Proceedings of CONF-CIAP 2026 Symposium: International Conference on Atomic Magnetometer and Applications
DOI: 10.54254/2753-8818/2026.HZ29369

Digital Twin-based Intelligent Operation, Maintenance, and Safety Early Warning System for Urban Rail Transit

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Abstract. With the advancement of the era, the digital and intelligent upgrade of safety operations and maintenance, as well as early warning systems, has become an essential trend, a trend embodied by the concept of the Digital Twin. This paper explores the current applications and outcomes of Digital Twin technology within various subsystems and the overall system of urban rail transit. It reviews the significant advantages and existing shortcomings of integrated information modeling, sensing technologies, big data, and Prognostics and Health Management (PHM) systems. The focus is on their roles in data collection, data transmission, simulation platform optimization, fault prediction, and proactive early warning concerning vehicles, track infrastructure, and the comprehensive Digital Twin architecture of urban rail transit systems. The paper also provides an in-depth analysis of the benefits and developmental challenges associated with multi-source data fusion, offering insights for the future development of intelligent operations and maintenance in urban rail transit systems.

Keywords: Digital Twin, Urban Rail Transit, Intelligent Operation and Maintenance, Fault Forecasting, Multi-source Data Integration

1. Introduction

In most modern cities, economic growth is propelled by the transportation system, while the daily mobility of the public is also fundamentally reliant on it. The massive passenger volumes characteristic of modern cities are primarily serviced by the Urban Rail Transit system, which functions as the backbone of urban mobility. The safety and reliability of its equipment are continually challenged by rising passenger loads and frequency, ultimately determining the stability of the socio-economic fabric and the order governing public commutes. The quality of equipment upkeep is progressively compromised by traditional operation and maintenance methods that depend on manual inspections and periodic schedules, methods known for their lagging responses and imprecision. This situation is intensified as maintenance windows are compressed under growing passenger demand. Specifically, inspections are required to be conducted by personnel at fixed points along the tracks, a method subjected to heavy workloads, low efficiency, limited coverage, and weather interruptions. This readily leads to maintenance being insufficiently performed, thereby creating potential safety hazards. Secondly, corrective maintenance occurs only after a failure has

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DOI: 10.54254/2753-8818/2026.HZ29369

happened, and is unable to prevent operational interruptions and the resulting economic losses caused by incidents.

The current research achievements mainly revolve around four aspects, namely vehicles, tracks, Bridges, and multi-system data fusion. During the research process, the method of combining digital twins and data was adopted to build virtual simulation models. Meanwhile, with the help of sensors and Internet of Things perception technology, big data was integrated. Based on the list theory, a construction digital model is built, and corresponding solutions are provided through simulation. After doing so, early warnings and predictions can be made, and the integration of operation and maintenance can also be achieved. This will transform the situation where maintenance is carried out only after the fact into one where prevention and maintenance are conducted in advance.

The existing research targets are relatively single. Due to cost issues, most technologies usually only focus on a certain aspect for research, such as the vehicle part, bridge part or road part, rather than conducting research on a complete operation system. In this way, it will lead to the inability to exchange data among various systems, resulting in problems such as technical information silos. If there are chain security reactions among different parts, it is also very difficult to predict.

This article will provide a detailed introduction to the application of digital twins in various systems and the achievements made, and also analyze the problems and shortcomings of each technology. This article will also analyze and evaluate the comprehensive benefits of these technologies and discuss the development of future urban rail transit systems towards intelligence and digitalization.

2. Development of vehicle operation, maintenance, and early warning

Traditionally, vehicle maintenance is generally carried out according to a fixed schedule based on operating time or mileage. However, this approach has rather prominent limitations. This "repair after failure" model brings safety risks and may also cause economic losses and damage to the reputation of operators. Carrying out routine maintenance work during the period when the vehicle has not broken down usually leads to a waste of resources, which will increase operating costs. Sometimes, it may even cause new problems due to excessive maintenance [1].

In terms of innovative research, Li Zixuan's team has applied digital twin technology to the monitoring of wheel status. By means of multi-source digital modeling and data fusion, they have established a prediction system that can connect the virtual domain and the physical domain. The method they adopted is to rely on simulation to calculate the optimal operating state that minimizes wear, and then use digital models to evaluate and predict the condition of the wheels [2]. Hou Anqi's team focused their efforts on realizing the five-dimensional digital twin model of the EMU. They used the MB-SE modeling tool to develop a dedicated platform. This platform can monitor the conditions of EMUs throughout their entire life cycle and provide optimization measures. It also offers targeted improvement suggestions, which have played a significant supporting role in maintenance decisions [3]. Hong Dongbao's team adopted another innovative approach. That is to create a vehicle maintenance system based on remote terminals. This system can track the status of components in real time through link communication and conduct evaluations on a digital twin virtual platform. It is particularly worth mentioning that after each trip, the on-board digital dual terminals will collect fault data through in-depth inspection and intelligent learning, handle emergency repair situations, and update the early warning database [4]. Shu Kewei's team focused on the pantograph system and developed a hybrid PHM system that integrates 3D simulation modeling and multi-source data. Their system determines the optimal replacement cycle based on the analysis of carbon plate thickness and wear rate data. In actual operation, the sensors embedded

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in the pantograph structure will continuously provide data to the system. The system will automatically compare the readings with the normal and faulty benchmarks, and then provide optimized solutions based on historical cases [5].

