Study on Reliability Evaluation and Maintenance Decision-Making of Metro Vehicles

Haichao Ma

Rail Transit Department, Southwest Jiaotong University Hope College, Chengdu, Sichuan, China

825182196@qq.com

Keywords: Metro Vehicles, Preventive Maintenance, Multi-level Group Maintenance, Maintenance Decision-Making Prototype System

Abstract: Aiming at the problems of traditional regular maintenance mode of subway vehicle maintenance: Based on the fault distribution theory, reliability theory and preventive maintenance theory, a preventive maintenance model based on fault correlation and a multilevel preventive maintenance model with key components as the core were established to develop a prototype system of group maintenance decision making considering occasional faults. According to method design, case analysis, comparative evaluation and test adjustment, the equipment maintenance strategy of low maintenance cost, high reliability and high availability is proposed in order to improve the effect of vehicle maintenance, realize the prediction of subway vehicle failure, and reduce the maintenance after failure.

1. Introduction

In recent years, the length of subway across the country has grown rapidly, the subway vehicle equipment is aging, the vehicle working environment is complex and changeable, and the vehicle maintenance work is facing severe challenges. The strategy of regular maintenance is difficult to adapt to the current maintenance task of subway vehicles. It is of great significance to study preventive maintenance methods and formulate scientific maintenance strategies for subway vehicles to ensure the safe and stable operation of subway vehicles and reduce maintenance costs.

ErguidoA developed a reliability-based multi-objective maintenance model to improve traditional maintenance and organizational key performance indicators through continuous evaluation of short-term information of light rail equipment, and adopted simulation optimization methods to solve the model [1]. Kamel G proposed a preventive maintenance scheduling model to optimize the cost of machines in complex repairable systems, improve the effective life of machines, and maintain a certain level of availability and reliability while reducing the total maintenance cost [2]. Wang Hong established the failure rate function of subway vehicle equipment based on Weibull distribution, and carried out the conversion between failure rate and reliability. When to maintain the equipment by setting the reliability threshold [3]. Wang Huashheng analyzed the logical functional relationship among various devices, and allocated equipment reliability indexes based on importance, complexity, maintainability and testability as comprehensive evaluation factors [4].

The above researches mainly focus on single equipment, limited to some key subsystems, and lack of research on dynamic adjustment of multi-equipment maintenance strategy. In this paper, a multilevel group preventive maintenance model and decision system with critical components as the core and occasional failures as the core is proposed to consider fault correlation. Based on the fault rule, the preventive maintenance strategy is established to provide reasonable arrangement for subway maintenance..

2. The Theoretical Basis of Preventive Maintenance

2.1. Fault Distribution Theory

The fault theory reveals the motion law of mechanical equipment in the process of use, which

DOI: 10.25236/icceme.2023.036

includes the fault statistical analysis theory, namely the fault macro theory and the fault physical analysis, namely the fault micro theory. The specific content of fault analysis is to take various faults of mechanical equipment in different conditions of use as the research object, with advanced testing technology and physical and chemical methods. This paper analyzes and studies the process of fault occurrence and development, including the mechanism, shape, rule and influencing factors of fault from micro and sub-micro perspectives.

Failure mechanism is to study the cause of mechanical equipment failure and its development law, namely the deterioration theory. It is generally characterized by fracture, wear, deformation, fatigue, corrosion and oxidation. The study of fault form is the joint study of fault mechanism and fault analysis, which boils down to the specific form, type and mode of fault. On the basis of a large number of statistics and analysis, it is intuitive to use the external characteristics of fault units as the basis to judge the internal connection of faults.

2.2. Fault tree FTA analysis and evaluation theory

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. Fault Tree Analysis (FTA) is a graphically deductive method that carries out hierarchical tracing analysis around a fault or failure state.

FTA is one of the most widely used methods in system reliability analysis. Through the analysis of hardware, software, environment and human factors that may cause product failure, the causes of product failure and various possible combination ways and their probability of occurrence are determined, so as to effectively determine various ways of system failure and improve the reliability and security of the system.

Fault tree is a special inverted tree logical causal diagram, which describes the causal relationship between various events in the system with event symbols, logic gate symbols and transition symbols. The input event of a logic gate is the "cause" of the output event, and the output event of a logic gate is the "effect" of the input event. 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. 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, so that the weak link of the system can be found and the improvement measures can be taken.

