 Rating scales of detection

Detection d_{ij}	**Membership function**
Hardly detectable (A)	[0.8 0.9 0.95 1.0]
Hard to detect (B)	[0.6 0.75 0.8 0.85]
Possible to detect (C)	[0.35 0.4 0.5 0.65]
Easy to detect (D)	[0.2 0.25 0.3 0.4]
Inevitable to detect (E)	[0 0.05 0.15 0.25]

TABLE 3 Rating scales of cost

Cost c_{ij}	**Membership function**
Very high (A)	[0.8 0.9 0.95 1.0]
High (B)	[0.6 0.75 0.8 0.85]
Moderate (C)	[0.35 0.4 0.5 0.65]
Low (D)	[0.2 0.25 0.3 0.4]
Very low (E)	[0 0.05 0.15 0.25]

2.2 CONSTUCTION OF DECISIONN MATRIX

After confirming the scale of the failure modes according to expert experience, the fuzzy comprehensive evaluation decision matrix can be established [9]. Supposing the system Si has m kinds of failure modes, the initial decision matrix Fi can be constructed as follows:

$$F_i = \begin{bmatrix} s_1 & d_1 & c_1 \\ s_2 & d_2 & c_2 \\ \vdots & \vdots & \vdots \\ s_m & d_m & c_m \end{bmatrix}, \tag{3}$$

where s_j, d_j, and c_j, are trapezoidal fuzzy numbers of rating scales for severity, detection, and maintenance costs of the failure mode M_j respectively.

The weight coefficient W is determined in consideration of research needs and on-site experience, and the weighted decision matrix V_i is rewritten using fuzzy composite operator:

$$V_i = W \circ F_i = [v_1 \quad v_2 \quad \dots \quad v_m]^T \,, \tag{4}$$

where the v_j is a trapezoidal fuzzy number.

2.3 CALCULATION OF COMPREHENSIVE QUANTITATIVE VALUES

The decision matrix in the form of fuzzy numbers should be transformed to crisp values using defuzzification methods. The center of gravity method [10] is one of the most commonly-used defuzzification methods and can solve ambiguity of the weighted fuzzy evaluation value. Given a fuzzy number $v_j=(a_j,b_j,c_j,d_j)$, the defuzzification value can be defined as:

$$Z_{ij} = v_j^{'} = \begin{cases} a_j, & a_j = b_j = c_j = d_j \\ \dfrac{d_j^2 + c_j^2 - b_j^2 - a_j^2 + d_j \cdot c_j - b_j \cdot a_j}{3(d_j + c_j - b_j - a_j)}, & \text{else} \end{cases} \,, \tag{5}$$

where Z_{ij} is the comprehensive quantitative value for j-th failure mode M_j of i-th system S_i considering the severity, detection, and maintenance costs.

2.4 PARETO DIAGRAM

A Pareto diagram [11] is an intuitive chart for analysis and selection of main factors for complex systems. All candidate factors are arranged from left to right as the horizontal axis, and the percentage or cumulative percentage of each factor is taken as the vertical axis value. According to Pareto's law, the factors whose vertical axis values accounts for 80 percent are identified as the main factors.

To measure the weight of different subsystems, the key degree of a subsystem is denoted as

$$K_i = \lambda_i \cdot \sum_{j=1}^{m} \alpha_{ij} Z_{ij} , \quad (6)$$

where K_i is the importance measure of the i-th subsystem. The bigger K_i is, the more important i-th subsystem is.

2.5 MAIN STEPS OF THE PROPOSED METHOD

The proposed approach used to identify key subsystems of urban rail vehicles can be summarized as follows:

1) Calculate the failure occurrence degree λ_i of i-th subsystems.
2) Calculate the failure mode probability α_{ij} of j-th failure mode.
3) Determine the scale of severity, detection, and maintenance costs.
4) Establish the decision matrix F_i.
5) Defuzzify the weighted decision matrix to get the comprehensive quantitative value.
6) Calculate the key degree K_i of the i-th subsystem.
7) Normalize the critical degree K_i and identify the key subsystems of urban rail vehicle.

