

Discussion on the Current Status and Strategy Optimization of Intelligent Operation and Maintenance for Urban Rail Transit Vehicles

Xueling Wang

Guangzhou Railway Polytechnic, Guangzhou, China
Email: wxlshirley@126.com

How to cite this paper: Wang, X.L. (2025) Discussion on the Current Status and Strategy Optimization of Intelligent Operation and Maintenance for Urban Rail Transit Vehicles. *Open Journal of Applied Sciences*, 15, 4260-4269.

<https://doi.org/10.4236/ojapps.2025.1512275>

Received: December 5, 2025

Accepted: December 26, 2025

Published: December 29, 2025

Copyright © 2025 by author(s) and Scientific Research Publishing Inc. This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).

<http://creativecommons.org/licenses/by/4.0/>



Open Access

Abstract

With the rapid expansion of the networked operation scale of China's urban rail transit, the number of vehicles has increased exponentially. The traditional operation and maintenance (O&M) model, which mainly relies on "scheduled maintenance" supplemented by post-event "corrective maintenance", is confronted with prominent challenges in terms of maintenance efficiency enhancement, life cycle cost (LCC) control, and operational reliability guarantee. As the core driver for the transformation and upgrading of the urban rail transit industry, intelligent O&M leverages the Internet of Things (IoT), big data, and artificial intelligence technologies to offer a novel solution to address these contradictions. This paper systematically reviews the application status of Prognostics and Health Management (PHM), intelligent inspection equipment, and physical reliability analysis in urban rail transit vehicles. It conducts an in-depth analysis of the primary contradiction in the current O&M system. The structural mismatch between advanced intelligent technologies and lagging management models. It further examines issues such as the absence of quantitative evaluation standards and insufficient integration of data-driven approaches with physical mechanisms. In response to these pain points, the paper proposes maintenance strategies based on Life Cycle Cost (LCC) management, a PHM architecture driven by both mechanisms and data, and an intelligent efficacy evaluation and dynamic decision-making mechanism. The objective is to promote the transformation of urban rail transit vehicle O&M from "passive execution" to "active decision-making" through the in-depth integration of technology and management, thereby providing a theoretical basis and practical reference for the high-quality development of the industry.

Keywords

Urban Rail Transit, Vehicle Operation and Maintenance, Prognostics and

1. Introduction

Since the dawn of the 21st century, China's urban rail transit construction has stepped into a phase of rapid development, emerging as a key infrastructure for alleviating traffic congestion in large cities and advancing green transportation, according to statistics released by the China Association of Metros, as of the end of 2024, approximately 58 cities in Chinese mainland have put urban rail transit systems into operation, with the total operating mileage exceeding 10,000 kilometers [1]. This large-scale network and high-density traffic intervals not only impose extremely high requirements on the safety and reliability of vehicle systems but also give rise to O&M pressures and cost burdens that grow geometrically [2].

For a long time, the operation and maintenance (O&M) of urban rail transit vehicles in China has mostly followed the guiding principle of “prevention first, combining maintenance and repair” from the railway system, adopting a “scheduled maintenance” model based on time and mileage benchmarks [3]. Although this rigid O&M system ensured operational safety in the early stages of development, its inherent flaws have become increasingly prominent. On one hand, some components are still in good working condition when reaching the scheduled maintenance cycle; forced disassembly not only causes resource waste but may also introduce human-induced “maintenance faults” [4]. On the other hand, affected by complex operating conditions, some components may deteriorate prematurely within the maintenance cycle, and periodic maintenance is difficult to cover the risk of sudden failures—especially for critical systems such as the running gear, where this risk may directly threaten driving safety [5].

