Research on Reliability Evaluation and Maintenance Decision Technology of Subway Vehicles

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Abstract: In view of the difficulty in determining the fault law of subway parts and the problem of excessive maintenance in maintenance methods, the reliability of main subway vehicle systems is systematically analyzed by using fault tree analysis (FTA), fault mode, influence and harmfulness analysis (FMECA) according to the theoretical basis of reliability analysis and maintenance cycle optimization. The fault tree model of the main system of subway vehicles is established, the maintenance strategy and the maintenance plan of each component in the system are determined by logical decision, and the standardized reliability analysis method and maintenance strategy development procedure of subway vehicles are studied, which provides a basis for reliability evaluation and development of the reliability maintenance management system of subway vehicles.

1. Introduction

In recent years, with the expansion of the scale of urban rail transit, passenger flow and passenger intensity have shown an explosive growth. Often, a equipment failure will cause a large area of service delays, which has a great social impact and high attention. Therefore, it has become an important task for major subway operating companies to study the reliability assessment and maintenance technology of subway vehicles to ensure the high reliability of urban rail transit operation.

Domestic reliability engineering is mainly developed in professional research, and related scholars have carried out a large number of reliability engineering research. Ni Shumin et al. carried out a study on the demarcation of equipment maintenance schemes by using fault logic decision method, and evaluated the importance of equipment by using Monte Carlo method, and proposed a maintenance cycle optimization model aiming at minimum average cost [1]. Sun Xiaoyu, Jin Yingchao et al. used the reliability evaluation method to analyze the reliability data of the main components of civil aircraft, calculate the relevant reliability indexes, and put forward the reliability modeling evaluation method of airborne equipment based on the fault process [2,3]. Wang Yang, Cui Youzhi et al. carried out relevant studies on reliabity-centered maintenance, studied the standardized fault tree analysis, fault mode impact and harmfulness analysis process (FMECA) in equipment maintenance, and proposed the development framework of equipment reliability analysis management software system based on FTA and FMECA [4,5].

According to the literature review, more rigorous reliability analysis and evaluation is needed to develop the maintenance procedures of subway vehicle parts, and economic and safety indexes should be uniformly included in the reliability analysis and evaluation of subway vehicle equipment. Therefore, the research on reliability analysis, evaluation and maintenance decision technology of subway vehicles should be practical and applied comprehensively.

Based on the actual fault data, this paper will establish the reliability analysis and evaluation model of subway vehicles, conduct fault sorting, fault pattern recognition and reliability index calculation for the main system of subway vehicles, study the maintenance decision-making technology, reveal the main system reliability law of subway vehicles, and form a set of feasible subway vehicle maintenance decision-making model. At the same time, a software system suitable

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for reliability analysis and evaluation of subway vehicles is developed by means of information technology.

2. The theoretical basis of reliability maintenance optimization

2.1. Reliability analysis and evaluation theory FTA

Regarding reliability analysis methods, fault tree analysis (FTA) and fault mode, impact and Harmfulness analysis (FMECA) are the most widely used methods in reliability engineering at present [6].

Fault Tree Analysis (FTA) is a graphically deductive method that carries out hierarchical tracing analysis around a fault or failure state. It is a top-down deductive failure analysis method, which uses Brin logic to combine low-order events to analyze the undesirable state in the system. Fault tree analysis is mainly used in the field of safety engineering and reliability engineering to understand the causes of system failure.

FTA is used to find the best way to reduce risk, or to identify the incidence of a safety incident or a specific system failure. Fault tree analysis is also used in high risk fields such as aerospace, nuclear power, transportation, pharmaceutical and petrochemical industries for risk identification. FTA is one of the most widely used methods in system reliability analysis. By analyzing hardware, software, environment and human factors that may cause product failures, the cause of product failures, various possible combination ways and their occurrence probability can be determined. Thus effectively determine the various ways of system failure, and improve the reliability and security of the system.

