

Research on the Design and Modeling of a Railway Brake Shoe Replacement System Based on NFC and Intelligent Optimization Algorithms

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Abstract. This research addresses the issues of low efficiency, high error rates in traditional manual railway brake shoe replacement, and the mismatch between existing automated equipment and actual needs due to insufficient technical adaptability. It designs an intelligent management and control system integrating NFC technology and intelligent optimization algorithms, adopting a hierarchical architecture (perception, transmission, decision-making layers). NFC realizes automatic data acquisition; SVM and GAM models achieve data matching and traceability; a hybrid GA-PSO algorithm optimizes scheduling. Experimental verification shows the system significantly improves recognition accuracy, scheduling efficiency, and anomaly response speed. Innovations include an NFC-based full-link data acquisition pathway, an SVM-KNN integrated model for accurate data alignment, and a GA-PSO hybrid mechanism for optimal resource allocation. It shifts from manual to algorithm-driven operations, providing a promotable paradigm for digital transformation of railway operation and maintenance.

Keywords: NFC technology; Industrial Internet of Things (IIoT); Genetic Algorithm (GA); Machine learning.

1. Introduction

In the field of railway transportation, the ever-increasing demands for operational safety and efficiency have driven intelligent and automated technologies to become core research paradigms [1]. Since the end of the 20th century, scholars both at home and abroad have embarked on explorations into intelligent railways. In 2000, the research team led by Li Ping from the China Academy of Railway Sciences, with the support of the Ministry of Science and Technology, successfully proposed the world's first railway intelligent transportation system architecture. In 2020, they released the "Intelligent High-Speed Railway System Architecture," establishing a tripartite framework of "technical system - standard system - data system," which laid a theoretical foundation for the development of intelligent railways [2]. During the same period, the Railway Technical Research Institute of Japan initiated research on the next-generation CyberRail system that integrates various IT technologies, aiming to enhance the connection between railway transportation and other modes of transportation [3].

As research progresses, intelligent technologies have gradually been applied in various aspects of railways [4]. In terms of the scheduling system, the world's first 5G + AI intelligent scheduling system on the Beijing-Zhangjiakou High-Speed Railway dynamically adjusts the departure interval to 3 minutes by real-time analysis of data from more than 2,000 sensors [5]; China State Railway Group uses machine learning algorithms to optimize the national train operation diagram, increasing line utilization by 18% and reducing the delay rate to 0.3% [6]. In terms of safety assurance, the computer vision-based track foreign object recognition system piloted on the Shanghai-Kunming High-Speed Railway has a detection accuracy of 98.7% and a false alarm rate controlled within 0.02%; the on-board AI diagnostic device can predict bogie faults 48 hours in advance, significantly reducing the incidence of major mechanical accidents [7]. In the field of equipment maintenance, Shenyang



Railway Bureau uses digital twin technology to build a 3D model of the catenary [8], reducing the equipment fault location time from 2 hours to 10 minutes; the bearing life prediction algorithm developed by Chengdu EMU Depot controls the error of key component replacement cycles within ± 3 days, saving 120 million yuan in maintenance costs annually [9].

Although intelligent and automated technologies have made significant progress in some railway scenarios, in the critical operational link of brake shoe replacement, the traditional manual-dominated mode still has prominent problems such as low efficiency and high error rates. Existing automated equipment has not yet formed a standardized paradigm suitable for large-scale complex scenarios due to insufficient technical adaptability and limited system integration [10], resulting in a significant structural mismatch between technical supply and actual demand [11]. From the perspective of technical application, traditional manual and semi-automatic operation modes have inherent defects of low efficiency and high error rates, and auxiliary equipment is also difficult to meet the needs of large-scale application due to limited reliability; although IoT and intelligent sensor technologies have improved monitoring accuracy to a certain extent, their application scope is limited by deployment costs and transmission stability [12]; NFC/RFID technology has a high application threshold due to its strong dependence on infrastructure [13]. At the same time, machine learning models and optimization algorithms have shown application potential in job scheduling [14, 15], but they have problems such as dependence on training data, high consumption of computing resources [16], and insufficient real-time performance under complex working conditions, and there are significant bottlenecks in system integration and interoperability [17]. Although existing intelligent systems have made progress in local scenarios, their integration efficiency on the scale of the entire railway network is insufficient, and problems such as data islands and cross-system compatibility restrict their large-scale promotion, and a technical system adapted to complex railway maintenance scenarios has not yet been built.

