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New generation intelligent operation and control management system enhancing metro station operations

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Abstract: This article discusses the need for digitalization, as well as the concept and features of a next-generation intelligent operation and control management system （IOCMS） based on digitalization. It highlights the differences between this new system and the existing standard architecture of rail transit stations, and summarizes the advantages of the new intelligent operation and control management system. The feasibility of digitally upgrading rail transit station operations is analyzed, and a system architecture plan for the intelligent management platform is proposed. Several key technologies of the intelligent operation and control management system are explored, and major innovative business aspects are listed. By conducting a comparative analysis before and after the digitalization upgrade of rail transit operations, a brief evaluation of the digitalization upgrade is presented. Finally, other aspects to consider in the construction of the new generation digitized intelligent operation and control management system are summarized.

Keywords: transportation engineering: operation and control management; intelligent; digitalization; snnovative businesses; rail transit

1 Introduction

With the continuous development of digital and intelligent technologies, digitalization has directly empowered enterprises, enhanced their production efficiency and even changed their production relationships. Therefore, it is essential to explore the digitalization and intelligent upgrading of rail transit.

The digitalization of rail transit involves digitizing the entire lifecycle of rail transit, including design, construction, and operation. By studying the end-to-end rail transit business processes and comprehensively digitizing them, a new generation intelligent operation and control management system (hereafter referred to as ‘IOCMS’) can be developed. By utilizing technologies such as artificial intelligence and big data, the system can analyze the correlations among various business data and explore the digital reconstruction of station operations. The goal is to streamline operational management processes, efficiently allocate production tasks, and effectively schedule equipment operations, thereby reducing operational costs, conserving energy consumption, and improving passenger satisfaction.

Currently, research on intelligent station operation management system in various cities in China is still in the exploratory stage. Cities such as Beijing, Shanghai, Guangzhou, and Chongqing are actively attempting to build station management system that focus on passenger management, equipment coordination, and operational supervision. These systems have to some extent improved the passenger travel experience, enhanced system integration efficiency, and reduced operational management and maintenance costs. However, there are still common challenges that need to be addressed.

One of the challenges is the lack of a unified big data platform for infrastructure. The data sharing among different disciplines and lines is not fully achieved, preventing the realization of a data-driven closed-loop business process. Furthermore, there is a lack of deep-level application and improvement of big data and AI technologies in traditional operations. The integration among different professional fields is relatively low, and the ability to address onsite issues is not prominent.

Overall, while progress has been made in the development of intelligent station operation and control management systems in Chinese cities, there is still room for improvement in terms of infrastructure integration, data sharing, and the application of advanced technologies to enhance traditional operations.

According to the results obtained from relevant technical literature, the following research has been conducted on intelligent subway operation and control management systems in China: Huo [1] focused on the comprehensive monitoring system as the main object of study and investigated the key aspects of intelligent development centered around the comprehensive monitoring system. This included data intelligence analysis and decision support, safety measures related to station operation scenarios, and structured timing data. Wang [2] provided an overview of parallel transportation management systems (PtMS), discussing the background, concepts, basic methods, major issues, and current applications of PtMS. Zhu [3] presented an approach and main ideas for building smart transportation systems in smart cities, specifically focusing on ACP (artificial system, computational experiment, and parallel execution)-based parallel transportation management and control systems (PTMS). Liu [4] studied the path and implementation methods for building intelligent subways, forming a set of con-

