

# ***Analysis of the Application and Prospects of Intelligent Technology in Sustainable Railway Operations***

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**Abstract:** With the rapid development of technology, intelligent technology plays an increasingly important role in the sustainable operation of railways. This paper explores the application and prospects of intelligent technology in sustainable railway operations, emphasizing its key roles in enhancing operational efficiency, strengthening safety assurance, optimizing passenger experience, and promoting environmental protection and energy conservation. Through intelligent dispatching, real-time monitoring, big data prediction, personalized services, and mobile ticketing technologies, the railway system achieves efficient resource allocation and service innovation. The intelligent transformation of railways demonstrates significant economic and social benefits, contributing to emission reduction targets and sustainable development. Future efforts should focus on strengthening top-level design, technological innovation, standard construction, and network security to advance the intelligent railway process and co-create a new era of smart, green, and efficient railway transportation.

**Keywords:** Intelligent Technology, Railway Operations, Sustainable Development, Prospects Analysis.

## **1. Introduction**

In today's society, railways, as an essential mode of transportation, play a significant role in the economic development of a country and the lives of its people. The introduction of intelligent technology brings new opportunities for the sustainable operation of the railway industry. This paper aims to analyze the specific applications of intelligent technology in railway operations and its role in promoting sustainable railway development.

## **2. Application of Intelligent Technology in Railway Operation Management**

### **2.1. Construction and Optimization of Intelligent Dispatch Systems**

The construction and optimization of intelligent dispatch systems are crucial for achieving sustainable railway operations, directly related to the economic, environmental, and social dimensions of sustainability. Economic Sustainability: By integrating advanced algorithms and real-time data processing capabilities, intelligent dispatch systems can accurately predict passenger and freight transport demand, optimize train schedules and formations, reduce empty runs, and increase

transportation efficiency and capacity, thus enhancing revenue and reducing costs, bringing direct economic benefits to railway operators [1]. Environmental Sustainability: The system effectively controls energy consumption and reduces carbon emissions by minimizing ineffective operations and waiting times, promoting the development of green and low-carbon transportation modes. Social Sustainability: Intelligent dispatch ensures the stability and reliability of transportation services, reducing delays and cancellations, enhancing public travel satisfaction. It also efficiently allocates transportation capacity, enabling quick responses in emergencies, ensuring the timely transport of disaster relief, medical supplies, and other societal goods, thereby increasing the resilience of the social system.

## **2.2. Application of Real-Time Monitoring and Data Analysis in Railway Operations and Maintenance**

In railway operations and maintenance management, the application of intelligent technology is mainly reflected in the real-time monitoring and fault prediction of key infrastructure and equipment. IoT (Internet of Things) sensors are widely deployed on critical components such as tracks, signaling systems, bridges, tunnels, and vehicles to continuously collect vast amounts of operational data. This data is transmitted via high-speed communication networks to a central data analysis platform, where big data analytics and machine learning technologies are used for in-depth analysis. This enables the timely detection of potential faults and prediction of maintenance needs, transforming maintenance from reactive to proactive. For example, monitoring bearing conditions through vibration spectrum analysis can identify early signs of wear, preventing safety accidents and large-scale operational disruptions due to equipment failures. Additionally, this real-time monitoring mechanism provides a scientific basis for the lifecycle management of railway assets, helping to optimize maintenance schedules, extend equipment life, and reduce maintenance costs.

## **2.3. Big Data-Based Railway Passenger Demand Forecasting and Management**

In railway passenger management, big data-based predictive analysis is key to improving operational efficiency and service quality. For passenger flow prediction, models such as Auto-Regressive Integrated Moving Average (ARIMA) and Long Short-Term Memory (LSTM) networks effectively capture the complex dynamic patterns of passenger volume over time, including holiday effects, and differences between weekdays and weekends [2]. These models learn periodic, trending, and random fluctuations from historical data to accurately forecast passenger flow for specific future periods, providing scientific support for train scheduling, ticketing management, and station resource allocation. For freight volume forecasting, understanding logistics demand patterns and considering external economic factors are more critical. Multiple linear regression analysis evaluates various factors (economic growth rate, industrial output, commodity prices, etc.) impacting freight demand, while machine learning models such as decision trees and random forests handle nonlinear relationships and complex interactions between variables. These models exhibit higher predictive accuracy, especially in addressing seasonal fluctuations and sudden changes in freight demand due to unforeseen events. Data visualization technologies play a crucial role in this process. Using professional tools like Tableau and Power BI, statistical results are transformed into intuitive charts and dashboards, allowing managers and decision-makers to quickly understand forecast outcomes and promptly identify trend changes and anomalies.

### **3. Practice of Intelligent Technology in Railway Safety Assurance**

#### **3.1. Core Role of Intelligent Dispatch in Railway Safety**

The intelligent dispatch system is a critical component of railway safety assurance. By integrating advanced information technology and artificial intelligence algorithms, it not only enhances operational efficiency but also builds a solid defense line for railway safety. Take China's CTC (Centrally Controlled Train Operation) system as an example. This system collects diverse real-time data on train positions, speeds, track conditions, and weather. Through big data analysis and machine learning models, it achieves centralized monitoring and intelligent dispatching of the national railway network. The CTC system can automatically avoid potential conflicts, optimize train paths, and reduce human errors, significantly lowering the risks of train collisions and derailments. During the 2021 Spring Festival, facing the dual challenges of surging passenger demand and harsh winter weather, the CTC system successfully dispatched over ten million train operations without any major safety incidents, ensuring the safety and smoothness of railway transportation during the festival [3]. This case fully demonstrates that the intelligent dispatch system can accurately predict and flexibly adjust to ensure railway safety.