The comprehensive operation and maintenance system developed by Liu Xishun's team is also worth everyone's attention. They combine PHM with the intelligent support system and track the changes in component status. In this way, the comprehensive operation and maintenance system can achieve precise component life prediction and fault identification. Through long-term case learning and data accumulation, the system will recommend the optimal spare parts solution. It can effectively reduce the failure rate and maintenance costs [6].

Essentially, digital twin technology is transforming vehicle maintenance into a predictable and precisely intelligent process. This approach effectively addresses the delays and inefficiencies associated with traditional regular maintenance through comprehensive data collection, physical modeling, multi-source data integration, and intelligent decision-making. It has become a key technology for enhancing the safety, reliability and cost-effectiveness of rail transit.

However, there are still some challenges. The multi-source data required by the digital twin platform demands a large amount of resources during transmission, processing, and fusion analysis. Currently, the technology cannot fully guarantee the accuracy of the entire life cycle prediction. When modeling vehicles, the high complexity requires more advanced algorithms and higher-precision modeling techniques. For complex components, prediction still mainly relies on secondary parameters such as transmission speed and temperature, which to some extent limits the accuracy of diagnosis [7].

3. Development of operation, maintenance, and early warning for line infrastructure

The track system is the most critical line infrastructure in urban rail transit, and the intelligence and digitalization of its operation and maintenance have received significant attention from government departments. He Xiuxia established physical models for key signal equipment like switches and signal machines within the track system. Using historical fault state data from these devices as test data, a digital twin model was built, and virtual testing was conducted on a cloud client. This model can continuously learn and update test data, thereby improving early warning accuracy and reducing maintenance costs. Furthermore, the digital transformation of signal equipment can lead to a reduction in the number of detection devices, lower energy consumption, shorter fault recovery times, and improved reliability of equipment warnings [8]. Zhang Yan et al. studied the establishment process of the five-dimensional digital twin model. They used programming languages and framework models to construct a 3D model of a switch machine. By real-time monitoring of internal power and tip displacement, data is transmitted to a base station for comparison with historical data and storage, then sent to the cloud for analysis, with results finally fed back to a visual platform [9]. Li Huan et al., addressing the issues of slow speed and low precision in manual track inspections, developed an automatic track detection device. Utilizing network data transmission, data is sent in real-time to a cloud-based station. Cloud images are analyzed using a PHM health monitoring platform for prediction and fault analysis, achieving unmanned inspection and improving its efficiency and accuracy [10].

Viaducts and bridges represent another type of line facility in rail transit. Their structure is more complex than tracks, and they endure long-term traffic loads and environmental factors, making material aging and damage to key structural components harder to detect and address. Based on these challenges, Zhang Mengdong et al. identified the prevailing lack of emphasis on prevention in current maintenance practices. Analyzing cases of equipment fitted with digital twin sensors, they

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found that such a system could detect crack changes as small as 0.08mm in the cable tower anchorage zone, providing an early warning nearly a year in advance. It can also simulate corresponding measures for various conditions, reducing counterproductive interventions during bridge repair, extending service life, and achieving goals of economic efficiency, environmental protection, and safety assurance [11]. Ni Yuancheng et al., leveraging existing advanced R&D technologies and equipment, analyzed how digital twins, through 3D modeling with BIM and GIS, multi-source data integration, and intelligent algorithms, can achieve bridge health monitoring, safety prediction, and real-time maintenance optimization [12]. Pan Yue et al. and Luo Haocheng et al., reviewing technical literature on bridge inspection, pointed out the inefficiency and inaccuracy of manual data collection via drones. They proposed enhancing human-drone collaboration for real-time data acquisition and processing. Using three self-developed detection tools to build a 3D sensing array, they created a digital twin product capable of transmitting various parameters of the bridge surface structure back to the cloud in real-time, enabling early warnings and preemptive maintenance [13,14]. Ye Peng and Wen Bohua analyzed the current technological development of BIM and digital twin technology in railway bridge engineering. They utilized VR equipment and scenarios for more realistic simulations aimed at training maintenance personnel to handle various repair situations. This can effectively improve the efficiency of professionals repairing equipment that current AI cannot handle autonomously, while also collecting material for future fully autonomous unmanned maintenance. Based on the existing five-dimensional digital twin model for railway bridges, they proposed that digital twins can play a verification role during BIM implementation, providing assessment and measures, making maintenance proactive and automated, thereby offering predictive measures and optimized maintenance solutions throughout the bridge's lifecycle [15, 16]. Javier Sánchez Haro et al. established a digital model by collecting basic information from the Espartxo Bridge and conducting physical tests to develop a finite element model for data analysis. They ultimately identified a relationship between the vibration frequency of the pier's lower column and scour depth, allowing assessment of the column's durability through real-time scour intensity monitoring to achieve an early warning effect [17]. Zhe Sun et al. designed a new digital twin modeling approach, DT-DTM. This system can collect bridge data in real-time through a spatial model to assess health status, and analyze changes in bridge health over time through a temporal model, thereby achieving an early warning effect [18].