Against this backdrop, intelligent O&M has emerged as a key direction to break through the predicament, with its core lying in reconstructing traditional O&M logic through technological innovation. By leveraging Prognostics and Health Management (PHM) technology, real-time monitoring of the operating status and fault early warning for key vehicle components can be achieved, breaking the passive situation of traditional O&M [6]. However, in practical industrial applications, despite the continuous improvement in the intelligence level of hardware equipment, O&M management strategies have not undergone synchronous iteration, leading to a mismatch between “advanced technology” and “backward management”. Although some lines have introduced intelligent equipment, the lack of a scientific intelligent level evaluation system makes it difficult to accurately determine the direction of O&M improvement, and the application value of intelligent technology has not been fully exerted.

How to break this bottleneck, establish scientific intelligent evaluation stand-

ards and adapted maintenance strategies, and realize true “condition-based maintenance” and “smart maintenance” has become a common focus of attention in both academic and industrial circles. This paper will analyze existing problems based on the current technological status and propose targeted strategy optimization paths.

To ensure the rigor of this study, a systematic narrative review approach was adopted. Relevant literature published between 2020 and 2025 was surveyed using databases such as CNKI and IEEE Xplore, focusing on keywords including Urban Rail Transit, Intelligent O&M, and PHM. The study follows a logical framework of “Status Review-Problem Identification-Strategy Optimization”. Key issues were identified through a comparative analysis of current technological capabilities versus actual operational efficiency reported in the literature, which formed the basis for the proposed LCC and PHM integration strategies.

2. Current Status of Intelligent O&M Technology for Urban Rail Transit Vehicles

Intelligent O&M is not a standalone technology application but a comprehensive system that encompasses the cognition of physical mechanisms, status perception, and data analysis. Currently, the technological development in this field mainly focuses on the following three dimensions.

2.1. Physical Reliability of Key Systems and Sensing Technology

The physical safety of vehicles serves as the cornerstone of intelligent O&M. To achieve accurate fault prediction, it is essential to first gain a thorough understanding of the failure mechanisms of key components. At present, research on the physical characteristics of core systems such as bogies, traction systems, and braking systems has achieved relatively in-depth results. Gu Zhenglong *et al.* [7] employed finite element models and virtual simulation technology to conduct an in-depth analysis of the fatigue life of vehicle bogie swing arm positioning nodes, determining the fatigue limit and failure path of rubber bushings under different stress levels, which provides a solid physical basis for formulating targeted inspection cycles. Gao Yue [8] further explored the reliability analysis methods for key metro vehicle systems, establishing a reliability assessment framework based on physical models by systematically sorting out the failure modes of traction and braking systems.

At the sensing level, modern urban rail vehicles have widely deployed a variety of sensors for monitoring vibration, temperature, current, and pressure. The effective linkage between the Train Control and Monitoring System (TCMS) and ground analysis platforms enables real-time monitoring of key parameters such as bearing temperature rise rates, wheel polygon wear, and pantograph contact pressure. This “mechanism cognition + status perception” mode allows O&M personnel to move away from “blind operation” and gain insights into the physical essence of equipment through data analysis.

2.2. Application of Intelligent Maintenance Equipment

To replace the labor-intensive, repetitive manual maintenance work that is susceptible to subjective factors, various types of intelligent maintenance equipment have been widely applied in depots and maintenance bases. Zhang Hanlin [9] elaborated on the latest progress of intelligent maintenance systems in metro vehicles, including under-vehicle intelligent inspection robots and trackside 360° dynamic image fault identification systems. These devices utilize high-precision industrial cameras, LiDAR, and deep learning algorithms to automatically identify appearance faults such as loose bolts, missing dust covers, and foreign object intrusion.

For example, automated under-vehicle inspection robots adopt SLAM navigation technology to perform autonomous work around the clock in narrow under-vehicle pits. Their high-definition cameras and thermal imagers can cover blind spots that are difficult to reach through traditional manual inspection, significantly reducing the fault-missed detection rate. Meanwhile, the detection data is uploaded to the management platform in real time, realizing the digital storage and traceability of the maintenance process and accumulating valuable raw data for subsequent big data analysis.