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struction and management methods for intelligent subways. Liu [5] discussed the necessity of intelligent subway development from economic background, technological advancements, and societal demands. They analyzed the characteristics of intelligent subways from multiple perspectives and proposed construction goals, system architecture, and implementation methods. They also explained the application of intelligent subways in Shanghai's rail transit system from the perspectives of construction, operation, and maintenance. Wei [6] focused on fundamental theoretical issues related to intelligent subways, such as the concept and content. They constructed a conceptual model for intelligent subways, summarized the essence and typical features of intelligent subways, and divided the development of intelligent subways into five stages based on the evolution of subway functions and collaboration methods. Based on this, they analyzed the application scenarios of intelligent subways from the perspectives of passenger travel, operation management, and equipment maintenance, and proposed functional planning with intelligent services, intelligent operation, intelligent maintenance, and intelligent management as core businesses, providing a theoretical foundation. Fu [7] expounds the overview of the smart subway system, introduces the overall structure of the smart subway system, and puts forward suggestions on the integration of application layer and function design of the smart subway system. Ling [8] focuses on the specific deployment and implementation of intelligent applications, including intelligent station management control system, intelligent transportation organization, intelligent train operation, intelligent operation and maintenance system, intelligent technology and equipment, intelligent energy management system, intelligent infrastructure management and intelligent network management. It also describes the application scheme of Changsha characteristic smart metro from the aspects of platform construction and the eight systems above. Changsha smart metro construction plan is implemented step by step according to short, medium and long-term, to build a cloud computing and big-data platform, and build a system framework of perception layer, processing layer and business layer. Chen [9] proposes to establish an intelligent subway operation system from four aspects: The automation of operation equipment, the intensification of management system, the three-dimensional data analysis and the intelligence of operation system, so as to effectively deal with the large passenger flow in the subway and ensure the efficient,safe and high-quality operation of the subway. Li [10] described the overall structure of the smart subway system and the interrelations and main contents of each level. Meanwhile,the consideration of large data fusion application in the subsequent smart subway construction is put forward. Fan [11] elaborated the structure, function, key technologies and difficulties of the smart station system. Cai [12] research focuses on data acquisition, data storage, data fusion functions and equipment interface of the smart station system. Pu [13] introduces the construction mode and functions of Shenzhen metro intelligent operation and maintenance platform. Chen [14] Illustrate the functions and implementation methods of various systems to achieve the purpose of building a modern and intelligent urban rail.

2 Features of digitalized IOCMS

2.1 Requirements of station electromechanical management system in China metro design standards

According to the design specification for the station electromechanical operation management system in the China metro design standards GB50157—2013, the following requirements are specified:

Metro stations should be equipped with a comprehensive monitoring system to meet the operational management needs of train dispatching, disaster prevention and safety, and passenger services. The comprehensive monitoring system should be composed of integrated and interconnected subsystems. It should integrate power monitoring, environmental and equipment monitoring, and platform door control systems into the comprehensive monitoring system. Additionally, it should be interconnected with systems such as broadcasting, video monitoring, passenger information system (PIS), clocks, automatic fare collection (AFC), access control system (ACS), and can also be interconnected with floodgate systems, communication alarm systems, and other monitoring systems.

2.2 Design and working mode of current mainstream station operation management systems in rail transit

Currently, the station operation management systems in various regions of China are centered around comprehensive monitoring systems. They have achieved deep integration (interface integration, software integration) with automation systems such as power supervisory control and data acquisition (PSCADA), fire alarm systems (FAS), and building automation systems (BAS). In addition, they have implemented hard-wired interlocking control or data transmission with the following systems and devices: public address (PA), Closed-circuit television (CCTV), automatic fare collection (AFC), and signaling (SIG) systems.

The triggering of integrated functions and interlocking control is determined by manual judgment. Once the conditions for interlocking are met, manual start/stop buttons are used to achieve interlocking control.

2.3 Analysis of current issues in station operation management systems

The current station operation management systems, with comprehensive monitoring as the interconnection platform, have high skill requirements for personnel, demand a large number of maintenance staff, and require various types of equipment. Due to the low integration level of data from different disciplines, management processes mainly rely on manual instructions, resulting in complex information dissemination hierarchies and processes within operating units. With the expansion of rail lines, different systems and equipment manufacturers bring about variations in operation and management, which increases the need for qualified personnel with corresponding skills. Additionally, there is a wide range of spare parts to be procured, leading to high costs in various aspects. Inadequate training in operation and management may also increase safety risks.

2.4 Key features of IOCMS

IOCMS features cloud, data, and intelligence characteristics. It is human-centered and driven by data. By utilizing big data technology and intelligent means, it models business scenarios, workflows, and work item models to reconstruct business and management systems. Through the synergy of “human intelligence” and “machine intelligence”, it enhances decision-making and coordination capabilities. IOCMS digitally identifies scenarios, enabling autonomous or collaborative decision-making, automatically matching dispatch personnel, and transitioning from device control automation to business scenario automation through continuous optimization.

