GEORGE BROWN PRESS
JOURNALS, BOOKS & PROCEEDINGS

International Journal of Engineering Advances

Article

Design and Research of the Signal Intelligent Operation and Maintenance System for Nanning Metro Line 4 Based on PHM Technology

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Abstract: As urban rail transit expands rapidly, the operation and maintenance of metro signal systems are crucial. Traditional methods face challenges, like relying too much on manual work and not predicting faults well. This study uses Prognostics and Health Management (PHM) technology to create Nanning Metro Line 4's signal intelligent operation and maintenance system. By carefully analyzing requirements, it details the system's design, including its architecture and working principle. It also covers technical implementation, such as how to collect and process data, monitor equipment, predict faults, and make maintenance decisions. The goal is to boost the operation and maintenance levels and efficiency, guarantee metro safety, and offer a model for other urban rail transit signal intelligent operation and maintenance projects.

Keywords: metro signal system; intelligent operation and maintenance; PHM technology; fault prediction; health diagnosis

Received: 5 March 2025
Revised: 13 March 2025
Accepted: 27 March 2025
Published: 31 March 2025

1. Introduction

1.1. Research Background

In the intelligence era, "intelligent operation and maintenance" of urban rail transit is an inevitable trend. The metro signal system is vital for train operation safety and efficiency. The China Urban Rail Transit Association aims to promote such systems by 2025. Many Chinese metros have started intelligent operation and maintenance practices. Nanning Metro has grown fast, and Line 4 faces rising operation and maintenance pressure. Its existing mode has limits; for instance, intelligent inspection robot technology isn't mature, failing to meet the needs and in urgent need of improvement [1].

1.2. Research Objectives and Significance

This research is dedicated to developing a cutting-edge signal intelligent operation and maintenance system for Nanning Metro Line 4, leveraging Prognostics and Health Management (PHM) technology. In the context of the rapid development of urban rail transit, Nanning Metro Line 4 is playing an increasingly important role in urban transportation. However, the traditional operation and maintenance methods can no longer meet the requirements of modern development. The designed system is expected to achieve the whole-life cycle management of equipment. This means that from the procurement, installation, operation, to the final decommissioning of the equipment, the system will comprehensively monitor and manage every stage. By continuously collecting and analyzing data, it can timely detect potential problems, optimize equipment performance, and extend the service life of the equipment. This not only improves the operation and maintenance level and efficiency but also reduces unnecessary maintenance costs. Moreover, the system is set to promote the intelligent development of Nanning Metro. Through advanced technologies like artificial intelligence and big data analysis, it can enhance the safety and reliability of the entire system. For example, by accurately predicting faults in advance, maintenance personnel can take preventive measures, minimizing the risk of train disruptions and ensuring the smooth travel of passengers.

2. Demand Analysis of the Signal Intelligent Operation and Maintenance System for Nanning Metro Line 4

2.1. Current Operation and Maintenance Status Analysis

Jiaokong Zhiwei is tasked with the operation and maintenance of Nanning Metro Line 4. To manage the signal system, it has implemented the Maintenance Support System (MSS), Data Communication System (DCS), and Big Data Management System (BDMS), which have enabled partial monitoring and management capabilities. These systems have indeed contributed to the overall operation to some extent, for instance, they can collect certain data and perform basic analysis on the signal system's performance. However, the current approach of combining intelligent inspection robots with manual inspection falls short of a true intelligent operation and maintenance model. The inspection robots used are restricted in their functionality. They can only carry out a limited range of tasks, such as basic visual inspections in some areas, and are unable to comprehensively assess the complex components and hidden problems within the signal system. Meanwhile, this model requires a significant amount of labor input. Maintenance workers have to spend a large amount of time and energy on manual inspections, which not only increases the workload but also reduces the efficiency of the overall operation and maintenance process. Moreover, the MSS has its own drawbacks. It fails to provide sufficient monitoring for some key equipment in the signal system. There are blind spots in its monitoring scope, and it may not be able to detect potential problems in a timely manner. This situation could pose risks to the safe and stable operation of the metro. Therefore, it is urgent to enhance the equipment monitoring capabilities and improve the intelligent maintenance management of the signal system for Nanning Metro Line 4.