3 Experiments and results

3.1 SUBSYSTEM OF URBAN RAIL VEHICLES

Given that there is no uniform standard for the partitioning of urban rail vehicles, metro corporations often classify different subsystems of rail vehicles. In our experiment, urban rail vehicles were divided into nine subsystems according to such items as function, principle, and behavioral and structural characteristics [12], including door S_1, air brake S_2, auxiliary system S_3 , body S_4, running gear S_5, passenger information S_6, air-conditioner S_7, traction/electronic brake S_8, train control and diagnosis S_9.

3.2 KEY SUBSYSTEM IDENTIFICATION OF URBAN RAIL VEHICLES

The failure modes were counted, and the failure occurrence degrees of each subsystem were calculated based on three-year historical failure data collected from Guangzhou Metro Corporation. The obtained failure occurrence degree λ_i of subsystem S_i is listed in Table 4.

Due to space limitations and the large number of subsystems failure modes, the door subsystem S_1 was selected as an example and was analyzed in detail. Table 5 shows the statistics of failure modes and its probability of the door subsystem.

TABLE 4 Failure occurrence degree of subsystems

S_i	S_1	S_2	S_3
λ_i	0.129	0.076	0.136
S_i	S_4	S_5	S_6
λ_i	0.117	0.079	0.111
S_i	S_7	S_8	S_9
λ_i	0.156	0.167	0.029

TABLE 5 Failure mode probability of door subsystem

Failure Mode M_j	α_{ij}
Door switch indicator does not light M_1	0.079
Red dot display M_2	0.118
Yellow dot display M_3	0.02
Wear/deformation/loss of parts M_4	0.047
Display system error M_5	0.17
Abnormal noise M_6	0.02
Cannot be closed properly M_7	0.012
Cannot be opened properly M_8	0.098
Malfunction of cab door M_9	0.266
Activation of obstacle detection M_{10}	0.17

Knowledgeable engineers and experts of the metro corporation were invited to evaluate scales of severity, detection, and maintenance costs for each failure mode. The final results are shown in Table 6. The decision matrix F_1 was established according to the trapezoidal fuzzy numbers defined in Section 2.1:

$$F_1 = \begin{bmatrix} (0.20 & 0.25 & 0.30 & 0.40) & (0.00 & 0.05 & 0.15 & 0.25) & (0.20 & 0.25 & 0.30 & 0.40) \\ (0.35 & 0.40 & 0.50 & 0.65) & (0.00 & 0.05 & 0.15 & 0.25) & (0.35 & 0.40 & 0.50 & 0.65) \\ (0.20 & 0.25 & 0.30 & 0.40) & (0.00 & 0.05 & 0.15 & 0.25) & (0.20 & 0.25 & 0.30 & 0.40) \\ (0.00 & 0.05 & 0.15 & 0.25) & (0.35 & 0.40 & 0.50 & 0.65) & (0.20 & 0.25 & 0.30 & 0.40) \\ (0.35 & 0.40 & 0.50 & 0.65) & (0.20 & 0.25 & 0.30 & 0.40) & (0.35 & 0.40 & 0.50 & 0.65) \\ (0.00 & 0.05 & 0.15 & 0.25) & (0.35 & 0.40 & 0.50 & 0.65) & (0.20 & 0.25 & 0.30 & 0.40) \\ (0.35 & 0.40 & 0.50 & 0.65) & (0.20 & 0.25 & 0.30 & 0.40) & (0.35 & 0.40 & 0.50 & 0.65) \\ (0.35 & 0.40 & 0.50 & 0.65) & (0.20 & 0.25 & 0.30 & 0.40) & (0.35 & 0.40 & 0.50 & 0.65) \\ (0.35 & 0.40 & 0.50 & 0.65) & (0.20 & 0.25 & 0.30 & 0.40) & (0.20 & 0.25 & 0.30 & 0.40) \\ (0.35 & 0.40 & 0.50 & 0.65) & (0.20 & 0.25 & 0.30 & 0.40) & (0.35 & 0.40 & 0.50 & 0.65) \end{bmatrix}$$