2.3. Prognostics and Health Management (PHM) Technology

If sensors are regarded as the “senses” and intelligent equipment as the “limbs” of intelligent O&M, then PHM technology can be considered as its “brain”. The core objective of PHM is to extract effective features from massive monitoring data, assess the current health status of equipment, and predict the Remaining Useful Life (RUL). Zhou Jian [10] systematically expounded the application path of PHM technology in urban rail vehicles, which includes four key stages: data cleaning (e.g., using cubic spline interpolation to handle missing values), feature extraction, status assessment, and fault prediction.

In practical applications, data-driven PHM models have demonstrated strong application potential. For instance, by establishing a health evaluation model based on the variable weight fuzzy comprehensive evaluation method, quantitative scoring of health indices for systems such as vehicle doors and air conditioning can be achieved; by utilizing algorithms such as the Particle Swarm Optimization (PSO) grey dynamic model, high-precision trend prediction for gradual faults such as wheel flange wear can be realized. Research conducted by Liu Jing *et al.* [11] also indicates that the feasibility of intelligent O&M systems lies in their ability to discover performance degradation laws through historical data mining that are imperceptible to humans, thereby issuing early warnings before faults occur and providing guidance for preventive maintenance.

3. Problems and Challenges in the Current O&M Model

Despite significant progress in hardware equipment and algorithm research, the practical application of intelligent technology in the O&M field still faces the awk-

ward situation of being “data-rich but information-poor” and “technologically advanced but with insignificant benefits”. This phenomenon indicates that there are structural defects in the management, evaluation, and in-depth integration of technologies within the current O&M model.

3.1. Lagging Management Models Limit Technical Efficacy

This constitutes the primary contradiction restricting the development of intelligent O&M at present. Dai Jie [12] clearly pointed out in his research that although technical capabilities for condition monitoring have been established, the management systems of metro operating enterprises still adhere to the traditional “scheduled maintenance” model. Specifically, even if the PHM system indicates that a component is in good health condition, it must be disassembled for maintenance once the prescribed maintenance schedule (such as overhaul or heavy repair) is reached.

This “disconnect between technology and management” phenomenon brings about serious consequences: firstly, it leads to a large number of over-maintenance activities, resulting in the waste of human and material resources. This disconnect is not merely accidental but is rooted in the industry’s strict adherence to safety regulations established for traditional mechanical systems and a natural organizational resistance to changing proven workflows. Consequently, the existing management system lacks flexible mechanisms to accept intelligent diagnostic conclusions, often reducing intelligent O&M systems to auxiliary reference tools rather than genuine decision-making bases.

3.2. Lack of Quantitative Evaluation Systems for Intelligence Levels

Currently, the level of intelligent O&M construction varies significantly across different cities and lines, and the industry lacks unified construction standards and evaluation specifications. Research by Ding Hua [13] shows that operating units often invest heavily in the construction of various intelligent systems but encounter difficulties in quantitatively evaluating the actual benefits brought about by these systems. For example, after the introduction of intelligent inspection robots, to what extent have maintenance costs been reduced? How much has the work efficiency of personnel been improved? Are the false positive and false negative rates of the system within a controllable range?

The absence of a scientific evaluation system leads to ambiguous construction directions, easily resulting in the problem of simply accumulating hardware equipment while neglecting the in-depth mining of data value and the verification of actual application effects. Without effective evaluation, it is impossible to make reasonable distinctions between different systems, and a virtuous cycle of “investment-output-optimization” cannot be formed.

3.3. “Data Silos” and Insufficient Mechanism Integration

Although a large amount of data is collected in the O&M process, the data quality

and utilization rate remain relatively low. On one hand, there is a serious “data silo” phenomenon. The on-board TCMS data, trackside detection data, and historical maintenance records in bases are often stored in different systems with inconsistent data standards, making it difficult to conduct multi-source data fusion analysis. This leads to one-sided fault diagnosis results and the inability to perform full life cycle fault tracing.