2.2. Operation and Maintenance Demand Analysis

Improve the signal data collection and processing, increase data collectors, and expand the data collection scope; formulate data monitoring standards and judgment methods, realize the transformation from breakdown maintenance to scheduled maintenance and then to condition-based maintenance, and conduct the operation management of the health diagnosis of signal equipment [2].

2.3. Demand Analysis of the Level of the Intelligent Operation and Maintenance System

The intelligent operation and maintenance levels of metro signal systems are divided into GoM0-GoM4. Each level represents a different stage of development in the capabilities of system operation and maintenance. The GoM4 level, a crucial target in this framework, uses artificial intelligence and big data technology to carry out fault prediction and comprehensive health management of the signal system. This can help detect potential problems early and take preventive measures to ensure the stable operation of the metro. For Nanning Metro Line 4, Prognostics and Health Management (PHM) technology is fundamental. By integrating this technology with the operation and maintenance management system, a complete process is formed. It includes data collection from various parts of the signal system, data processing to obtain useful information, detection of abnormalities, diagnosis of problems, decision-making for appropriate maintenance strategies, and reporting to record and convey the system status, which is beneficial for system management and improvement (as shown in Figure 1).

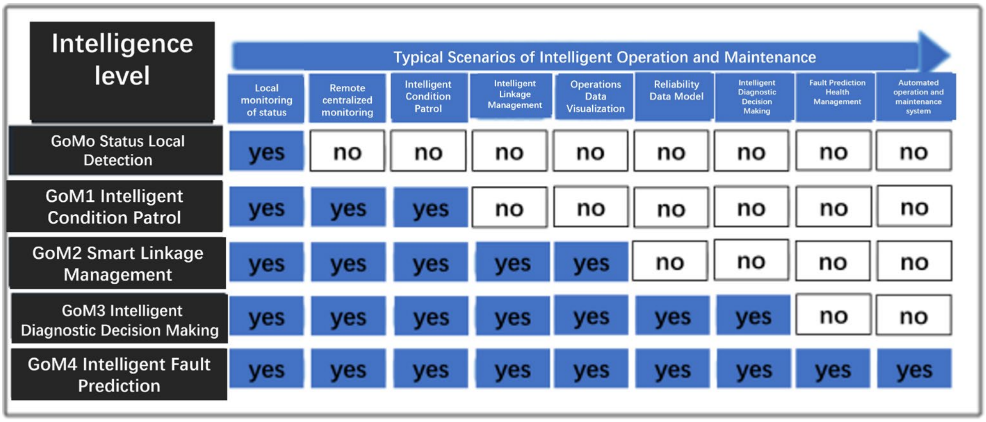

Figure 1. Intelligent Operation and Maintenance Levels and Typical Scenarios.

3. Design of the Signal Intelligent Operation and Maintenance System for Nanning Metro Line 4

3.1. Working Principle of the System Based on PHM

The metro signal intelligent operation and maintenance system based on Prognostics and Health Management (PHM) technology is structured around six essential modules (as shown in Figure 2). The data collection module is the cornerstone of the entire system. It carefully defines the equipment to be monitored, selects the relevant information parameters that can reflect the equipment's operation status, and determines the appropriate sensors. This ensures that the data collected is comprehensive and accurate, providing a reliable basis for subsequent analysis. Data processing is where the collected raw data is refined. It first preprocesses the data to filter out noise and outliers, and then extracts key features. These features are crucial for understanding the equipment's behavior patterns. The operation status detection module plays a vital role. It monitors the data in real-time and compares it with normal operating values. Any deviation can be quickly identified, allowing for early detection of potential problems. Health diagnosis uses methods like threshold judgment or inner product matching to precisely identify equipment faults. This helps the maintenance teams quickly understand the nature and location of the problem. Based on the fault information, the operation and maintenance decision-making module formulates targeted maintenance plans. These plans are designed to resolve issues efficiently and minimize downtime. Finally, the operation and maintenance report formation module documents all aspects of the process. This not only helps in tracking the system's performance but also enriches the expert knowledge library, facilitating continuous improvement of the operation and maintenance process.