TABLE 6 Scales of door subsystem failure modes

M_j	s_{ij}	d_{ij}	c_{ij}
M_1	D	E	D
M_2	C	E	C
M_3	D	E	D
M_4	E	C	D
M_5	C	D	C
M_6	E	C	D
M_7	C	D	C
M_8	C	D	C
M_9	C	D	D
M_{10}	C	D	C

The weight coefficient of severity, detection, and maintenance costs was chosen as [0.5 0.3 0.2], which means that the weight of severity is 0.5, the weight of detection is 0.3, and the weight of maintenance costs is 0.2. The quantitative value Z_1 and the weighted decision matrix V_1 were calculated as follows:

$$Z_1 = [0.2372 \quad 0.3790 \quad 0.2372 \quad 0.2728 \quad 0.4317 \quad 0.2728 \quad 0.4317 \quad 0.4317 \quad 0.3846 \quad 0.4317]^T ,$$

$$V_1 = W \cdot F_1 = \begin{bmatrix} (0.140 & 0.190 & 0.255 & 0.355) \\ (0.255 & 0.315 & 0.405 & 0.530) \\ (0.140 & 0.19 & 0.255 & 0.355) \\ (0.160 & 0.225 & 0.300 & 0.400) \\ (0.315 & 0.375 & 0.450 & 0.575) \\ (0.160 & 0.225 & 0.300 & 0.400) \\ (0.315 & 0.375 & 0.450 & 0.575) \\ (0.315 & 0.375 & 0.450 & 0.575) \\ (0.275 & 0.325 & 0.400 & 0.525) \\ (0.315 & 0.375 & 0.450 & 0.575) \end{bmatrix}.$$

The key degree of the door subsystem K_1 was computed from:

$$K_1 = \lambda_1 \cdot \sum_{j=1}^{n} \alpha_{1j} Z_{1j} = 0.0494.$$

The above process was repeated until all the key degrees of other subsystems were calculated. Table 7 shows the obtained results.

TABLE 7 Key degree of rail vehicle subsystems

S_i	S_1	S_2	S_3
K_i	0.0494	0.0241	0.0371
S_i	S_4	S_5	S_6
K_i	0.0278	0.0480	0.0301
S_i	S_7	S_8	S_9
K_i	0.0521	0.0647	0.0087

The key degrees of the subsystems were normalized and sorted by size, and then the Pareto diagram was drawn in Figure 1, which indicates that when the number of accumulated normalization key degrees reached 0.8, the key subsystems were identified as the first five subsystems, including traction/electric brake, air conditioner, door, running gear and auxiliary system. The obtained results are consistent with most knowledgeable engineers and experts.

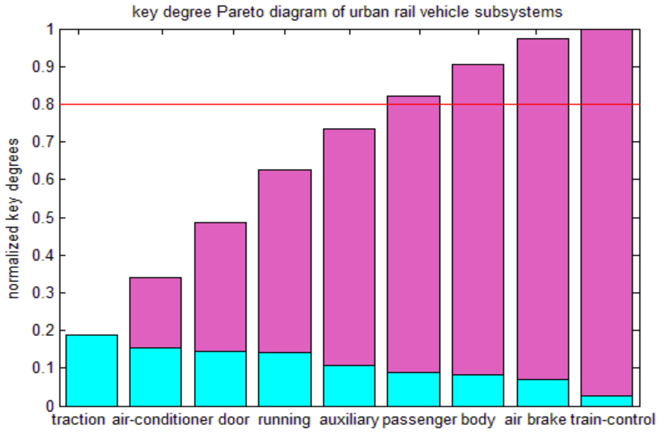

FIGURE 1 Pareto diagram of urban rail vehicles

4 Conclusions

The fuzzy comprehensive evaluation method was applied in this paper to identify the key subsystems of urban rail vehicles. Occurrence, severity, detection, and maintenance costs were selected as evaluation factors, and these qualitative and quantitative indicators were combined to determine the key subsystems more comprehensively and reasonably. The proposed approaches were applied to Guangzhou Metro Corporation, and the five subsystems whose normalization accumulated key degrees reached 0.8 were identified: traction/electric brake subsystem, air conditioning subsystem, door subsystem, running gear subsystem, and auxiliary subsystem.