On the other hand, the current PHM technology mainly relies on pure data-driven algorithms (such as neural networks and deep learning) and lacks sufficient support from physical mechanisms. Li Xi [14] pointed out that pure data models have weak generalization capabilities when facing sudden faults with scarce samples and are prone to generating false alarms. For example, for certain fracture faults caused by material fatigue, it is difficult to achieve early prediction by relying solely on the statistical laws of vibration data; it is necessary to combine physical mechanism models, such as fracture mechanics. The separation of data and mechanism limits the ability of the PHM system to solve complex engineering problems.

4. Strategy Optimization Paths for Vehicle Intelligent O&M

4.1. Establishing a Full Life Cycle Health Management Model

The optimization of urban rail transit vehicle operation and maintenance (O&M) strategies requires transcending the singular focus on “repair” and attaching equal importance to “management,” which entails breaking the traditional mindset limited to fault diagnosis and introducing the concept of Life Cycle Cost (LCC) management as a core guiding principle. This shift is supported by existing research: Wu Liang *et al.* [15] proposed a maintenance strategy research framework that integrates Failure Mode and Effects Analysis (FMEA) with the Analytic Hierarchy Process (AHP), providing a systematic methodological basis for balancing maintenance effectiveness and cost control throughout the vehicle’s life cycle. By combining FMEA’s ability to identify failure modes and their potential impacts with AHP’s capacity to quantify the weight of each component’s importance, this method lays the groundwork for more scientific and targeted O&M decision-making, moving beyond the rigidity of conventional scheduled maintenance.

The practical implementation of this LCC-oriented O&M strategy unfolds through three interconnected pathways. First, constructing “one vehicle, one archive” health record systems enables the structured storage of data spanning the entire vehicle lifecycle—from design, manufacturing, and commissioning to operation and scrapping—encompassing not only real-time operational data but also static information such as maintenance logs and spare parts replacement records, which collectively form a comprehensive data foundation for LCC analysis. Crucially, this structured archive provides the necessary historical failure data and real-time status inputs required to execute the FMEA risk assessments and AHP weight calculations described above, ensuring that strategy adjustments are based on empirical evidence rather than theoretical assumptions. Second, quantitative risk assess-

ment leverages FMEA to analyze the failure modes, potential effects, and criticality of each subsystem, while AHP is applied to determine the weight of individual components; this allows for differentiated maintenance measures, such as high-frequency inspections and preventive maintenance for high-risk components like braking systems, and proactive adoption of corrective or condition-based maintenance for low-risk components such as interior decoration parts. Third, dynamic strategy adjustment ensures that maintenance decisions are no longer dependent solely on real-time fault alarms but instead integrate multiple factors, including a component's design life, historical failure rate, current health index, and predicted remaining useful life; for instance, components with consistently high health scores may have their inspection intervals dynamically extended from "annual repair" to "no repair if the condition is good," thereby achieving the refined allocation of maintenance resources and maximizing the efficiency of LCC management.

4.2. Constructing a PHM System with Mechanism and Data Fusion

To enhance the prediction accuracy and robustness of the Prognostics and Health Management (PHM) system for urban rail transit vehicles, a development path centered on the in-depth integration of "physical mechanism and data" is essential—this addresses the inherent limitations of single-modal approaches, where pure data-driven algorithms are susceptible to interference from data noise and pure physical models fail to capture the real-time individual differences of equipment.