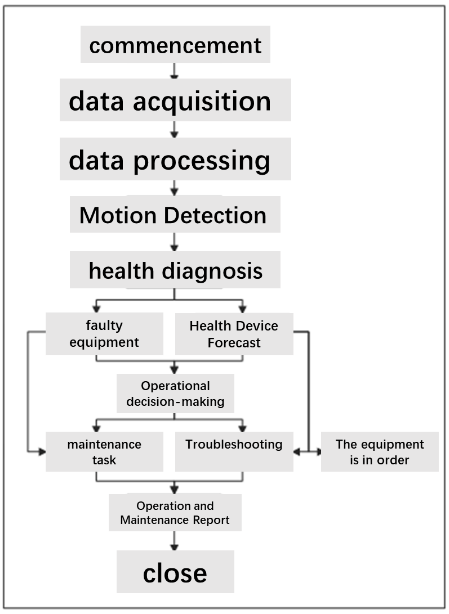

Figure 2. Working Principle of PHM-based Metro Signal Intelligent Operation and Maintenance System.

3.2. Architecture Design of the Metro PHM Signal Intelligent Operation and Maintenance System

The system consists of a data source layer, a data processing layer, and an application platform layer (as shown in Figure 3). The data source layer collects data from various devices via periodic and event-triggered transmission. The data processing layer stores data on the Hadoop platform, screens it for fault prediction, and visualizes it. The application platform layer enables functions like intelligent monitoring and operation and maintenance decision-making, and health management [3].

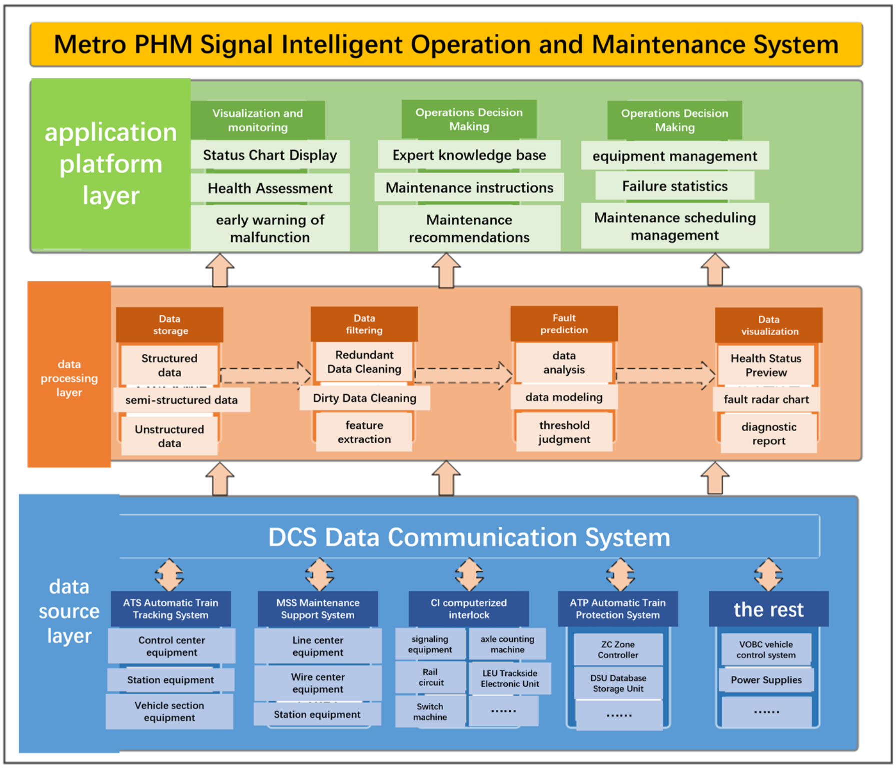

Figure 3. Nanning Metro Line 4 PHM Signal Intelligent Operation and Maintenance System.

3.3. Network Architecture Design of the Metro Signal System Intelligent Operation and Maintenance

The network architecture of the signal system intelligent operation and maintenance of Nanning Metro Line 4 includes the Vehicle On-Board Controller (VOBC) control system, the station-level signal system, the line-level signal intelligent operation and maintenance system, and the network-level control center service system (as shown in Figure 4). All levels work together, transmit data through the maintenance network, and use big data technology to realize monitoring and early warning, providing decision-making support for operation management [4].

