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Improving Reliability and Maintainability of Urban Rail Vehicles in Complex Environments: Factors and Responses Analysis

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Abstract: The urban rail vehicle is a critical component in transforming a large transportation country into a strong transportation country. However, the vehicle's reliability and maintainability are put to the test due to the complex environment it encounters throughout its entire life cycle. This environment can be divided into two parts: a complex natural use environment and a complex human interaction environment. The former encompasses the regional characteristics of comprehensive environmental loads and their own incentive environmental loads, while the latter is divided into three stages: the design, procurement, and integrated manufacturing stage; the delivery stage; and the final operation user use stage. To address the challenges posed by this complex environment, it is essential to use environmental technology to analyze the natural environment of the territory. Additionally, it is crucial to establish localized, standardized, and specialized operation and maintenance technical teams, consider existing operation data as a supplement to vehicle performance acquisition, and ensure that operation is a continuation of vehicle reliability testing and maintenance program development. By taking these steps, the performance of national urban rail vehicles can be steadily improved.

Keywords: Complex Environment; Urban Rail Vehicles; Reliability; Maintainability; Development Ideas

Introduction

The reliability and maintainability of urban rail vehicles are crucial for ensuring their safe and efficient operation throughout their life cycle. The complex environment in which they operate can have a significant impact on their performance, which can be categorized into two broad areas: the influence of the natural environment and the influence of the human-interaction environment. These factors are shaped by the physical and social aspects of the overall environment. Improving the reliability and maintainability of urban rail vehicles is a key objective in their design and development, and it requires addressing both of these environmental factors.

1. Analysis of Factors Influencing Reliability And Maintainability of Urban Rail Vehicles Under Natural Use Environment

Urban rail vehicles are subject to different environmental conditions throughout their life cycle, including during manufacturing, storage, transportation, and operation. The external environment can vary depending on the location of deployment and the specific usage conditions. In China, there are several key natural climate characteristics and environmental factors that can have a significant impact on the operation of urban rail vehicles. These include a range of environmental loads that are unique to the urban rail vehicle operation process.

1.1 Low temperature, dry and sandy environment

Urban rail vehicles in northern China are subject to a range of extreme environmental loads, mainly related to low temperatures, dryness, and increased dust accumulation. These environmental factors can cause various types of damage to the vehicle's components, such as brittle failure, cracking, and reduced structural strength of seals made of plastic and rubber. Low temperatures can also cause physical shrinkage and structural failure of materials. Dryness and dust can lead to clogging of filters, increased wear between parts, and reduced lubrication due to increased viscosity and concentration of the lubricant. These factors can also cause changes in the performance of electronic components.

1.2 High temperature and humid environment

The humid heat and hot temperature zones, which cover East China, South Central China, Southwest China, and other areas of the Yangtze River basin, are known for their high temperatures and humidity levels. Cities like Wuhan, Chongqing, and Nanjing are part of this region, where the average maximum temperature in summer can reach 42 degrees Celsius, and the average relative humidity can reach 80%. The combination of high temperatures and humidity can significantly reduce the reliability of urban rail vehicles, leading to a range of issues. The heat expansion of each system component can cause them to bind together, while evaporation of lubricants reduces their viscosity and lubricating capacity. Metal parts can corrode, and exterior coatings can crack due to moisture and heat expansion. These effects are the result of a combination of multiple factors and not a single cause.

1.3 Salt spray humid environment

The environmental characteristics of southeast coast and island areas, such as Xiamen Metro Line 3 and Sanya trams, create salt spray due to the air's ability to hold water vapor. Higher temperatures mean more water vapor in the air, which dissolves salt particles and reduces insulation resistance. This accelerates electrochemical corrosion of metals, causing blistering of paint layers and corrosion and aging of seals. These factors weaken structural strength and decrease sealing performance.