2.3. FMECA analysis and evaluation theory

Fault mode, Impact and harmfulness analysis (FMECA) is an inductive analysis method aimed at all possible faults of a product or system, which determines the consequences of each fault mode on the system according to the analysis of the fault mode, and determines its harmfulness according to the severity of the fault mode and its occurrence probability. 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. 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. Each failure mode of subway vehicles was analyzed and evaluated in three dimensions of severity, frequency and detection, and the grade of each failure mode was determined, and different maintenance strategies were formulated.

3. Multilevel group preventive maintenance decision model

3.1. Multi-level group preventive maintenance problem hypothesis

At present, the research on preventive maintenance of subway vehicles takes the minimum maintenance cost as the optimization goal. However, due to the complex structure of numerous subway vehicles, it is difficult to carry out preventive maintenance. Therefore, preventive maintenance strategy of key equipment should be combined with multi-level maintenance mechanism for group maintenance. In group maintenance, the adjustment of the original maintenance strategy may lead to the delay of maintenance nodes, resulting in accelerated deterioration of equipment status, and higher depreciation costs and failure risks. Therefore, in addition to the traditional maintenance cost, the cost of delayed maintenance of equipment should be considered. At the same time, the maintenance policy should meet the principle of flexibility as far as possible and consider the maximum availability target to improve the feasibility of the maintenance policy.

Considering the feasibility of the model and the difficulty of solving it, the following assumptions are made about the background of the model: the subway vehicles are in a new state when they start to work, that is, the initial service age is zero; After the preventive maintenance node of key equipment of subway vehicles is combined with multilevel maintenance mechanism, the maintenance work is implemented in normal shutdown state, and no additional shutdown loss cost will be generated. The maintenance nodes where the critical equipment is not grouped and the nodes where the critical equipment is grouped together need to calculate the shutdown cost.

The corresponding maintenance effects of different maintenance methods are as follows: after maintenance, the status of subway vehicles is restored to the level after last maintenance; after minor repair, the status of subway vehicles can be restored to a certain extent, but cannot be restored to the level after last minor repair; after major repair, the status of subway vehicles is restored to a new level; The accidental failure of subway vehicle equipment is repairable, and the reliability of the equipment can only be restored to the level before the failure after the repair.

3.2. Group maintenance

Group maintenance means that all units of the system are maintained at the same time. The main purpose of this maintenance strategy is to ensure system reliability or reduce system operation cost. One strategy is to divide a unit into different classes, and when a unit in a class fails, replace all the units belonging to that class; The second model assumes that the failure rate of each unit in the system has the same distribution, and the entire system is replaced when the age of the system reaches T or the number of system failures reaches m. However, in practice, the relationship between maintenance nodes of key equipment is not just integer multiple, which makes centralized maintenance difficult.

Opportunity maintenance: Due to the economic correlation between units, preventive maintenance of non-faulty units while maintaining faulty units can obviously reduce the maintenance cost of the system. Sometimes, the fault of one unit affects other units. Therefore, you can maintain related units while maintaining the faulty units. Therefore, group maintenance and opportunity maintenance are combined. Firstly, the method of opportunistic maintenance is used to determine whether other devices can be maintained at the same time during the maintenance of a certain device, and then the group maintenance principle is used to combine the maintenance nodes of the two devices.

The preventive maintenance model is used for critical equipment, while other equipment still uses a multilevel maintenance mechanism. Combining key equipment preventive maintenance strategy with multilevel maintenance mechanism can reduce maintenance frequency, reduce maintenance cost and improve the practicability of the model. Preventive maintenance nodes in the maintenance strategy of key equipment should be advanced or postponed to be maintained together with nodes of biweekly inspection or balanced repair, thus reducing the number of vehicle downtime and making full use of down time.