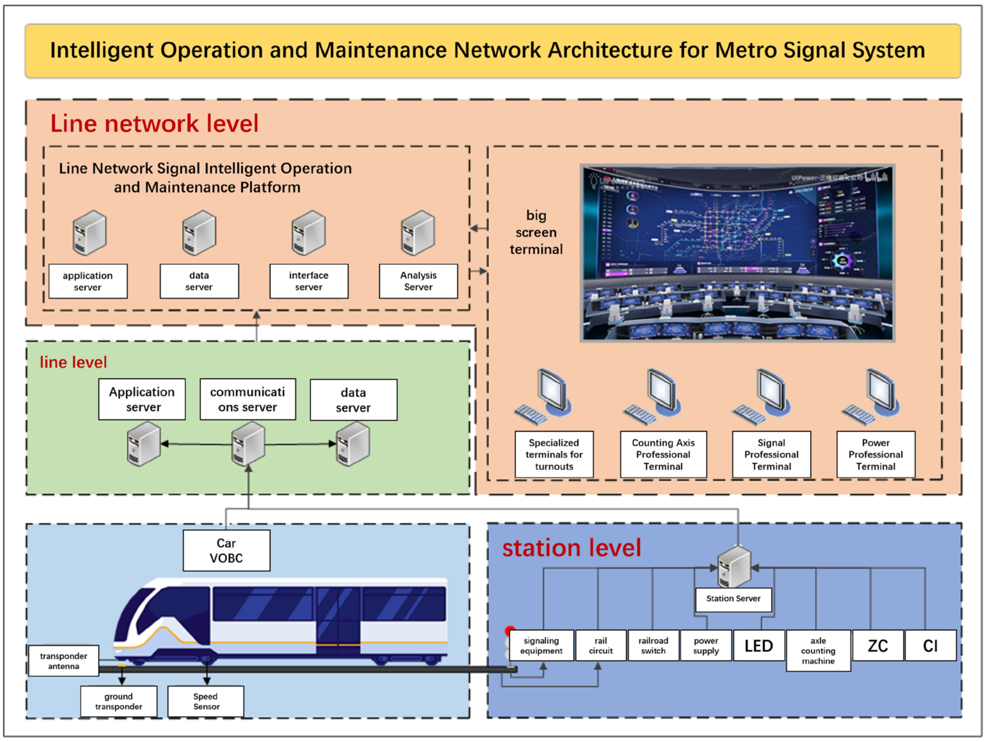

Figure 4. Nanning Metro Line 4 Signal System Intelligent Operation and Maintenance Network Architecture.

4. Technical Implementation of the Signal Intelligent Operation and Maintenance System for Nanning Metro Line 4

4.1. Data Collection and Processing

For data collection, corresponding collectors are used for different devices. The collection process includes signal conversion, filtering and amplification, and analog-to-digital conversion (as shown in Figure 5). The collected data is processed by methods such as time-domain analysis to extract features, and time-domain characteristic parameters such as the mean value and standard deviation are calculated to describe the operation status of the equipment [5].

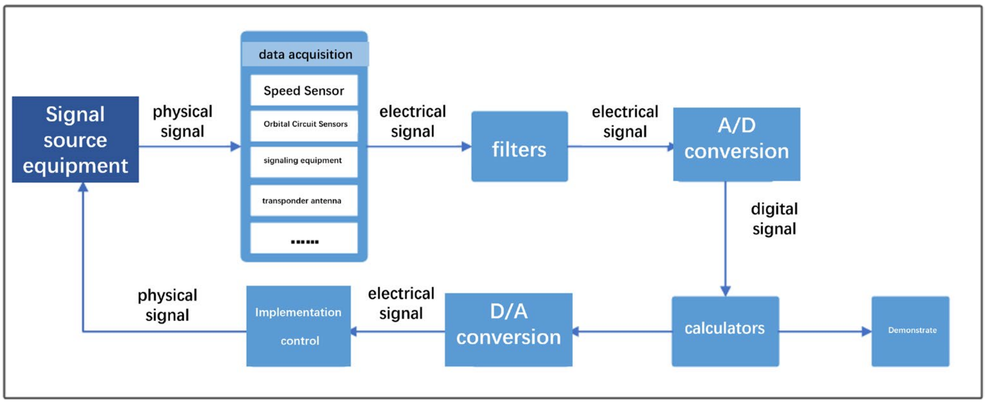

Figure 5. Schematic diagram of data acquisition technology flow.

4.2. Status Monitoring and Diagnosis

By setting fault thresholds and using the three-principle method of adaptive thresholds, the health status of the equipment is judged, realizing the status monitoring and diagnosis of the signal system, determining the fault location and time, and facilitating the handling by maintenance personnel [6].