1.4 Electromagnetic radiation environment environment

The urban rail vehicle system consists of several electrical systems, including braking, traction, and auxiliary power supply. It contains both low voltage electrical components for operation and maintenance control, as well as high-power, high voltage electrical components and various complex electromagnetic components. As a result, the electromagnetic environment of the vehicle system deteriorates due to the integration and intertwining of these components. Additionally, there are various external sources of electromagnetic interference, such as high-voltage transmission lines, large power plants, and television and radio transmission systems, that further complicate the electromagnetic environment. Improving the electromagnetic compatibility of the urban rail vehicle system is essential to ensure the proper functioning of each electronic device in the vehicle without any interference, thus enhancing its overall reliability.

2. Analysis of factors influencing reliability and maintainability of urban rail vehicles in human-caused interaction environment

The vehicle is a complex electromechanical system, which is condensed into three stages according to the ownership of urban rail vehicles in the product human interaction environment, namely ① design, procurement, and integrated manufacturing stage, ② delivery stage, and ③ user use stage.

2.1 Brief analysis on the problems affecting reliability and maintainability of rail transit vehicles in design, procurement and integrated manufacturing stages

Good maintenance design and reliability are key to ensuring the integrity of urban rail vehicles. Inherent reliability, maintenance strategies, quality control methods, and other maintenance attributes are shaped by design technology, means, and theory.

However, some designers currently neglect to formulate detailed life and mission profiles for actual operating locations, environmental protection design for key components, and dynamic reliability test outlines. Furthermore, failure mode and impact analysis and fault tree analysis tend to only focus on the failure itself, rather than considering maintenance design aspects, such as the accessibility of components and operational spaces.

Considering the supply chain, each component of the rail transit industry's vehicles is procured from a complex network of upstream and downstream enterprises. This can lead to situations where some components do not meet the required standards. Centralizing procurement and standardizing components can be essential steps to enhancing reliability and maintenance.

2.2 Brief analysis on the problems affecting reliability and maintainability of rail transit vehicles in the delivery stage

China's rail vehicles have expanded globally, but this process is complex due to the differing certification standards of international and domestic organizations. Third-party certification adds another layer of complexity, as it involves the review of operational reliability parameters and future vehicle maintenance management. Additionally, the reliability certification only confirms the urban rail vehicle function level, and not the complex trial operation environment. This lack of strict definition of key reliability and maintenance parameters approved by the supplier means that data traceability is crucial during the vehicle's operation process to ensure the most accurate and real information is obtained.

2.3 Brief analysis on the problems affecting reliability and maintainability of rail transit vehicles in the use stage

Operators in different cities have varying understandings of vehicle parameters, maintenance processes, and management methods, resulting in significant differences in load characteristics even for the same operator in the same city.

On the one hand, In such an environment, operators prioritize vehicle mission reliability through maintenance to reduce failure rates and ensure adequate commissioning rates. However, major accidents rarely prompt operators to trace vehicle inherent reliability parameters drift and maintenance procedure adjustments. Differences in reliability parameters such as the average failure interval mileage and failure probability density function between the department's set values and the designer's preset values can result in varying degrees of over-repair or out-of-repair.

On the other hand, the operation and maintenance technical teams face complexities in data acquisition and preservation processes. The vehicle system's facilities and parts categories can dynamically change during the operation and maintenance process, while technical standards also change. Furthermore, maintenance personnel have varying professional knowledge and lack a unified failure criterion guideline or record specification, leading to highly specialized domain terms, abbreviations, and unique codes that result in different natural language expressions of the same failure mode after processing.

3. Some thoughts on improving the reliability and maintainability of urban rail vehicles under complex environment

In view of the complex environment on the vehicle reliability and maintainability bring hard to ignore the impact, in order to continue to maintain stable performance, reliability and economic efficiency, I suggest that the relevant units to start from the following aspects.

3.1 Emphasis on the application of environmental technology in improving the reliability of urban rail vehicles

3.1.1 Enhanced environmental protection design

To determine the environmental stresses experienced by a vehicle product from manufacturing to decommissioning, we analyze the life profile and identify the sensitive stresses under each condition. We evaluate the performance of materials and components used in such environmental conditions and select appropriate environmental protection measures based on sensitive load stresses and local environmental characteristics. Table 1 below provides an overview of the chosen guidelines and measures.