IOCMS promotes deep integration of business, technology, and management, reshapes job responsibilities, optimizes and reshapes business processes, establishes an evaluation system guided by value and benefits, and effectively promotes the transformation of rail transit into an intelligent system through digital upgrades.

2.5 Differences between IOCMS and traditional rail transit integrated monitoring system

As shown in Table 1, the IOCMS and traditional rail transit systems exhibit significant differences in terms of system design, data integration degree, and operation management.

Table 1 Difference between IOCMS and traditional integrated monitoring system

Mode	System design	Data integration degree	Operation management
Single-point intelligent application mode	The product form relies on the specialty to realize the scattered intelligent application of partial optimization of discrete specialties	Data silos	Manual operation and independent operation of each discipline
Mode based on ISCS	Realize linkage control between system equipment	Limited data interconnection	Operation management of manual operation platform
Mode based on IOCMS	Realizes data-driven linkage between different professional system	Almost all professional system data of rail transit is fully integrated through data-driven linkage between different professional system	Man-machine cooperative operation management

3 Feasibility analysis of station business digitization upgrade

A step-by-step analysis of various types of station business in rail transit is conducted to explore the feasibility of digitization as a replacement for manual processes. A comparison is made between the investment costs and differences in effectiveness between system implementation and manual implementation. The feasibility of business function digitization transformation is evaluated from three aspects: economic viability, passenger satisfaction, and feasibility of implementation.

Through investigation and statistics, station business functions can be categorized into four major categories: passenger services, train safety, ticketing operations, and equipment management, totaling 71 items. Among them, 54 items, accounting for 76%, can be potentially enhanced or replaced through digitization, while 17 items, accounting for 24%, are difficult to replace.

Based on investigation and analysis, it can be concluded that adopting a new model that combines the "IOCMS as the core" with supplementary human collaboration is more reasonable for station business.

4 IOCMS architecture design

The architecture of IOCMS includes intelligent station platform,intelligent network platform. Carry out overall scheduling for the services of stations, lines and line networks respectively. Fig. 1 illustrates IOCMS physical architecture. The platform adopts the direct full control mode of equipment and systems, and supports more agile and efficient modeling intelligent linkage. Among them, the smart station platform is interconnected with station-level AFC, PSD, SIG, FAS, CCTV, PA, passenger information system (PIS), integrated supervisory control system (ISCS), power supply system, escalator, and other systems to achieve station data aggregation. The smart line platform is interconnected with the smart station platform to realize the convergence of line data and realize the intelligent application at the line level. The line network platform is interconnected with the line platform to realize the convergence of line data and realize the intelligent application at the line network level. The software architecture design of IOCMS is illustrated in Fig. 2.

5 Research on key technologies of the IOCMS

5.1 Lightweight video analysis technology

Video analysis technology is the fundamental technology for IOCMS. The result of video analysis provides input conditions for other modules of the intelligent platform and serves as a key foundation for scene recognition and judgment.

Video analysis is directly based on image classification. For the recognition of specific scenes, convolutional neural networks are used to extract image features, and the model parameters are gradually optimized using classification loss functions to reduce detection errors. From the initial seven-layer AlexNet to the 16-layer VGG16, 19-layer VGG19, and 22-layer GoogleNet, as well as deep learning network models like ResNet and DenseNet with thousands of layers, recognition accuracy improves as the depth of the model increases. This model is deployed on the server of the online network and station IOCMS. However, this model has some issues, such as the presence of a large number of redundant parameters and high memory consumption, resulting in high latency during inference. Therefore, it is not suitable for deployment on mobile devices.