4.3. Fault Prediction

The method combining wavelet transform and Back Propagation (BP) neural network is used for fault prediction. The wavelet transform conducts time-frequency analysis of the signal, and the BP neural network learns and trains. The combined model processes and predicts the collected data to grasp the health status of the equipment in advance (as shown in Figure 6 and Figure 7) [7].

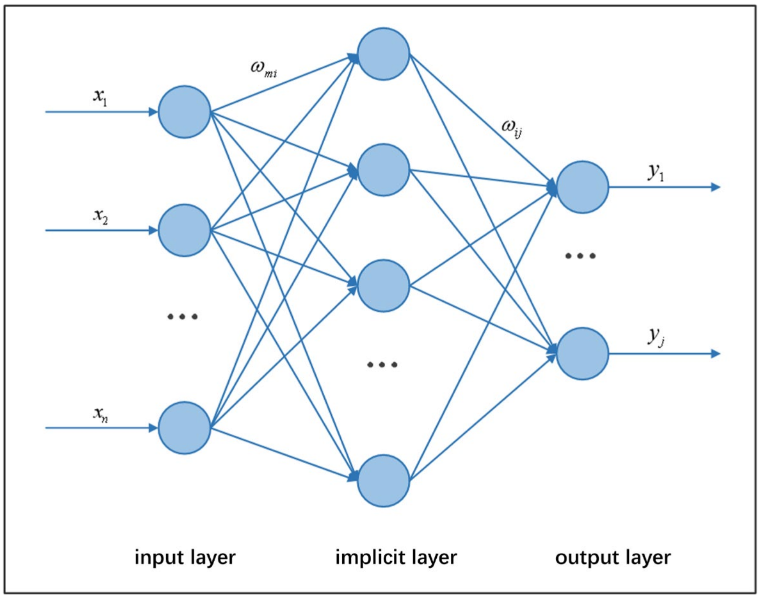

Figure 6. BP neural network structure diagram.

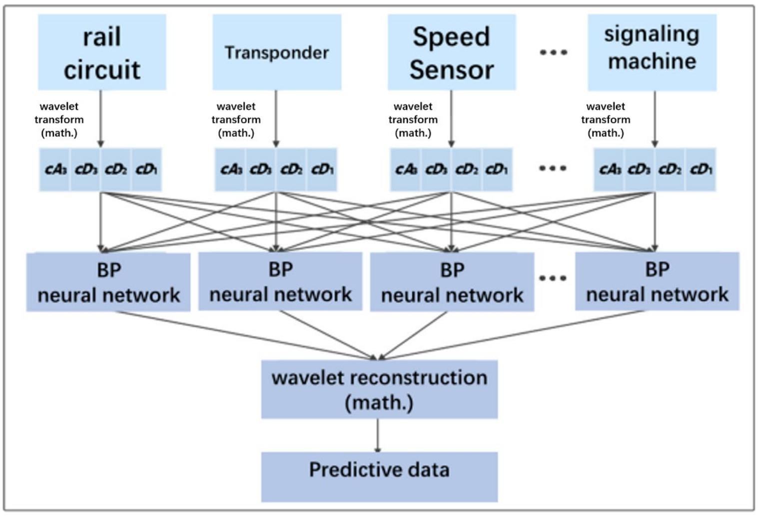

Figure 7. Wavelet BP Neural Network Predictive Structure.

4.4. Operation and Maintenance Decision-making Management

An expert knowledge base based on the Hadoop Distributed File System (HDFS) is constructed to integrate various data and experiences. When a fault occurs, the expert knowledge base provides maintenance suggestions and historical records for reference, realizing intelligent operation and maintenance decision-making management [8].

5. Conclusions and Prospects

5.1. Summary of Research Results

The signal intelligent operation and maintenance system designed for Nanning Metro Line 4 in this study represents a significant step forward in urban rail transit management. By leveraging PHM technology, it enables real-time equipment monitoring, which means that any changes or anomalies in the signal system can be detected immediately. This real-time aspect is crucial as it allows for prompt responses to potential issues, minimizing disruptions to train operations. In terms of diagnosis, the system can accurately identify faults through advanced algorithms and data analysis. It doesn't just detect that a problem exists but can also pinpoint the exact nature and location of the fault. This precision is a vast improvement over traditional methods, reducing the time spent on troubleshooting. Fault prediction is another key strength. By using a combination of wavelet transform and BP neural network, the system can anticipate equipment failures before they occur. This proactive approach gives the maintenance teams time to plan and carry out preventive maintenance, which in turn boosts operation and maintenance efficiency. Overall, the system meets the demands of urban intelligence development by providing a more intelligent, efficient, and reliable solution for metro signal system management.