References

[1] Xing L 2008 *IEEE Transactions on Systems, Man, and Cybernetics—Part A: Systems and Humans* **38**(1) 105-15

[2] Li Y, Yu Y 2012 Quality risk analysis of submarine pipeline in construction period base on FEMA and fuzzy theory *China Safety Science Journal* **22**(1) 112-7 *(in Chinese)*

[3] Zi Z, Cho K-H, Sung M-H, Xia X, Zheng J, Sun Z 2005 In silico identification of the key components and steps in IFN-γ induced JAK-STAT signaling pathway *FEBS Letters* **579**(5) 1101-8

[4] LiSha P, Ling G, LingLi M 2012 Study on reliability of key systems of urban rail vehicles *China Railways* **51**(7) 80-3 *(in Chinese)*

[5] Xian S 2010 A new fuzzy comprehensive evaluation model based on the support vector machine *Fuzzy Information and Engineering* **2**(1) 75-86

[6] Chang K-H, Chang Y-C, Lai P-T 2011 Applying the concept of exponential approach to enhance the assessment capability of FMEA *Journal of Intelligent manufacturing* **22**(2) 113-29

[7] Awasthi A, Chauhan S S, Omrani H, Panahi A A 2011 Hybrid approach based on SERVQUAL and fuzzy TOPSIS for evaluating transportation service quality *Computers & Industrial Engineering* **61**(3) 637–46

[8] Ouédraogo A, Groso A, Meyer T 2011 Risk analysis in research environment – Part I: Modeling Lab Criticity Index using Improved Risk Priority Number *Safety Science* **49**(6) 778-84

[9] Liang Z, Yang K, Sun Y, Zhang H, Zhang Z 2006 Decision support for choice optimal power generation projects: Fuzzy comprehensive evaluation model based on the electricity market *Energy Policy* **34**(17) 3359-64

[10] Hao G, Yang Y, Wang Y, Cao Z, Guo H 2012 Research on the spares provisioning of the breech system based on fuzzy multiple attribute decision making *Value Engineering* **31**(29) 21-3 *(in Chinese)*

[11] Hill L G, Maucione K, Hood B K 2007 A Focused Approach to Assessing Program Fidelity *Prevention Science* **8**(1) 25-34

[12] Li G, W J, Zhang M, Gong, J, Chang P 2009 Approach to product modular design based on FPBS *Journal of National University of Defense Technology* **31**(5) 75-80 (*in Chinese)*

Authors

Zongyi Xing, born in February, 1974, Linyi City, Shandong Province, P. R. China

Current position, grades: Associate Professor at School of Automation, Nanjing University of Science and Technology, China.
University studies: Doctor degree at China Academy of Railway Science and Technology in China.
Scientific interest: Fuzzy modeling, industry process control and rail traffic safety.
Publications: more than 30 papers published in various journals.
Experience: teaching experience of 10 years, 5 scientific research projects.

Lingli Mao, born in April, 1990, Nantong City, Jiangsu Province, P. R. China

Current position, grades: the Graduate student of School of Mechanical Engineering, Nanjing University of Science and Technology, China.
University studies: Bachelor degree from Nanjing University of Science and Technology in China.
Scientific interest: Reliability, mechatronics and rail traffic safety.
Publications: more than 4 papers published in various journals.

Limin Jia, born in January, 1963, Altay City, Xinjiang Province, P. R. China

Current position, grades: Professor at School of Transport of Beijing Jiao tong University, China.
University studies: Doctor degree at Academy of Railway Science and Technology in China.
Scientific interest: Intelligent transportation system, rail traffic control and safety.
Publications: more than 150 papers published in various journals.
Experience: teaching experience of 20 years, 20 scientific research projects.

Yong Qin, born in December, 1971, Xuzhou City, Jiangsu Province, P. R. China

Current position, grades: Professor at School of Transport of Beijing Jiao tong University, China.
University studies: Doctor degree from Academy of Railway Science and Technology in China.
Scientific interest: Intelligent transportation system, rail traffic control and safety.
Publications: more than 50 papers published in various journals.
Experience: teaching experience of 12 years, 6 scientific research projects.