Key improvement: To improve efficiency and reduce recognition response latency on mobile devices, lightweight network models based on image segmentation are used to classify objects at the

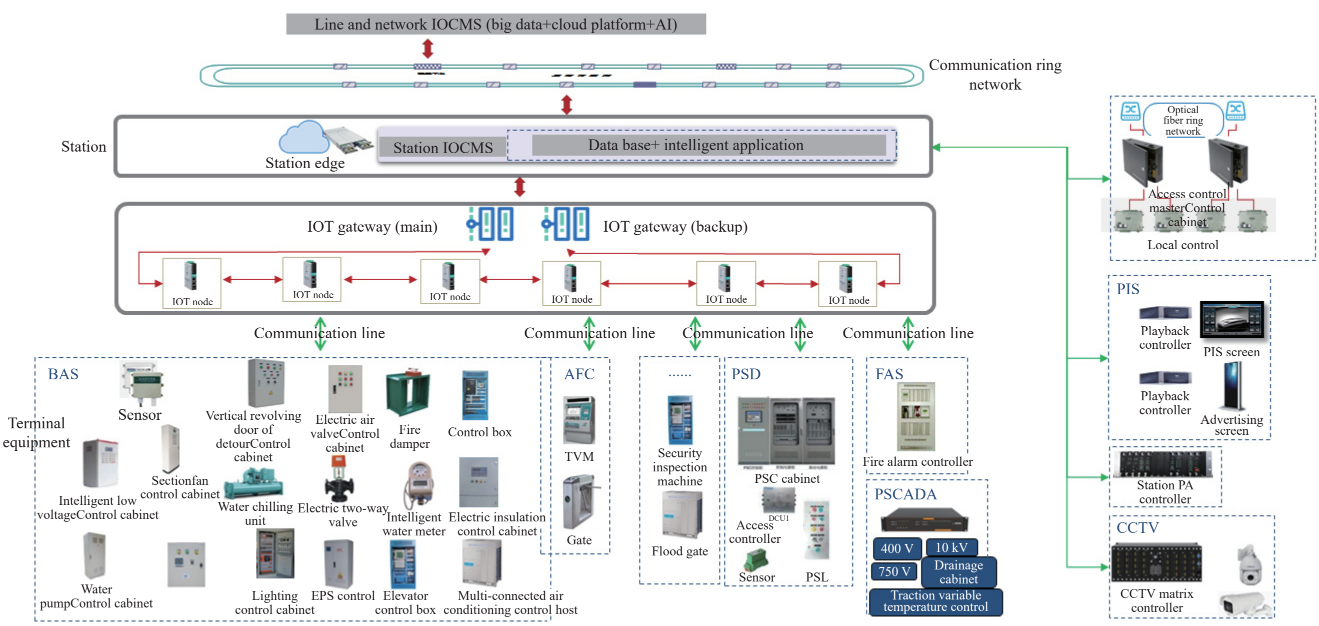

Fig. 1 IOCMS physical architecture

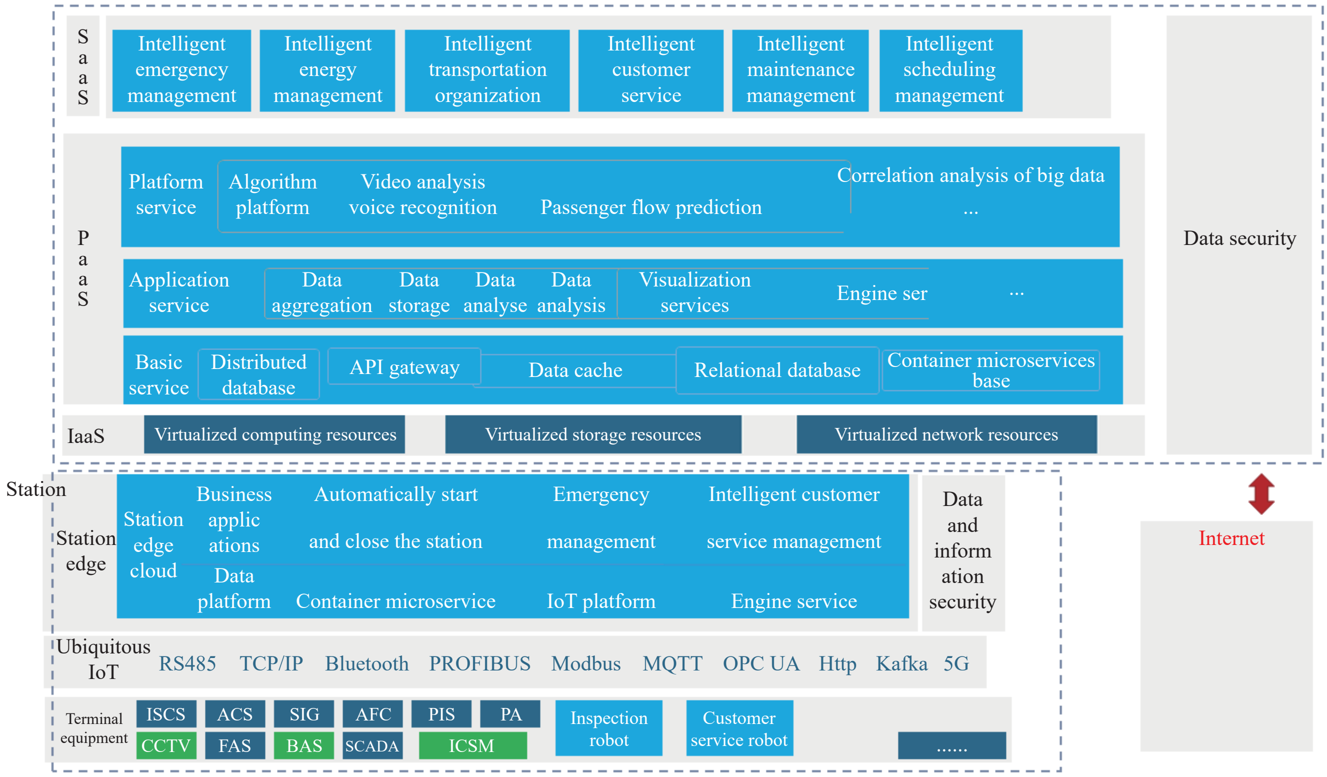

Fig. 2 IOCMS software architecture

level of feature maps.

5.2 Research on big data

The IOCMS is built on a unified big data digital foundation, establishing a business application system. The digital foundation provides an open, iterative, and reusable technical support system for the digitalization of urban rail transit. It includes the intelligent application unified digital foundation, which adopts a microservices architecture. It supports technologies such as DevOps, containers, and cloud-native, providing common Internet of Things (IoT), microservices, database, algorithm services, business services, general services, and development services for intelligent applications. It also supports software-defined business optimization and restructuring.

The big data platform consists of hardware resources, basic support software for big data, foundational support platforms, and business applications. The platform utilizes the foundational data services platform of big data technology to provide comprehensive data services such as data aggregation, fusion governance, storage, computation, analysis for the safety production network, internal management network, and external service network. It establishes a unified foundational management platform for resource sharing, business and data governance. The big data platform provides technical support and service capabilities to different business application systems, empowering upper-level big data applications.

The data source layer, based on the content of three network domains, organizes the application system composition and data content at the granularity of individual application systems. It analyzes and compiles data exchange situations of various application systems to generate a comprehensive inventory of urban rail transit data assets.