5.2. Research Limitations and Future Research Directions

While this research has made important progress, it has several limitations. The study was mainly centered around Nanning Metro Line 4, which means it didn't fully account for the differences among various metro lines. Different lines may have distinct operational environments, equipment configurations, and passenger demands. For example, some lines might operate in areas with extreme weather conditions that could affect the signal system differently. The actual application effect of the designed system also remains to be verified. Although the theoretical design seems promising, real-world implementation could face unforeseen challenges. In the future, it's essential to expand the research scope to include multiple lines. Conducting application tests in different scenarios will help optimize the system, making it more adaptable. Additionally, exploring the integration of new technologies such as the latest advancements in sensor technology or more sophisticated artificial intelligence algorithms can further enhance the system's performance, ensuring it stays at the forefront of urban rail transit signal operation and maintenance.

Funding: This research was funded by Guangxi Science and Technology Base and Talent Project for Guangxi Science and Technology Plan Project: Construction of Guangxi Transportation New Technology Transfer Center Platform (No. Guike AD23026029); Construction of Scientific and Technological Innovation Bases for Science Research and Technology Development Plan Project of Nanning City: Intelligent Operation and Maintenance of Transportation Infrastructure and Health Monitoring Platform (No. 20223230).

References

1. Y. Chen, X. Zeng, and T. Yuan, "Data-driven safety model on urban rail transit signal system," in *Proc. Int. Symp. Intell. Transp. Smart City (ITASC) 2019*, Branch of *ISADS (Int. Symp. Auton. Decentralized Syst.)*, Springer Singapore, 2019, pp. 145-154, doi: 10.1007/978-981-13-7542-2_14.
2. M. Li, X. Zhou, J. Liu, et al., "Topological modeling and analysis of urban rail transit safety risk relationship," *J. Intell. Manag. Decis.*, vol. 1, pp. 108-117, 2022, doi: 10.56578/jimd010204.
3. D. Zhu and D. Shi, "Research on intelligent operation and maintenance scheme of railway signal system based on big data," in *Proc. Int. Conf. Electron. Inf. Technol. (EIT 2022)*, SPIE, 2022, vol. 12254, pp. 432-439, doi: 10.1117/12.2640054.
4. J. Yu, S. Xiao, Y. Guo, G. Gao, G. Wu and X. Zhang, "High-speed Train Fault Diagnosis and Condition Monitoring Based on PHM Technology," in *2023 Panda Forum on Power and Energy (PandaFPE)*, Chengdu, China, 2023, pp. 1630-1635, doi: 10.1109/PandaFPE57779.2023.10140461.
5. Y. Zhou, R. Zhang, and H. Xue, "Research on fault tracing method of communication-based train control system," in *Proc. 4th Int. Conf. Artif. Intell. Electromech. Autom. (AIEA 2023)*, SPIE, 2023, vol. 12709, pp. 1006-1012, doi: 10.1117/12.2685086.
6. Y. Cao, L. Ma, and W. Li, "Monitoring method of safety computer condition for railway signal system," *J. Traffic Transp. Eng. (Jiaotong Yunshu Gongcheng Xuebao)*, vol. 13, pp. 107-112, 2013, doi: 10.19818/j.cnki.1671-1637.2013.03.015.
7. D. Liu, K. Liu, X. Xu, et al., "Research and application on prognostics and health management technology for high-speed train traction system," in *Proc. Int. Conf. Electr. Inf. Technol. Rail Transp.*, Springer Nature Singapore, 2023, pp. 316-321, doi: 10.1007/978-981-99-9315-4_32.
8. J. Farooq and J. Soler, "Radio communication for communications-based train control (CBTC): A tutorial and survey," *IEEE Commun. Surv. Tutor.*, vol. 19, no. 3, pp. 1377-1402, 2017, doi: 10.1109/COMST.2017.2661384.