Table 1. Protective design measures under various environmental stresses.

Environmental stress	**Environmental protection design measures**	**Environmental stress**	**Environmental protection design measures**
High temperature	Add heat sink, cooling system, thermal insulation and heat resistant material materials, etc.	Damp	Take waterproof, anti-mold and anti-rust materials; provide air circulation system or drainage system; use of dry layer, etc.

Low temperature	Low temperature sensitive device can add heating device, heat exchange insulation and low temperature resistant materials, etc.	Electromagnetic radiation	Control the source of electromagnetic interference; use shielding, filtering and other means to suppress interference from the propagation path; use grounding and overlap technology.
Shock vibration	Eliminate the source design, correctly design the structural parameters to reduce the response amplitude of vibration or shock, use appropriate reduction vibration isolation system or vibration isolation measures	Sand and dust	Add sandproof cover or seal, set up the import and export of air circulation dust filtering device, etc.
Salt spray	Choose metals that are not easily corroded or metal surfaces painted not easily corroded; reduce the potential difference between metals; exclude electrical contacts etc.		

3.1.2 Environmental stress screening tests should reflect the actual environment as much as possible

Environmental stress screening (ESS) aims to evaluate a product's adaptability to different environments and expedite the detection and elimination of potential internal defects before they cause early failures. By reflecting the characteristics of field use environments, ESS tests can inform product design and process improvements, and provide a practical basis for enhancing product reliability.

3.2 Integration of operations into the reliability test program and maintenance program development program

Before vehicles are put into operation, manufacturers use experimental test verification methods to obtain reliability performance parameters. While a conservative vehicle maintenance program outline against national standards may meet the operator's most important reliability indicators, the operator's business philosophy and refinement of vehicle management may not be fully understood. To address this, rail transportation operation data can be used to determine the load spectrum of the line, perform standing environment tests and full load tests on vehicles, and determine key components through FMECA analysis. An optimization model for maintenance cycles can then be established for urban rail vehicles, enabling the identification of different failure impact level components and scientifically optimizing the maintenance program. This approach helps to eliminate over-repair and out-of-repair situations, ensuring maximum cost efficiency and safety while maintaining continuous vehicle operation. The following statistical model provides a way to modify maintenance intervals for rail vehicles territorially.

$$\text{MTBF}^* = \frac{\sum_{i=1}^{L_n}\sum_{j=1}^{T_i}\sum_{m=1}^{D_j}\left(t_{ijm} - t_{ijm-1}\right)}{\sum_{i=1}^{L_n}\sum_{j=1}^{T_i}\sum_{m=1}^{D_j} N_{ijm}} \tag{1}$$

In this formula:

t_{ijm} : the moment of failure of a certain type of fault in a certain vehicle of a certain line for a certain object of analysis, replaced by the moment of the end of the observation period when there is no fault.

t_{ijm-1} : the moment of the last failure of a certain type of fault of the object of analysis in a certain train of a certain line, the initial value is the beginning moment of the observation period

N_{ijm} : the number of failures of this type of fault of the object of analysis in each train of the observation period, the value is replaced by 1 when no failure occurs.

D_j : the total number of the analysis object of the vehicle

T_i : the total number of trains on a line.

L_n : the total number of lines

The formula enables to anticipate the moment of failure of the object and decide when to maintain the object to prevent that type of failure of the object according to the technically or administratively acceptable reliability index.

3.3 Establishment of localized, standardized and professional O&M technical teams

Urban rail vehicle reliability and maintenance rely on the technical team and their investigation. Operators should select the appropriate vehicle type based on the operating environment and plan the maintenance resources for each line. Maintenance bases should be positioned and laid out strategically. Manufacturers should deploy management and technical personnel to ensure regular assessment and training of maintenance technology. This process results in a localized, standardized, and professional maintenance team.

4. Conclusion

To improve the reliability and maintenance of urban rail vehicles in complex environments, we must consider the situation, review operation data, adopt new technology, standardize management, optimize and improve continuously, and quickly respond to potential risks and failures. By doing so, we can enhance China's competitiveness in the urban rail vehicle market.

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