In summary, the application of digital twin technology in the operation, maintenance, and early warning for line infrastructure shows a trend evolving from single technical aspects towards systematic integration and multi-source fusion. For real-time monitoring of bridges, it currently demonstrates significant advantages in perceiving internal and external states of targets, automatically assessing aging and damage levels, and real-time status monitoring. Although a limited number of studies reviewed have introduced virtual simulation and multi-technology fusion to provide predictive maintenance data and integrated solutions for infrastructure upkeep, such methods place very high demands on the costs, software capabilities, and project compatibility of the involved transportation departments or companies.

4. Integrated digital twin architecture for urban rail transit systems

The goal of digital twin for urban rail transit is to build a digital entity that can achieve real-time perception, two-way communication, intelligent analysis, and informed decision-making. It aims to drive the evolution from digitalization and intelligence at the subsystem level to multi-system integration digitalization. In this way, a unified analysis platform can be relied upon to achieve security monitoring and prediction for the entire system. Zhang Boyu and some others discovered a

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key defect in the integration of train monitoring and dispatching systems, which is the lack of a shared simulation modeling mechanism for infrastructure and trains. This limitation hinders accurate analysis of the interaction between trains and infrastructure. To address this issue, their research proposed a framework. This framework utilizes multi-source heterogeneous data interfaces to transmit multi-dimensional information to the visual monitoring platform, thus breaking down information barriers and data silos. Within this framework, the team developed a 3D visual environment and achieved digital reconstruction of the entire system life cycle through three-end collaboration. This approach can collect static and dynamic data from the train and surrounding equipment, and then transmit these data to the cloud to build simulation models. Researchers have also established a dedicated power supply equipment detection and decision support platform. These platforms can simulate the response of train components to electrical loads on the virtual side, which is conducive to providing real-time optimization solutions and emergency measures. This comprehensive approach addresses the issue of isolated simulation and prediction across different systems and combines the interactions among various rail system components, ultimately providing more accurate and effective solutions [19].

The prevention of emergency situations was stated to be enabled by a Digital Twin-based security architecture, a solution that was advanced by Yan Han et al. after analysis of safety assurance status in urban rail transit domestically and internationally. This architecture is realized through an active safety assurance system that is structured into three layers: Data Management, Simulation & Deduction, and Decision-Making. The Data Management Layer is tasked with the collection of basic data, simulation data, and real-time sensor data from urban rail subsystems; these data are then fed to an interactive platform where health status is analyzed, safety risks are assessed, and maintenance decisions are furnished. Simulation of changes across the urban rail system from multiple perspectives is performed by the Simulation & Deduction Layer, and by comparing historical with current data, health state assessments and fault predictions are generated. Operational decisions ensuring normal system functioning and optimization plans for track subsystems are delivered by the Strategy Layer, following the classification of risk levels based on the simulation layer's assessments [20].

In summary, the Urban Rail Transit Digital Twin integration is characterized by the dissolution of information barriers between subsystems, the facilitation of global condition monitoring, and the replacement of passive maintenance with proactive prevention.

5. Conclusion

The integration of Digital Twin technology with operation and maintenance is identified as a promising direction for digitally transformed urban rail transit systems. This approach is characterized by data being collected from physical assets, transmitted to the cloud for analysis, and predictions being provided. Consequently, the efficiency of maintenance personnel is enhanced, operational costs are reduced, and the overall safety of the rail system is improved. A comprehensive assessment and prediction of a train's condition throughout its entire lifecycle is facilitated by the application of both three-dimensional and five-dimensional Digital Twin models, through which maintenance costs are lowered, the train's service life is extended, and its safety is improved.

The Digital Twin framework for urban rail transit systems is characterized by the dissolution of information silos between subsystems, which allows for precise analysis of problems arising from chain reactions. Through this framework, comprehensive system-wide maintenance and accurate early warnings are realized, while a closed-loop optimization system of data collection, simulation analysis, decision-making, and feedback on decision effectiveness is established. Consequently,

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more efficient and accurate maintenance and prediction outcomes are attained through this cyclical process.