The integration layer uses the combination of various monitorable data techniques such as message queues, stream computing, structured data synchronization and extract-transform-load (ETL) to meet the needs of data integration and processing in different business scenarios. The data integration layer is responsible for functions such as data collection, cleansing, transformation, and loading from source systems. The big data platform collects data from source systems through database interfaces, file interfaces, or other interfaces. After cleansing and transformation, the collected data is loaded into the data storage layer for data integration.

The data storage layer adopts hybrid storage technologies to support massive data. Different data storage technologies are applied to meet the storage requirements of structured, semi-structured, and unstructured data. The data storage layer integrates and consolidates data in the big data platform after the data has been preprocessed by the data integration layer. Once various types of data are loaded into the big data platform, data integration is performed within the database through processing programs, generating storage for the foundational data layer. Following the principles of hierarchical data modeling, data is consolidated within the database to generate storage for the summary data layer. Subsequently, based on application needs, data is organized into topic-based storage for the application data layer, supporting various types of applications and functions in rail transit data analysis systems.

The application support layer is responsible for processing, managing, and correlating internal and external data resources within urban rail transit systems. It provides a range of service capabilities to the data application layer, including data computation, retrieval, and mining, all tailored to specific application scenarios. This layer lays the groundwork for the data application layer, which gradually develops domain-specific data application scenarios, supported by a unified framework for data exchange and integration from an industry-wide perspective.