2. Methodology

2.1. System Architecture Design

To address the issues of inefficient data entry and insufficient precision in information matching during railway brake shoe replacement operations, this paper presents an intelligent management and control system that integrates NFC technology with embedded optimization algorithms. By means of in-depth integration of cloud platforms and Internet of Things (IoT) technologies, the system establishes an intelligent monitoring and optimization framework covering the entire process of brake shoe replacement. It adopts a hierarchical architecture consisting of the perception layer, transmission layer, and decision-making layer, with each layer achieving collaboration through modular interfaces.

The perception layer, supported by IoT sensing technologies, realizes the digital identification of physical entities by embedding NFC electronic tags in brake shoe components. In conjunction with handheld terminals, it completes the automatic reading of information and the collection of key parameters, thereby achieving the automated acquisition of operational data. The transmission layer constructs a heterogeneous communication architecture relying on ubiquitous wireless networks, employing protocols such as Message Queuing Telemetry Transport (MQTT) and Long Range Radio (LoRa) to realize low-consumption and high-efficiency data transmission. It integrates data encryption and verification mechanisms to ensure data integrity and confidentiality, providing reliable data link support for cloud-based management and control. The decision-making layer, by virtue of a cloud-based big data platform, constructs an operation optimization model through an improved genetic algorithm, enabling dynamic task scheduling, intelligent resource allocation, and path planning optimization. It generates visual monitoring and plan adjustment schemes, thereby enhancing operational efficiency and resource utilization.

Through hierarchical function division and technical adaptation, the system architecture realizes full-link closed-loop management from bottom-level data perception to top-level intelligent decision-

making, effectively improving the digital management and control level of brake shoe replacement operations. Experimental verification demonstrates that this architecture exhibits significant advantages in enhancing data processing accuracy and operational efficiency, providing a promotable technical paradigm for the intelligent transformation of railway operation and maintenance.

2.2. NFC Technology and Data Acquisition

As the core support for the data collection component of this system, NFC technology has established an efficient information acquisition mechanism by virtue of its technical features including contactless interaction, high-speed data transmission, and low-power operation. In specific applications, each brake shoe is pre-embedded with an NFC electronic tag, whose unique identifier forms an accurate mapping with the full attribute information of the brake shoe in the cloud management system (encompassing production batch, technical parameters, service records, etc.). It not only stores basic attributes such as model specifications and manufacturers but also dynamically records the whole life cycle data (including historical replacement records, cumulative operating mileage, wear evaluation results, and theoretical replacement cycles).

The NFC read-write module built into the handheld terminal of train inspection personnel can automatically trigger the identification process when entering the effective sensing range, complete the reading and parsing of tag data, and upload it to the cloud in real-time via wireless links such as 4G/5G or Wi-Fi. The cloud system, based on the received data, automatically determines the brake shoe replacement demand and synchronously updates the status records in conjunction with the preset wear threshold model and operation and maintenance rule database. This mechanism realizes full-process automation through contactless identification and real-time cloud synchronization without manual intervention, eliminating the operational redundancy and data error risks of manual entry at the technical level, and providing high-precision and high-timeliness data support for brake shoe operation and maintenance decisions.

2.3. Data Matching and Traceability Algorithm Design

To achieve accurate mapping between brake shoe replacement records and physical operational status, this system establishes an automatic data matching and traceability algorithm framework based on machine learning. By extracting multi-dimensional feature vectors, including the unique identifier of the brake shoe, wear status characteristics, and replacement timing parameters, this framework enables the automatic association of historical records and the traceability of full life-cycle information.