Fault tree analysis uses logical diagrams of the entire system to find relationships among failures, subsystems, and redundant safety design elements. The fault tree is composed of many different types of gates and events. The door includes or door, and door, or no door, and no door, no door, xOR door, voting door, prohibition door, transfer door, priority door; Event types include basic event, room event, undiscovered event, and duplicate event. Priority gate depends on the order of input and is supported by Markov model. Event data includes fault information, maintenance information, and detection period. The main purpose of fault tree analysis is to find the cause and combination of causes of the fault events related to the system, that is, to find all the fault modes leading to the occurrence of top events. The main method is to find the minimum cut set of all the top events in the fault tree. Generally, the lower the order of the minimum cut set, the more prone to failure, which represents the weak link of the system.

2.2. Steps of FTA fault tree analysis

Unwanted events can be difficult to define, but there are also events that are easy to analyze and observe. Engineers who are well versed in system design or systems analysts with an engineering background are best placed to define and enumerate unwanted events. Unwanted events can be used for fault tree analysis. A fault tree analysis can only correspond to one unwanted event.

Obtain relevant information about the system: If an unwanted event is selected, all influencing factors and their probability should be studied and analyzed. Knowing the exact probability requires a lot of cost and time, and is probably impossible. Computer software can be used to study the relative probabilities and can be used to perform low-cost system analysis. A system analyst can understand the entire system. The system designer knows all there is to know about the system, and this knowledge is important to avoid missing any cause of an unwanted event. Finally, all events and probabilities are listed so that the fault tree can be drawn.

Draw a fault tree: After selecting an unwanted event and analyzing the system to know all the reasons (and possibly the probability) for the event, you can draw a fault tree. The fault tree is composed of OR gate and gate and defines the main characteristics of the fault tree.

Evaluate the fault tree: After mapping the fault tree for unwanted events, evaluate and analyze all possible ways to improve, in other words, manage the risk, and try to improve the system. This step leads into the next step, which is to control the identified risks: in short, this step tries to find ways to reduce the probability of unwanted events occurring.

Controlling Identified risks: This step will vary from system to system, but the main focus is to verify that all available ways are available to reduce the incidence of an event after all risks have been identified.

2.3. Reliability analysis and evaluation theory FMECA

In the actual operation of enterprises, it is difficult to draft preventive maintenance plan from scratch or optimize it. The maintenance team not only needs to identify potential equipment problems, but also needs to anticipate their potential impact and take appropriate preventive measures to avoid failures. To this end, enterprises need to implement systematic fault management methods, and one of the most well-known and effective in the industry is "failure mode and impact analysis and harm analysis", hereinafter referred to as FMECA, sometimes simplified to FMEA.

FMECA can be used to systematically analyze the causes and effects of failures, and analyze their possible consequences on operations. By using FMECA, you can help enterprises develop necessary preventive maintenance work, so as to improve the reliability of facilities and equipment, improve production quality, and achieve the purpose of safe operation.

2.4. FMECA maintenance method

Failure Mode, Effects and Hazard Analysis (FMECA) is a method of inductive analysis of all possible failures of a product or system. GBT 7826-2012 System Reliability Analysis, Failure Mode and Impact Analysis, based on the analysis of failure modes, determine the consequences of each failure mode on the system, and determine its hazard according to the severity of the failure mode and its probability of occurrence. The main purpose of FMECA is to comprehensively identify system weaknesses and critical items by analyzing the impact of different failures on each component of the system, and to provide basic information for evaluating and improving the reliability of the system design. For the division of train equipment levels: minimum replaceable unit of train system subsystem [7]. Equipment failure mode, impact and hazard analysis (FMECA) plays an important role in the process of equipment design, manufacturing, maintenance and application. FMECA is used to decompose the equipment system layer by layer and carry out multidimensional analysis of various failure types of the minimum replaceable unit. According to GBT 7826-2012, the fault modes of subway vehicles were analyzed and evaluated in three dimensions: severity, frequency and detection. According to the evaluation results, the classification of each failure mode is determined and different maintenance strategies are formulated.

Based on the FMECA analysis of the running gear system and the maintenance logic decision of each component, the maintenance methods of each component of the running gear system are initially divided into short cycle maintenance: ATC antenna support, ATC beam; Medium cycle maintenance: frame, wheelset, ground carbon brush, first spring, air spring, rim lubrication pipeline, rim lubrication pipeline; Fault repair or long period maintenance: transverse shock absorber, vertical shock absorber, gear box, ground carbon brush. The braking method adopted by the research object is the wheel braking in disk shape braking. The power of friction braking comes from compressed air, which is called the air supply system. Each car is equipped with a set of independent brake air supply system. The main components of the brake air supply system include air supply equipment, brake control equipment, basic brake unit, air suspension device, pantograph air equipment, edge lubrication air equipment, coupler air equipment, etc.