The data application layer is dedicated to the continuous development of various business applications. This development typically involves the creation of decision support systems, business analysis systems, expert systems, and other specialized systems. At its foundation, the data application layer encompasses indicator systems, thematic analysis, business simulations, and other application types. In the subway industry, indicator systems commonly track operational and management metrics. Thematic analysis of-

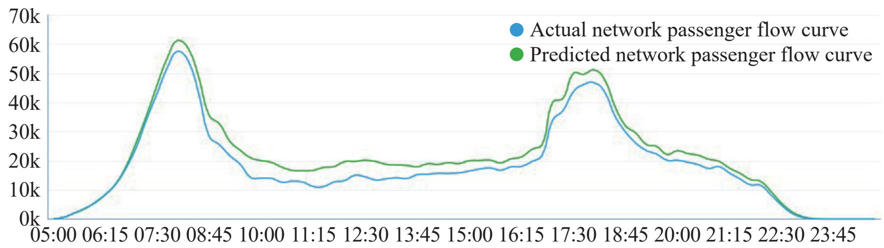

Fig. 3 Comparison between actual and predicted passenger flow

ten includes passenger flow Origin-Destination (OD) analysis, capacity matching analysis, historical passenger flow distribution analysis, and train connection query analysis. Business simulations may involve network operation simulations and passenger flow predictions. These applications are gradually being developed and expanded.

The data stored in the big data platform is time-sensitive, with information stored in chronological order. Strong real-time status information for all devices requires high-performance data writing capabilities, which traditional relational databases cannot provide. Therefore, it is essential to use timestamps as markers within time-based data structures to efficiently store and process historical data.

5.3 Research on some key algorithms

Passenger flow prediction is a core function of the IOCMS, providing curtail data support for station management, energy management, transportation organization, and emergency and maintenance management. The accuracy of these predictions directly impacts the overall effectiveness of the IOCMS. Presented below are several passenger flow prediction scenarios and algorithms that have demonstrated strong practical results.

Short-term passenger flow prediction in rail transit networks: This model utilizes historical data analysis and fractal interpolation. It is trained by known historical passenger flow data to predict the minutely passenger flow for a future period. Based on the findings of this research project, the actual prediction performance of the short-term passenger flow prediction model is shown in Fig. 3.

Passenger flow Predicting in anticipated high volume situations: This model quickly predicts the distribution of OD volume across the entire network using a passenger flow allocation model. An improved gravity model is commonly used for this purpose.

Holiday passenger flow prediction: This model is based on historical passenger flow data and uses a combination of historical data analysis and exponential smoothing to make predictions.

6 Innovative business of IOCMS

6.1 Intelligent scheduling management and station management

By analyzing various business scenarios during the 24 h operation of rail transit, IOCMS identifies detailed operational processes and manual tasks based on time axis. It establishes corresponding scenario models that include scenario control flows, control algorithms, task labels, and employee skill labels. The system assigns skill labels and estimates task durations for station staff, creating a profile of their abilities. With real-time situational awareness, the system analyzes and calculates based on the corresponding scenario models. It utilizes model algorithms to optimize the matching process considering factors such as task labels, employee skill labels, staff locations, equipment status, and priorities. It enables autonomous decision-making or human-machine collaborative control, issuing work scheduling instructions and achieving automated flow of business processes. Through data accumulation and intelligent upgrades, the system continuously optimizes and reconstructs business processes, reducing workload.

6.2 Intelligent energy management

IOCMS prioritizes passenger needs while integrating environmental control, train operations, and energy management to develop comprehensive energy-saving strategies that align with passenger flow patterns and operational maintenance. Intelligent energy management within the system is grounded in the principles of 'data collection, quality analysis, model development, and strategy generation.' By gathering data on both traction and non-traction energy consumption, the system enables comprehensive energy monitoring, indicator analysis, and energy consumption forecasting, supporting refined energy management. Furthermore, IOCMS explores energy cost quota management systems and establishes energy-saving standards, driving the adoption of innovative operational management models.

IOCMS formulates intelligent energy-saving strategies that include:

(1) Load prediction: By analyzing passenger flow and meteorological data, it predicts future air conditioning loads and intelligently regulates equipment such as air conditioning and lighting.

(2) Optimal operation parameters: Utilizing simulation models of various electromechanical equipment, it identifies the optimal operating parameters under current system conditions.