In the construction of machine learning models, the system adopts a collaborative architecture integrating SVM and GAM. It leverages the classification advantages of the SVM algorithm in high-dimensional feature spaces to achieve precise partitioning of decision boundaries, and relies on the GAM model which combines the strengths of nonlinear fitting capability and interpretability. The model parameters are optimized using historical operational and maintenance data of brake shoes. The trained integrated model can accurately determine whether the brake shoe replacement threshold is met based on real-time operational records and equipment status parameters, and automatically update the full life-cycle traceability information.

The data matching and traceability mechanism realizes the precise binding between replacement operations and brake shoe entities by comparing the feature vectors of NFC tag scanning information with historical records in the database, combined with the aforementioned algorithm system. This effectively avoids data association confusion caused by tag recognition errors or scanning anomalies. The information traceability system not only covers a single operational process but also extends to the full life-cycle management dimension of brake shoes, enabling full-process traceability from production, operation and maintenance to scrapping.

By integrating machine learning models and intelligent data matching algorithms, this system realizes the automatic association and matching of brake shoe information, and constructs a full life-cycle

traceability system. It ensures that the replacement records of each brake shoe can be traced throughout the entire process from operational and maintenance operations to physical status. This technical scheme significantly enhances the operational reliability of the system and the accuracy of data processing, providing core technical support for the intelligent management and control of railway brake shoe replacement operations.

2.4. Optimization Algorithms and Operation Scheduling

To enhance the operational efficiency of workflow processes and the rationality of resource allocation, this system introduces a hybrid mechanism integrating Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) algorithm, which is employed for dynamic scheduling and optimal resource allocation in brake shoe replacement operations. Taking historical operation and maintenance data as well as real-time operational scenario parameters as inputs, this hybrid algorithm addresses the requirements of multi-task parallel scenarios and dynamic resource configuration. Through the collaborative solution leveraging GA's global search capability and PSO's local optimization characteristics, it achieves the minimization of total operational time and the optimal allocation of resources such as equipment and personnel under resource constraints. On the premise of ensuring operational safety and quality standards, it significantly improves operational time efficiency and resource utilization efficiency, providing efficient algorithmic support for the intelligent management of brake shoe replacement operations.

The system realizes seamless collaboration and global information sharing among various functional modules through a sophisticated integration architecture. It adopts standardized interface design and distributed data interaction protocols to ensure efficient flow of data streams between the perception layer, transmission layer, and decision-making layer. Meanwhile, a closed-loop real-time feedback mechanism is introduced. Based on dynamically perceived data from the operation site (including equipment status parameters, operation progress nodes, environmental interference factors, etc.), it modifies operation plans and scheduling strategies in real-time through adaptive control algorithms, rapidly responding to changes in on-site working conditions and avoiding efficiency losses in static planning modes. Relying on the cross-platform data sharing system built on a unified data middle platform, it realizes interoperability between heterogeneous devices, supports real-time data interaction and authorized access among on-site operation terminals, management monitoring platforms, and dispatch center decision-making systems, and ensures that operators, managers, and dispatchers form a collaborative work closed-loop based on a consistent data benchmark. The aforementioned system integration and real-time feedback mechanisms collectively constitute self-optimization capabilities. Through continuous iteration, they enhance the operational efficiency of each operation link, promote the evolution of railway brake shoe replacement operations towards a higher level of intelligence and automation, and provide an extensible technical paradigm for the digital transformation of railway operation and maintenance systems.

3. Experimental Design and Result Analysis

3.1. Experimental Objectives and Design Ideas

To validate the effectiveness of the proposed intelligent brake shoe replacement system in real-world railway operation environments and the engineering applicability of its algorithmic models, this study constructs a comprehensive experimental platform integrating real-scenario simulation and field testing, and conducts systematic experimental design centered on the following core issues:

- 1) Recognition precision of the NFC data acquisition system and accuracy of data matching.
- 2) Convergence efficiency and solution optimality of the operation scheduling algorithm under varying load conditions.
- 3) The extent of improvement in time efficiency throughout the system's overall operational workflow.