2.5. Maintenance cycle optimization method

IAt present, there are three types of maintenance cycle optimization models widely used: preventive maintenance cycle model based on safety requirements; Preventive maintenance cycle model based on economic requirements; Preventive maintenance cycle model based on availability requirement.

(1) Safety-oriented preventive maintenance cycle. This paper mainly conducts preventive maintenance cycle modeling for parts whose faults may lead to serious safety consequences, and requires that such parts have high reliability in preventive maintenance cycle. When the reliability

of the equipment is required to continue operating Δt after normal operation of Ti, the conditional reliability from Ti to Δt is defined as:

$$R[(T_i + \Delta t) \parallel T_i] = \frac{R[(T_i + \Delta t)}{R(T_i)}$$

(2) The preventive maintenance cycle based on economic requirements is expressed as a maintenance cycle T. Cn is the total maintenance cost per unit time, Cf is the average maintenance cost of fault repair, Cp is the average cost of preventive maintenance, N(t) is the average number of failures within time (0,T). There are:

$$C_n(T) = \frac{C_f N(T) + C_P}{T}$$

Preventive maintenance cycles based on maximum availability requirements. The average total maintenance downtime during the preventive maintenance cycle (0,T) of the equipment is:

$$\overline{t_d} = R(T) \cdot \overline{t_P} + [1 - R(T)] \cdot \overline{t_f}$$

3. Maintenance strategy Optimization for reliability analysis

3.1. Reliability maintenance strategy

EN50126 is a European standard applicable to high-speed rail as well as subways and light rail. EN50126 defines product reliability as the ability to perform specified functions under specified conditions and within specified time limits. Reliability analysis methods are mainly divided into three categories: 1. Fault tree analysis and deductive methods such as fault mode, impact and hazard analysis (FMECA) are used to find the deficiencies and defects of materials, components and manufacturing processes, and provide data and theoretical basis for reliability technology improvement. 2. Summarize and analyze the data collected in the actual application process or the test to evaluate the reliability level of the products; 3. For mechanical parts, life evaluation and reliability analysis are carried out by using fatigue life theory and finite element analysis method.

Two deductive methods, fault tree analysis (FTA), fault mode and impact and hazard analysis (FMECA), are used to analyze the weak links of each main system of subway vehicles. Then, according to the logical decision process, maintenance schemes of the main parts of each system are studied and evaluated, schemes are selected and maintenance strategies are formed.

3.2. FMECA analysis

The bottom event obtained by fault tree analysis (FTA) is the most basic fault mode of FMECA analysis. Therefore, after the FTA is completed, it is necessary to conduct FMECA analysis on the system to analyze the severity, frequency of occurrence, and detection degree (inspection degree) of each failure mode. The purpose is to quantitatively analyze the severity, frequency and detection of the fault of parts and components according to the faults occurred in the operation process of subway vehicles. Finally, according to the calculated risk priority RPN value, priority is given to the severity, and the weak link of the system is found out, which provides a basis for the reliability assessment of subway vehicles and the optimization of management and maintenance schemes.

According to the international standard IEC 60812 failure mode and impact analysis, the FMECA analysis form suitable for subway vehicles is developed, and the code rules are defined.

(1) Code rules

Establishing uniform coding rules for systems, subsystems and parts is conducive to importing FMECA analysis results into subsequent software systems, and is also conducive to data management and inquiry for vehicle manufacturers and metro companies.

Parts code rules, system code: auxiliary power supply system 01; Room door system 02; Traction system 03; Running gear system 04; Brake air supply system 05, subsystem numbered from 01, parts numbered from 01.

(2) Failure mode

Fault mode refers to a form of failure, such as fracture, wear, deformation, parameter deviation, etc. The direct manifestation of such a failure of a component.