(3) Automatic train operation curve optimization: By optimizing the calculation of transition points between train operating conditions—traction, cruising, coasting, and braking, it selects the most efficient operating conditions and target speeds, generating energy-saving train trajectories that minimize energy consumption within a given travel time.

(4) Multi-train timetable optimization: By applying rules for the absorption of regenerative energy between different trains — it balances the optimization of train energy consumption and regenerative braking energy, reducing overall substation energy consumption and maximizing the utilization of regenerative braking energy.

(5) Other energy-saving strategies: Based on passenger flow patterns and trends, it implements strategies such as mixed train formations and flexible routing to reduce the number of trains in operation, achieving energy-efficient operations.

Enhancement of green travel service system: It optimizes integration with urban transportation and deepens the synergy with intelligent and diversified operations to provide convenient travel and lifestyle services. This approach encourages more passengers to choose rail transit, thereby reducing overall societal energy consumption.

6.3 Intelligent transportation organization

IOCMS establishes a coupling relationship between traffic flow, passenger flow, equipment flow, and information flow, driven by data to provide intelligent assistance for scheduling. This includes intelligent timetable compilation, operational capacity analysis, operation adjustments, and emergency command, all aimed at enhancing the resilience of the rail network operations. The system's goal is to achieve energy-efficient operations while ensuring fast and stable travel services for passengers.

6.4 Intelligent customer service

IOCMS offers a range of features designed to enhance customer service and improve the overall passenger experience. These features include popular station displays, intelligent ticketing with self-service options, and intelligent route guidance for both station navigation and journey planning. Additionally, the system offers one-touch call buttons, enabling passengers to easily contact station staff for any assistance.

6.5 Intelligent emergency management

IOCMS pays high attention to both passenger safety and operational safety. It establishes a comprehensive safety system which covers pre-event, in-event, and post-event scenarios. By integrating multiple sources of information and utilizing intelligent decision-making capabilities, IOCMS supports the dispatch personnel on risk identification, risk prediction, and decision making, enabling the dispatch to effectively handle risks and minimize losses, ensuring the safety and well-being of passengers.

6.6 Intelligent maintenance management

Intelligent maintenance management leverages advanced artificial intelligence technology to develop a new system for real-time evaluation and prediction of equipment status, with a professional knowledge graph at its core. By intelligently analyzing equipment logs using a semi-supervised time-series knowledge graph, the system significantly reduces the manpower and time required for maintenance

7 Conclusions

After implementing IOCMS in actual station pilot projects, the majority of station operational tasks, such as passenger services, operational safety, ticketing operations, and equipment management, can be replaced by the system, leading to the formation of a highly self-service-oriented business model with "intelligent system as the core + human collaboration as a supplement".

IOCMS promotes further consolidation of station positions, optimizing the configuration to include "one supervisor + several administrators", and defining new roles to reduce the demand for station personnel. At the same time, it facilitates the development of localized general technical positions and centralized professional technical positions: routine inspection and simple fault handling tasks are assigned to station-level personnel, while specialized maintenance and intelligent maintenance tasks are handled by the IOCMS and technical experts. IOCMS fosters a new management approach of "job integration and business intensification", resulting in a reduction of approximately 40% in the number of station personnel. Overall, energy consumption is reduced by approximately 5%.

In conclusion, IOCMS aims to achieve proactive passenger service, automated station operations, accurate passenger flow prediction, and Breakdown forecast and fault prognosis. Additionally, IOCMS needs to establish a new construction and operational management workflow that is adapted to the new technological framework. This represents a systematic and profound revolution to the rail transit industry. The scope of this transformation is extensive and requires continuous research and enrichment through practical implementation by rail transit companies. The rail transit industry will embrace new opportunities and challenges through digital upgrading.

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Author contribution statement

Jiabin Zhu: conceptualization, data curation, methodology, software, writing draft, writing-review, investigation.

Data availability statement

Data can be accessed upon reasonable request from the corresponding author at zhujiabin2200023@163.com

Use of AI statement

During the preparation of this research, I did not use AI to improve grammar and readability. I reviewed and edited the content as needed and take full responsibility for content of the publication.

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