4) Real-time performance and accuracy of the data traceability mechanism and anomaly detection module.

In terms of experimental design, the research team selected the Huoerguosi Operation Workshop of Urumqi West Rolling Stock Depot, China Railway, as the field application scenario. A testing platform that conforms to the real operating environment was built here to carry out data collection and system performance evaluation. Specifically, a comparative experimental method was adopted, where various operating indicators of the developed system during operation were compared and analyzed with historical data from traditional operating modes in multiple aspects and angles. This was done to comprehensively examine the performance improvement brought by the system under actual working conditions and its application value in engineering practice.

3.2. Experimental Environment and Configuration

The experimental platform constructed in this study adopts a distributed architectural design. Its cloud infrastructure is built on an Aliyun Elastic Compute Service (ECS) to form a cloud server cluster, leveraging Redis in-memory database for high-concurrency data caching and integrating PostgreSQL relational database to establish a structured data storage system. For data acquisition terminals, industrial-grade NFC Android handheld devices are employed, which support the ISO 14443 Type A/B protocol, operate at a frequency of 13.56 MHz, and feature a passive reading mode to ensure the reliability of data acquisition. As for the tag configuration scheme, industrial-grade NFC anti-metal magnetic tile tags are adopted, complying with the ISO/IEC 15693 standard, with an IP68 protection rating, enabling stable operation within an ambient temperature range of -40°C to 85°C.

The algorithm layer of the system adopts a modular design. Specifically, the operation scheduling module constructs a hybrid intelligent algorithm framework based on GA and PSO, realizing multi-objective optimization solutions through the design of an adaptive weight adjustment mechanism. The data matching engine establishes a hybrid model combining a SVM classifier with K-Nearest Neighbor (KNN) verification, employing 5-fold cross-validation and grid search for hyperparameter tuning. The anomaly detection component implements unsupervised anomaly detection based on the Isolation Forest algorithm, and completes the automatic classification of anomaly types through feature importance analysis.

The dataset established in this study comprises two parts: the historical operation dataset, which is collected from the historical brake shoe replacement records of 12 rolling stock depots under 5 national railway administrations, encompassing 13,500 samples covering the complete operation cycle from January 2022 to December 2023; and the NFC tag dataset, which involves uniquely encoding and marking 3,000 newly installed brake shoes. The data collection process adheres to the ISO/IEC 18000-3 standard to ensure data integrity and consistency. All data are subjected to Z-score standardization and partitioned into a training set and a test set in an 80:20 ratio.

3.3. Definition of Evaluation Metrics

Table 1. System performance evaluation metrics

Variable	Variable Explanation	Variable Description
Accuracy	Recognition Accuracy	The success rate of the system recognizing brake shoe tags and matching database records after NFC scanning
T_s	Scheduling Convergence Time	The average convergence iteration time of the optimization algorithm in on-site scheduling
ΔT	Reduction ratio of total operation duration	The proportion of the difference in average operation time between the intelligent system and the traditional process
T_a	Anomaly Response Time	The average response and alarm time of the system to traceability failures or scanning errors
R_s	System Robustness	The stable operation capability of the system under high-load and high-frequency operations (ratio of fault-free operation times to total tasks)

To comprehensively quantify the system performance, we have defined the following evaluation metrics, as shown in Table 1:

3.4. Key Experimental Results

To verify the application effect of NFC technology in the recognition and data matching links, the key performance indicators of this system and traditional code scanners are compared, and the results are shown in Table 2:

Table 2. Results of NFC recognition and data matching

Project	Traditional code scanner	This system (NFC)
Average recognition time (ms)	880	138
Recognition accuracy rate (%)	92.4	99.3
Data matching success rate(%)	87.6	98.9

Note: After adopting the NFC automatic scanning and recognition scheme, the system not only outperforms the code scanner significantly in recognition speed but also achieves an accuracy improvement of nearly 7%.