Three interconnected optimization strategies underpin this integration: first, constructing a dual-drive model by combining the safety assessment methodology which uses physical mechanism models (e.g., fatigue damage accumulation theory) to define fault boundary conditions and evolution laws as the model's "skeleton" while leveraging real-time data-driven models (e.g., particle swarm optimization algorithms) for parameter correction and state tracking as the model's "flesh," thereby retaining the interpretability of physical models and the flexibility of data models; second, refining the fault feature library by drawing on the high-speed railway key technologies highlighted by Ma Jianjun *et al.* [16] to establish a knowledge base covering typical fault feature graphs, and using digital twin technology to build vehicle virtual models for fault injection and simulation in a virtual environment—this compensates for the scarcity of fault samples in actual operations and enables the training of more accurate algorithm models; third, implementing multi-source data fusion by establishing a smooth vehicle-ground data link and conducting cross-validation between on-board real-time data and trackside detection data (such as the Shanghai Metro trackside system detailed by Fu Jiajun) [17], for instance, triggering an alarm only after dual confirmation that on-board sensors detect abnormal axle temperatures and trackside infrared probes verify the high temperature, which significantly reduces the system's false alarm rate.

4.3. Establishing Intelligent Efficacy Evaluation and Dynamic Decision Mechanisms

To address the lag in operation and maintenance (O&M) management systems for urban rail transit vehicles, the fundamental solution lies in establishing a set of scientific evaluation and dynamic decision-making mechanisms to drive in-depth reform of management systems. A core starting point is constructing an intelligent O&M evaluation indicator system, which draws on the research findings of Zhang Wei to cover multiple dimensions critical to O&M performance [18]. This system includes technical level metrics (such as equipment configuration rate and fault prediction accuracy), management efficiency indicators (including fault response time and staff-to-vehicle ratio), economic benefit measures (e.g., spare parts turnover rate and energy consumption), and safety-related indexes—collectively forming a quantitative and comprehensive framework for assessing the effectiveness of intelligent O&M practices, and avoiding the ambiguity of “blind construction” caused by the lack of evaluation standards.

Building on this evaluation system, a dynamic decision-making mechanism guided by “promoting reform through evaluation” should be further implemented to translate evaluation results into actionable management adjustments. For systems with complete condition monitoring means and clear operational mechanisms (such as running gear bearings), operating units, after undergoing long-term data verification and rigorous safety assessment, should formalize regulatory revisions to shift maintenance modes from rigid “periodic disassembly” to flexible “condition-based maintenance.” In terms of spare parts management, the classification method offers important reference value, enabling dynamic adjustments to inventory strategies based on PHM system fault predictions—moving away from the traditional “reserve redundancy” model toward a more efficient “supply on demand” approach to reduce inventory capital occupation. Additionally, intelligent maintenance equipment should be used to restructure O&M workflows, as emphasized by Guo Zekuo [19]. This involves liberating personnel from repetitive, high-intensity inspection tasks to focus on high-value fault analysis and decision-making, while establishing talent training mechanisms adapted to intelligent O&M needs to cultivate composite professionals who possess both expertise in vehicle technology and capabilities in data analysis.

5. Conclusions and Outlook

Intelligent operation and maintenance of urban rail transit vehicles is an inevitable trend in the development of the industry, essentially representing a productivity revolution centered on data. This paper analyzes and points out that the main bottleneck currently faced by intelligent O&M is not the unattainability of the technology itself, but the mismatch between management models and technical capabilities, as well as the insufficient depth of data value mining.

By establishing a full life cycle health management model based on FMEA/AHP, a PHM system integrating physical mechanisms and data-driven approaches, and

constructing a scientific efficacy evaluation and dynamic decision-making mechanism, this bottleneck can be effectively broken. This will not only significantly reduce the LCC maintenance cost and resolve the contradiction between “over-repair” and “under-repair” but also greatly improve the operational safety and reliability of trains.

Looking ahead, with the continuous maturity of 5G, edge computing, and digital twin technologies, vehicle O&M will enter a new stage of “virtual verification and physical feedback”. Meanwhile, unmanned depots and fully automated O&M will become achievable goals. However, the realization of these future scenarios is predicated on the successful implementation of the dynamic decision-making mechanisms proposed in this paper; without these foundational governance structures, fully automated systems cannot operate safely or effectively. Operating units should maintain strategic determination, adhere to the principles of “business-oriented and data-driven”, and continuously promote the evolution of O&M models towards safety, efficiency, and green development.