(3) fault severity, frequency and detection degree

According to "GBT 7826-2012 System Reliability Analysis Technology FMEA Procedure", the three dimensions of severity, frequency and detection were evaluated, and the RPN value of risk priority was calculated. Meanwhile, the severity S was given priority to determine the preliminary maintenance mode. In the field of subway vehicles, fault repair or long-term maintenance could be carried out if the RPN value was lower than 6. It can be inspected again during overhaul. For RPN values between 6 and 18, the balance between maintenance cost and failure rate needs to be evaluated. If the RPN value is greater than 18 or the severity is equal to 5, it is a high-risk fault mode. You need to encrypt the check interval or use advanced detection methods to contain the fault trend.

3.3. Maintenance decisions based on logical decision processes

After determining the system fault bottom events and completing the preliminary division of the system fault mode maintenance modes according to FTA and FMECA, according to the reliability centered maintenance analysis process of GJB 1378A-2007 equipment, the logical decision method is adopted for the preliminary preparation of the maintenance plan. Firstly, according to the fault impact attributes, it can be divided into hidden fault consequence H, safety fault consequence S, driving delay consequence O and service quality consequence Q. The maintenance methods include maintenance, formulation (special inspection) measures, regular detection (measurement, inspection), regular disassembly and repair, regular replacement, fault maintenance, and comprehensive maintenance (integration of multiple maintenance methods). A logical decision process for subway vehicles is developed. Several order of consequence judgment: function loss caused by fault mode itself → Function loss caused by fault mode itself causes impact on traffic safety and rescue → Function loss caused by fault mode itself causes delay impact on train operation.

For each step of the above consequences, the following sequence of actions: 1) maintenance and function inspection, 2) formulate special protective measures, 3) adopt regular detection and status assessment, 4) regular disassembly and repair inspection, 5) regular replacement and scrap, 6) fault maintenance, 7) change the design.

3.4. Reliability data analysis method

The main purpose of reliability data analysis for each subway vehicle system is to study the fault law of the system and evaluate the reliability indicators of the system quantitatively. It is also the premise of the maintenance and economic analysis of the system, and an important method to formulate the optimal maintenance cycle of the system. Reliability data sources can be divided into a variety of: (1) product laboratory data; (2) Use data of similar products for reference; (3) Field application data.

The fault distribution is the parameter estimation of the exponential distribution model, and the probability density function f(t) :

$$f(\mathrm{t}) = \frac{\mathrm{dF(t)}}{\mathrm{dt}} = \frac{\mathrm{d}(1 - \mathrm{e}^{-\lambda \mathrm{t}})}{\mathrm{dt}} = \lambda \mathrm{e}^{-\lambda \mathrm{t}}$$

Reliability function R(t) :

$$\mathrm{R(t)} = 1 - \mathrm{F(t)} = \int_{\mathrm{t}}^{\infty} f(\mathrm{t})\mathrm{dt} = \mathrm{e}^{-\lambda \mathrm{t}}$$

The expression of failure rate (t) is:

$$\lambda(\mathrm{t}) = \frac{f(\mathrm{t})}{\mathrm{R(t)}} = \frac{\lambda \mathrm{e}^{-\lambda \mathrm{t}}}{\mathrm{e}^{-\lambda \mathrm{t}}} = \lambda$$

The estimated parameter of exponential distribution is failure rate λ,

$$\tilde{\lambda} = \frac{n}{\sum_{i=1}^{n} t_i}$$

The parameter estimation of Weibull distribution model is similar to the above method.

4. Development of subway vehicle reliability maintenance system

4.1. Device information management module

The equipment information management module is mainly used to construct the equipment product tree structure of each system of subway vehicles, and on this basis to build the product tree. The product tree is refined to the minimum replaceable unit in each system, and the failure mode of each minimum replaceable unit is analyzed. The tree structure is built addressing the code and ownership of each minimal replaceable unit.

The equipment information includes the factory information, code, fault performance, manufacturer, supply channel, drawings and other basic information of each minimum replaceable unit. Users can edit the information contained in the minimum replaceable unit, and add, delete, and modify nodes in the product tree structure. The average annual failure rate of the equipment and the impact time of each failure are calculated according to the fault data input in the later operation process of subway vehicles. The system automatically generates the frequency and severity of fault modes according to the input fault data. Then the technician completes the intermediate judgment of the logical decision process such as detection degree and consequence evaluation.