3.3. Multi-level group maintenance optimization model of subway vehicles

(1) Preventive maintenance cost M

Maintenance cost of subway vehicle equipment can be divided into basic maintenance cost and maintenance cost after accidental failure, among which basic maintenance cost can be further divided into maintenance cost, basic maintenance cost and replacement cost. Therefore, preventive maintenance cost of subway vehicle equipment within a maintenance cycle is:

$$M = \sum_{i=1}^{N} K_i C_t + (N-1)C_P + C_R \sum_{i=1}^{N} \left(\int_0^{T_i} f(t)dt\right) C_m \quad (1)$$

Where, Ct represents the average cost of single maintenance of subway vehicle equipment, Cp represents the average cost of single basic maintenance of subway vehicle equipment, Cr represents the cost of single replacement of equipment, Cm represents the average cost of maintenance after accidental failure of equipment, ki represents the number of maintenance times of subway vehicle equipment within the i minor repair cycle. N represents the number of minor repairs to subway vehicle equipment in the whole maintenance cycle, and the integral of f(t) is the number of failures of subway vehicle equipment in the i minor repair cycle.

(2) multi-level group maintenance cost

After the preventive maintenance strategy of critical equipment is grouped with the multi-level maintenance mechanism, the maintenance cost of repeated calculation must be deducted from the total cost because some maintenance nodes are merged. There are two key elements in group maintenance, one is the maintenance time node, the other is the maintenance time. In group maintenance, the maintenance time of two nodes must be roughly the same. Otherwise, even if the time of two nodes is similar, they cannot be grouped. Therefore, the maintenance time of preventive maintenance, minor repair and major repair should be adjusted so that the contents of the three levels of maintenance are consistent with those of daily inspection, balanced repair and scheduled repair respectively to ensure that the maintenance time is consistent. In this way, the maintenance cost of a certain maintenance node in preventive maintenance can be calculated separately. There are three types of cost calculation in multilevel group maintenance. The first type is the group of key equipment maintenance node and multilevel maintenance mechanism node. The second is the case of group maintenance between key equipment; The third is the ungrouped case, which does not result in double counting costs. The total cost of multistage group maintenance is calculated by the following formula.

$$C_z = D_d \sum_{i=1}^{N} G_i + \sum_{i=1}^{N} M + \sum_{i=1}^{N} Z_{ij} \quad (2)$$

Where, Cz represents the total maintenance cost, Dd represents the total maintenance cost of multilevel maintenance mechanism excluding key equipment, Gi represents the maintenance cost of key equipment under the multilevel maintenance mechanism, and Zij represents the cost of repeated calculation deducted from key equipment i after the grouping of maintenance node j.

3.4. Model solving based on adaptive immune algorithm

Aiming at the lowest maintenance cost rate and the highest availability of subway vehicles in a replacement cycle, the immune adaptive algorithm was used to solve the model. The algorithm simulates the immune principle in biological system, adopts the population search strategy, and obtains the global optimal solution through iterative calculation.

(1) Algorithm design

It can be seen from the above modeling process that multi-objective and multi-level group preventive maintenance is a complex computational problem. Artificial Immune Algorithm (AIA) is a new intelligent heuristic random search algorithm inspired by biological immune mechanism, which can solve the above problems.

The existing AIA is still unable to get satisfactory solution quickly when solving complex function optimization problems. In this paper, an adaptive artificial immune algorithm, including adaptive algorithm IAAIA, is used to improve the convergence speed, convergence accuracy and stability of the algorithm on the basis of the traditional immune algorithm. The immune adaptive algorithm can generate and maintain the diversity of the population, overcome the problem of local optimal solution in the general optimization process, and obtain the global optimal solution.

(2) Coding method

Binary coding was adopted, and 10 bits of binary number were used to represent the three variables of minor repair cycle N, maintenance cycle t0 and minimum reliability Rmin. From left to right, the first three digits represented N, the middle four digits represented t0, and the last three digits represented Rmin. Each antibody is represented by a 10-bit binary number. When calculating antibody fitness, it is necessary to extract the three segments of antibody data respectively, convert them into decimal numbers, and then substitute them into the objective function for calculation.

(3) algorithm program

When the algorithm is solved, the initial antibody population is generated first. Antibody variation enables the population to produce new antibodies while maintaining the original mass, which injects evolutionary potential into the population. The population affinity was calculated again and the number of iterations was judged. If the preset number of iterations was not reached, part of new antibodies were randomly generated in the population, and the antibodies with poor quality were removed, so an iteration was completed. When the number of iterations reaches the preset value, the antibody and its corresponding target value and maintenance strategy are output, and the solution is finished.