3.5. Comparison of Scheduling Algorithm Performance

To evaluate the time efficiency optimization effect of the system in task scheduling and the overall process, this study conducts a comparative analysis of data from two aspects: the scheduling time (T_s) under different task scales and the time efficiency improvement (ΔT) in each operation link. The specific analysis is shown in Table 3 and Table 4:

Table 3. Comparison of System Scheduling Time T_s under Different Task Scales

Operation scale (number of tasks)	Traditional manual scheduling (seconds)	GA+PSO scheduling model (seconds)	Improvement rate (%)
20	112	3.4	69.6
50	24.8	7.6	69.3
100	54.3	14.2	73.8

Table 4. Table of Analysis on Time Efficiency Improvement(ΔT)

Operation links	Traditional average time-consuming (seconds)	Improvement ratio (%)	Traditional average time consumption (seconds)
Data entry and recognition	4.8	0.9	81.2
Confirmation of warehousing and outbound and scan code feedback	5.4	5.1	72.2
Overall process (single task cycle)	18.7	6.4	65.8

Note: In the entire process, the system has significantly reduced the operation time, with the most obvious improvement particularly in the data collection and feedback links.

3.6. Anomaly Detection and System Robustness Testing

The system has conducted simulation tests on abnormal situations such as NFC recognition failure, brake shoe data missing, and information inconsistency to verify its self-recovery capability and alarm mechanism, as shown in Table 5.

Table 5. Comparison Table of Response Time (T_a) and Automatic Processing Rate Corresponding to Abnormal Types

Abnormal type	Response time (T_a , seconds)	Automatic processing rate (%)
NFC recognition failure	0.63	100
Data traceability anomaly	0.97	98.5
Tag redundancy detection	0.44	99.2

Note: The system can complete anomaly detection and trigger response strategies within <1 second, demonstrating excellent real-time performance and reliability.

3.7. User Feedback and On-site Sampling

A Likert 5-point scale questionnaire survey was administered to 30 frontline train inspection personnel in the field. The findings indicated that the satisfaction rating regarding the system's convenience stood at 4.7/5, the score for the perceived reduction in operational intensity reached 4.5/5, and the rating for the learning and usage curve was 3.2/5 (primarily attributed to the complexity of the algorithm's interactive interface). In general, user satisfaction is high; however, there remains room for optimization in terms of interface interaction.

4. Conclusion

This study focuses on the replacement operation process of brake shoes, a core component in railway transportation, and for the first time systematically constructs an intelligent operation system integrating NFC automatic identification, machine learning-based data matching, and intelligent optimization scheduling. It specifically tackles long-standing industry challenges in this domain, such as excessive manual intervention, inadequate data consistency, and low operational efficiency.

The research innovations are primarily manifested in three dimensions: firstly, the intelligent tag system based on NFC technology has established a full-link data acquisition pathway that is perceivable, interactive, and traceable, enabling paperless and contactless digital acquisition of brake shoe operations; secondly, an integrated learning model combining SVM and KNN is employed for data matching and traceability, effectively ensuring accurate data alignment and historical continuity; thirdly, by virtue of a hybrid intelligent scheduling mechanism integrating GA and PSO, the optimal allocation of resources and intelligent planning of operation paths in multi-task scenarios are achieved. This research has accomplished the paradigm shift from traditional manual operation to algorithm-driven operation in the field of railway intelligent maintenance, laying a solid algorithmic foundation and engineering application paradigm for the intelligent track inspection and repair system.

Future research intends to introduce edge computing and federated learning frameworks, in conjunction with a multi-modal perception fusion system, to construct an industry-level intelligent maintenance platform, thereby further enhancing the engineering adaptability and global intelligence of the system.

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