Funding

Research and Application of Key Technologies for Intelligent Maintenance Robots of Rail Transit Vehicles (Project No. GTXYYB250110), Guangdong Provincial Key Platforms and Research Projects, Guangdong-Hong Kong-Macao Rail Transit Industry-Education Integration Innovation Platform (Project No. 2022CJPT016).

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

- [1] China Association of Metros (2025) Annual Statistical and Analysis Report of Urban Rail Transit 2024. China Association of Metros.
- [2] Wang, S.G. (2024) Research on the Application of Overhaul and Maintenance Technology for Urban Rail Transit Vehicles. *Auto Time*, No. 12, 34-36.
- [3] Zhu, J.Y., Li, P., Li, X., *et al.* (2023) Intelligent Inspection Robot Positioning System for Vehicles of Urban Rail Transit. *Railway Transport and Economy*, **45**, 130-136.
- [4] Wang, X.J. (2023) Research and Practice on Condition Maintenance of Key Components in Running Gear of Metro Vehicles. *Smart Rail Transit*, **60**, 33-39.
- [5] Wu, C.G. (2024) Application of Intelligent Technology in the Operation and Maintenance of Rail Transit System. *Die & Mould Manufacture*, **24**, 179-181.
- [6] Xu, W.B. (2021) Classification of Metro Vehicle Maintenance Spare Parts Based on FMECA Method. *Urban Mass Transit Research*, **24**, 85-88+104.
- [7] Gu, Z.L., Ge, Y.F., Wang, Z.H., *et al.* (2024) Study on Fatigue Life Reliability of Vehicle Bogie Arm Positioning Node. *Urban Mass Transit*, No. 6, 68-71.
- [8] Gao, Y. (2024) Reliability Analysis and Application Discussion of Key Systems of Metro Vehicles. *People's Public Transport*, No. 6, 52-54.
- [9] Zhang, H.L. (2024) Application of Intelligent Maintenance System in Metro Vehicle Maintenance. *Internal Combustion Engines & Parts*, No. 15, 100-102.

-
- [10] Zhou, J. (2021) Research on Fault Prediction and Health Management Technology of Urban Rail Transit Vehicles. Nanjing Normal University.
- [11] Liu, J., Guo, X., Jiang, R., *et al.* (2021) Research and Feasibility Analysis of Intelligent Operation and Maintenance System for Urban Rail Transit. *China New Technologies and Products*, No. 5, 12-14.
- [12] Dai, J. (2024) Research on Maintenance Management Mode of Metro Operational Vehicles. *Modern Urban Transit*, No. 3, 82-89.
- [13] Ding, H. (2023) Research on Intelligent Evaluation and Improvement of Maintenance Strategy of Urban Rail Transit Vehicles. Chongqing Jiaotong University.
- [14] Li, X. (2011) Research on Safety Assessment Method for Running Gear of Urban Rail Transit Vehicles. Beijing Jiaotong University.
- [15] Wu, L., Xu, J., He, X.J., *et al.* (2023) Research on Maintenance Strategy Based on Full Lifecycle Health Status of Metro Vehicles. *Plant Maintenance Engineering*, No. 17, 76-81.
- [16] Ma, J.J., Li, P., Shao, S., *et al.* (2020) Research on Key Technologies and Development Roadmap of Intelligent High-Speed Railway. *China Railway*, No. 7, 1-8.
- [17] Fu, J.J. (2020) Intelligent Operation and Maintenance System of Shanghai Rail Transit Vehicles. *Urban Mass Transit*, No. 7, 23-26.
- [18] Zhang, W. (2020) Index System and Application of Intelligent Operation and Maintenance for Urban Rail Transit Vehicles. *Modern Urban Transit*, No. 8, 109-114.
- [19] Guo, Z.K., He, L.N. and Wang, L. (2022) Construction Scheme of Intelligent Operation and Maintenance System for Urban Rail Transit Vehicles. *Urban Mass Transit Research*, **25**, 176-181.