4. Multilevel group maintenance optimization model validation

4.1. Algorithm effectiveness analysis

In order to verify the feasibility of the above maintenance model, a subway company's vehicle equipment was taken as an example to solve the problem. Taking the actual maintenance situation into account, ΔT=3 days, Rs=0.75, R0=0.8 were taken to sort out the parameters required by the maintenance cost of key equipment in the model.

When r=1 or 0, the multi-objective model is transformed into the single objective model of cost rate or availability. With the increase of the weight coefficient r, the focus of the model gradually shifts from the optimization of equipment maintenance cost to the optimization of availability. Therefore, the maintenance cost per unit time shows a decreasing trend; On the contrary, there is an increasing trend. Maintenance plan makers can select the corresponding reliability threshold of each component R0 according to the weight of each objective required in the actual maintenance, so as to formulate the multi-objective preventive maintenance plan of subway vehicles.

In the process of solving calculation, as the maintenance cycle set in this paper is 3 years, the upper limit of the number of minor repairs N is set to 36 times, the actual maintenance data are substituted into the model for solving, 50 initial solutions are randomly generated, the step size is set as 1, and the iteration runs for 200 generations. At the same time, it is compared with the traditional genetic algorithm and immune algorithm. Compared with genetic algorithm and traditional immune algorithm, the immune adaptive algorithm has the fastest convergence speed, and has converged to the satisfactory solution set in the 57th generation. Genetic algorithm and immune algorithm converge in the 133rd generation and 120th generation respectively. The number of antibody clones can be determined dynamically according to the quality of antibody, which can effectively improve the efficiency, convergence speed and convergence accuracy of the algorithm.

4.2. Effectiveness analysis of optimization results

Through group maintenance, most of the minor repair nodes of the four critical equipment have been merged with the balanced repair nodes. According to the analysis of the solution results, before the scheduled repair in the 24th month, the interval between preventive maintenance nodes becomes smaller with the increase of maintenance time, which solves the defects of excessive maintenance in the early period and insufficient maintenance in the later period. After the scheduled repair, the key equipment is overhauled, the state of the equipment is restored as new, and the maintenance intensity is reduced appropriately. Therefore, 12 months after the maintenance strategy, the maintenance node interval of the key equipment becomes larger. The maintenance cycle of key equipment is divided into three stages: early stage, middle stage and late stage. Each stage is 1 month. Then, the change of maintenance interval of each stage is calculated.

As can be seen from the figure, due to the scheduled repair in the 24th month, equipment reliability was improved, so the interval between minor repair and maintenance decreased first and then increased. By comparing and analyzing various indexes of a subway vehicle before and after adopting the multilevel group maintenance strategy, and estimating the cost of multilevel group maintenance for multiple vehicles according to the solution results, it can be seen that the maintenance cost rate is reduced by 7.5% after adopting the preventive maintenance strategy for key equipment, and by 6.6% after further adopting the multilevel group maintenance strategy. This is 13.6% lower than the current maintenance system, while the average availability of key equipment is 77%. Although this is the lowest in the ownership revaluation results, it is still 1.8% higher than the current average availability of Line 1 vehicles. It can be seen that the multilevel preventive maintenance strategy can reduce maintenance costs, improve equipment reliability, and ensure vehicle availability.

5. Development of preventive maintenance decision prototype system

5.1. Functional requirement analysis

The development of preventive maintenance decision prototype system for subway vehicles is based on the historical fault data of equipment, combined with preventive maintenance theory and reliability theory, to build a graphical interface system that is convenient for maintenance personnel to operate, assist in the development of maintenance plan, and has a simple and easy to understand operation interface, equipment data query, numerical results and graphical report mechanism.

User login: identifies the identity of the user who logs in to the system, implements function and authority management, and ensures system security.

Maintenance strategy formulation: Preventive maintenance strategies are formulated according to the reliability-centered maintenance idea, and the maintenance cycle of each device is redetermined, which provides reference for vehicle maintenance managers.