4.2. FMECA module

According to the calculation results of the equipment information management module, such as frequency, severity, detection evaluated by technicians and maintenance plan based on logical decision, the system assists technicians to complete FMECA analysis and provides maintenance suggestions for the reference of subway technicians. In the fault tree on the right of the FMECA module interface, select the fault mode (or device name) that you want to analyze and click Search. FMECA module calls the fault information database to screen the fault information of the selected fault mode, automatically calculates the frequency and severity of the selected fault mode, and then combines with technical personnel to evaluate the detection degree and make logical decisions, and finally generates the FMECA analysis process and gives maintenance suggestions.

4.3. Failure data entry and reliability data analysis module

The data entry of the fault information database is generally completed by the maintenance team of the metro company. After the data entry into the database, the technical personnel will complete the data review and judge whether the data is included in the reliability calculation. The FMECA module selects the fault modes to be analyzed by screening the fault mode fields, completes the calculation of the frequency of the selected fault modes, and calculates the severity of the selected fault modes according to the fault influence fields. The reliability data analysis module can track the fault of the parts with the same serial number through the fault information database of the parts, and complete the calculation of the fault distance and the processing of the truncated data of the parts with the same serial number.

Tasks of reliability analysis module: According to the user input time range, the system and parts, and the distribution model to be fitted, the fault information database is called to automatically analyze the corresponding reliability data, arrange the data within the time range to be calculated, screen the truncated data for processing, estimate the parameters of the distribution model, and calculate the parameters of the optimal fit of the statistical model. Finally, the relevant calculation of the fault distribution model was completed, and the technical staff was assisted to evaluate the fault law and maintenance cycle.

5. Conclusion

This paper systematically carries out reliability analysis and evaluation on the main system of subway vehicles, establishes the maintenance cycle optimization model based on risk and availability, and develops the reliability maintenance management system suitable for subway vehicles. The main research work is summarized as follows:

(1) Using fault tree analysis (FTA) to identify the fault modes of the main system of subway vehicles, using fault mode, influence and hazard analysis (FMECA) to analyze the fault causes, consequences, fault frequency, detection and severity of each fault mode, and obtain the priority number of risk of each fault mode. According to the risk priority number and the severity priority condition, the maintenance cycle of each part is preliminarily divided, and the maintenance plan of main zero parts is formulated by logical decision method.

(2)The fault data generated during the actual operation of subway vehicles were collected, the truncated data were processed by the timed truncated test scheme, and the reliability indexes and fault rules of the main system of subway vehicles were analyzed and calculated by the statistical principle and reliability theory, so as to complete the reliability evaluation of the main system of subway vehicles.

(3) On the basis of studying three optimization models of maintenance cycle, which are safety oriented, economy oriented and availability oriented, the maintenance cycle optimization model based on risk and availability is proposed. The reliability analysis results are applied to the calculation of risk cost, and the solution is obtained when the availability reaches the predetermined target. The maintenance cycle of medium cycle maintenance with minimum overall cost per unit mile.

The reliability maintenance management system of subway vehicles is developed. Realize the information management of subway vehicle equipment, on-site fault data entry and review, FMECA analysis of vehicle equipment, and give maintenance suggestions. At the same time, the system relies on fault database to calculate and evaluate the reliability of vehicle equipment.

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References

[1] NI Shumin. Reliability Centered Maintenance Analysis of Missile Products [D]. Harbin Institute of Technology, 2013.

[2] JIN Yingchao. Research on Reliability Evaluation Method of Aircraft Airborne Equipment Based on Field Data [D]. Harbin University of Science and Technology, 2018.

[3] SUN Xiaoyu. Application Research of Reliability in Civil Aircraft Maintenance Engineering [D]. Kunming University of Science and Technology, 2006.

[4] WANG Yang. Research on reliability-centered Ship maintenance Auxiliary Decision System [D]. Wuhan University of Technology, 2009.

[5] CUI Youzhi. Research on Reliability-centered Maintenance Decision Technology of NC Machine Tools [D]. Chongqing University, 2012.

[6] Yu Jie, Zhou Hao, Huang Chunguang. Reliability centered maintenance Strategy [J]. High Voltage Technology, 2005(06): 27-28+58.

[7] Gu Meibang, Huang Yi, Li Yun. Application of Causal Analysis Diagram and FMEA in Ship Construction Quality Control [J]. Ship Standardization and Quality, 2015(03): 49-51.