The current stage of research is characterized by being situated in the testing phase of system integration, where attention is directed toward overcoming multi-source data fusion and high-fidelity challenges.

The remarkable progress that has been proven by Digital Twin technology in the aerospace sector provides a foundation for its application in train equipment, where sensors or other intelligent detection devices are utilized to collect data and transmit it to the virtual end, enabling vehicle health to be predicted. Through the rapid advancement of big data analytics and Digital Twins, fault detection capabilities are projected to be refined considerably by sophisticated artificial intelligence analysis in future applications. Meanwhile, the minimization of environmental factors' effects on monitoring data needs to be recognized as a central aim for future developmental efforts.

References

[1] Ding, Y. (2025) Exploration and practice of a new intelligent operation and maintenance-enabled inspection mode for Shanghai metro vehicles. Urban Rail Transit, (07), 43–46.
[2] Li, Z., Wu, Y., He, Y. et al. (2025). Research progress on digital twin technology in railway wheel prognostics and health management (PHM). High-Speed Railway New Materials, 4(04), 8–12.
[3] Hou, A., Huang, J., Chen, B. et al. (2025). Research on the five-dimensional model and platform construction method for EMU digital twin. Railway Locomotive & Car, 45(04), 57–63.
[4] Hong, D., Fang, W., Li, H., et al. (2024). Construction and application research of equipment digital twin for intelligent operation and maintenance. Journal of Astronautics, 45(06), 854–865.
[5] Shu, K., Han, J., Chen, Y., et al. (2025). Research on optimization of intelligent operation and maintenance management system for EMU pantograph. China Mechanical Engineering, (19), 96–99.
[6] Liu, X., Li, L., Li, W. et al. (2025). Design and application research of an intelligent operation and maintenance system for urban rail trains integrating new-generation information technology. Digital Transformation, 2(06), 106–115+126.
[7] Cao, G. (2025) Thoughts and exploration on a digital twin-based operation and maintenance system for metro vehicle bogies. China Plant Engineering, (06), 130–133.
[8] He, X. (2025). Research on equipment digitalization based on urban rail transit cloud signaling system. China Plant Engineering, (17), 213–215.
[9] Zhang, Y., Zhang, Z., Liang, C., et al. (2025). Research on visual monitoring and fault diagnosis method for switch machine based on digital twin. Urban Rapid Rail Transit, 38(03), 153–161.
[10] Li, H. Yang, G. (2025). Research and application of an automatic track geometry parameter detection device for urban rail transit. In Proceedings of the 7th Academic Exchange Conference on Engineering Technology Management and Digital Transformation. 44–46.
[11] Zhang, M., Wang, T., Zhang, J. (2025). Application of big data-driven digital twin technology in the full lifecycle design of roads and bridges. Information and Computer, 37(16), 22-24.
[12] Ni, Y. Chen, L. (2025). Application of digital twin technology in intelligent operation and maintenance of railway bridges. Railway Construction Technology, (09), 5-8.
[13] Pan, Y., Zhuang, X., Wang, D. et al. (2025). Bridge inspection technology integrated with digital twin: A review and prospect. China Journal of Highway and Transport, 1–23.
[14] Luo, H. Wang, Y. Sheng, B. et al. (2025) Application of digital operation and maintenance technology throughout the entire lifecycle of transportation infrastructure. Transport Energy Conservation & Environmental Protection, 21(4), 84–87.
[15] Ye, P. (2021). Research on the Application of BIM and VR-Based Maintenance Technology for CRTS II Slab Ballastless Track on Bridges.
[16] Wen, B. (2024). Application research on BIM and digital twin technology in railway bridges. Railway Engineering Technology and Economy, 39(5), 16–21.
[17] Javier Sánchez-Haro, Marianela García, Guillermo Capellán, Almudena da Costa, Paula Perez, Javier Añó (2025) Digital twin for predictive maintenance on the Espartxo Bridge. Application to early detection of under-foundation scour, Structures, Volume 71, 107916, ISSN 2352-0124.

DOI: 10.54254/2753-8818/2026.HZ29369

[18] Sun, Z. Liang, B. Liu, S. Liu, Z. (2025). Data and Knowledge-Driven Bridge Digital Twin Modeling for Smart Operation and Maintenance. Appl. Sci. 15, 231. https: //doi.org/10.3390/app15010231
[19] Zhang, B. Ke, Y. Liu, J. (2025) Research on rail transit operation and maintenance based on digital twin technology. In Proceedings of 2025 Annual Conference of Tianjin Electronic Industry Association. 130-132.
[20] Yan, H., Cheng, X., Ma, X. et al. (2025). Architecture and key technologies of an active safety assurance system for urban rail transit based on digital twin. Railway Transport and Economy, 47(6), 170–179.