Information query and data storage: provides a complete and comprehensive management platform for subway vehicle system fault information, and stores the changed information, including vehicle number, fault equipment, fault type, operating line, fault time, fault analysis, fault consequences, maintenance personnel, maintenance time, maintenance measures, remarks and other information.

Quick response to accidental failure: In case of an accidental failure of a certain equipment, other equipment shall be arranged for maintenance according to the fault level, so as to make full use of maintenance time and simple shutdown loss.Graphic printing: Prints out the schematic diagram of the maintenance policy for maintenance personnel.

5.2. Development environment and tools

The metro vehicle preventive maintenance decision function module developed in this paper is based on Windows10 operating system, PyQt5 graphical interface library, PyCharm compiler and Matlab2019 software code.

Matlab software will data visualization, numerical analysis, matrix calculation and many other functions in a simple and clear window environment, for scientific research, engineering design and other need to carry out complex numerical calculation of science provides a comprehensive solution, allowing users to modify the program when running, compared with the use of traditional non-interactive programming language writing efficiency.

The maintenance of subway vehicles involves a huge amount of information, and data is an indispensable element to maintain the system operation, so it is necessary to manage the data. This paper firstly sorts out all kinds of data required by maintenance decision prototype system and divides the data into 5 databases. Among them, fault information database, equipment information database and maintenance cost database provide basic information for formulating maintenance strategy, and maintenance strategy after formulation needs to be implemented by maintenance personnel. The maintenance personnel record the fault information that occurs during maintenance in the fault information database.The user input the equipment name, average maintenance cost, replacement cost, basic penalty cost and post-maintenance cost into the system, select the fault distribution type of the equipment, input the corresponding parameters, click the "calculation result" button, the system calls the pre-written Matlab program, the user input information into the program.

6. Conclusion

In this paper, a subway vehicle of a subway company is selected as the research object. After understanding its equipment maintenance status and main fault types, the equipment fault transfer relationship analysis, importance evaluation and fault distribution fitting are carried out. On this basis, the preventive maintenance model of key equipment is constructed. Finally, based on the above model, combined with Pycharm, Qt designer, Matlab and SQL Server software, a subway vehicle preventive maintenance decision prototype system was designed and developed. The research results are as follows:

(1) A multilevel group maintenance decision model of subway vehicles based on immune adaptive algorithm is established. Aiming at the lowest maintenance cost rate and the highest availability, a multilevel preventive maintenance model based on reliability was established by combining the group maintenance strategy with the existing multilevel maintenance mechanism. A model solving method based on immune adaptive algorithm was proposed to obtain the best preventive maintenance strategy.

(2) A prototype decision - making system for preventive maintenance of subway vehicles is developed. Taking the actual operation of a subway vehicle as an example, a prototype decision-making system for preventive maintenance of subway vehicles was developed, which realized the rapid formulation of preventive maintenance strategy, component maintenance information query and occasional fault response, etc., which verified the validity and feasibility of the model and method proposed in this paper, and improved the intellectualization of preventive maintenance strategy formulation. It has important engineering and practical significance to the safe operation of subway vehicles.

Acknowledgements

The authors greatly appreciate the following sponsors for their support to the study: Soft Science Project of Science and Technology Department of Sichuan Province, “Intelligent NUMERICAL control system based on physical motion control principle”22RCYJ0005.

References

[1] Erguido A, Crespo A, Márquez E. Reliability-based advanced maintenance modelling to enhance rolling stock manufacturers’ objectives[J]. Computers & Industrial Engineering, 2020, 96: 144-146.

[2] Kamel G, Fahmy MA, Mohib A., et al. Optimization of a multilevel integrated preventive maintenance scheduling mathematical modelusing genetic algorithm[J]. Computers and Industrial Engineering, 2020 ,15 (4): 247-257.

[3] Wang Hong, Liu Zhilong, Du Weixin, et al. Preventive Maintenance Strategy and Maintenance Model of Subway Vehicle Equipment Based on Multiple Maintenance Methods [J]. China Railway Science, 2016,37 (04) : 108-114.

[4] Wang Huasheng, Wang Yiyan, Xie Chuanchuan, et al. Reliability Modeling and Allocation of CRH2 EMUs [J]. Journal of the China Railway Society, 2009, 31 (05): 108-112.