#### **3.2. IoT-Based Railway Equipment Status Monitoring and Warning System**

The IoT-based railway equipment status monitoring system installs various sensors on critical equipment to collect real-time physical parameters such as temperature, vibration, and stress. Combined with wireless communication technology, this forms a vast data collection and analysis network. This system utilizes cloud computing platforms to process massive monitoring data and employs advanced analytical algorithms like pattern recognition and anomaly detection to assess equipment health in real-time and identify potential faults in advance. For instance, it precisely monitors minor cracks in rails and the wear levels of turnouts. Once abnormal parameters are detected, it immediately triggers warning signals, guiding maintenance personnel to intervene promptly and prevent faults from escalating into safety incidents. This predictive maintenance model greatly improves maintenance efficiency, reduces operational disruptions caused by equipment failures, and ensures the continuity and safety of railway transportation.

#### **3.3. Role of Artificial Intelligence in Railway Accident Prevention and Emergency Response**

Artificial intelligence technology shows great potential in railway accident prevention and emergency response. By integrating historical accident data, environmental data, and real-time monitoring information, AI establishes complex event prediction models that can forecast potential accident types, times, and locations, providing a scientific basis for preventive measures. For example, by analyzing past train derailment incidents, AI can identify risk factors highly associated with accidents, such as track irregularities and overspeeding, and thus guide the formulation of targeted prevention strategies. In the event of an accident, the AI system can quickly initiate emergency plans, automatically dispatching rescue resources based on the accident site situation, including the nearest rescue teams, medical facilities, and material supplies. It also provides the command center with the best evacuation routes and rescue plans to minimize casualties and property losses [4]. Furthermore, AI-assisted voice recognition and natural language processing technologies can quickly process passenger distress information in emergencies, enhancing the accuracy and timeliness of emergency responses and ensuring passenger safety.

## **4. Enhancement of Passenger Experience through Intelligent Technology**

### **4.1. Promotion and Application of Intelligent Service Facilities in Railway Stations**

With the continuous advancement of intelligent technology, railway stations are gradually transforming into smart transportation hubs. The widespread application of intelligent facilities such as self-service terminals, intelligent navigation robots, and virtual reality (VR) information query systems has greatly enhanced passenger convenience. Self-service terminals integrate functions like ticket purchase, changes, cancellations, and information queries, supporting various interactive methods such as facial recognition and electronic payment, significantly reducing passenger waiting times. Intelligent navigation robots use voice recognition and natural language processing technologies to provide precise station navigation, train information queries, and travel advice services. This is especially valuable for first-time railway users or foreign travelers, offering personalized guidance. Additionally, some stations have introduced VR technology, allowing passengers to virtually experience train layouts and view scenery along the route, adding enjoyment and anticipation to the journey and reflecting the human-centered care of railway services.

### **4.2. Implementation and Exploration of Personalized Services in Railway Passenger Transport**

Personalized services based on big data analysis are gradually becoming the new norm in railway passenger transport. Railway companies integrate data from passengers' ticket purchase history, travel preferences, and social media behavior to build personalized service models and provide customized travel plans [5]. The "TGVmax" service launched by the French National Railway Company (SNCF) is a successful exploration and practice of personalized services in the field of railway passenger transport. This service is specifically designed for young travelers aged 16 to 27. By analyzing passengers' travel habits and preferences through big data, it offers an innovative monthly subscription travel model. Users pay a fixed monthly fee and can take unlimited rides on TGV high-speed trains within a certain period, enjoying the flexibility and freedom of travel. Additionally, China Railway Corporation, through its "Railway 12306" APP, collects and analyzes billions of user data to provide personalized services throughout the entire travel process, from ticket purchase to journey. Based on passengers' historical behavior and preferences, the application intelligently recommends train services, seat types, and offers personalized travel assistant services. For example, it notifies passengers to bring rain gear based on weather forecasts or recommends tourist attractions along the route based on passengers' interests, greatly enhancing the travel experience.

### **4.3. Innovative Applications of Mobile Internet Technology in Railway Ticketing Services**

The deep integration of mobile internet technology has completely transformed the traditional landscape of railway ticketing services. Online channels such as mobile apps, WeChat mini-programs, and official websites have become mainstream methods for ticket purchases, supporting 24/7, cross-regional instant booking and payment. Utilizing cloud computing and big data analysis, the railway ticketing system can dynamically adjust fare strategies and introduce features like early bird tickets, surplus ticket reminders, and standby ticket purchases. These measures alleviate the difficulty of purchasing tickets during peak periods and increase seat utilization rates. Particularly, the standby ticket service allows passengers to register for a waitlist when tickets are sold out. The system automatically monitors for cancellations and issues tickets to passengers as soon as they become available, significantly improving the success rate of ticket purchases. Furthermore, mobile ticketing has achieved the widespread adoption of electronic tickets. Passengers no longer need to print paper

tickets; instead, they can complete the entire boarding process with their ID and a mobile QR code, simplifying procedures, reducing costs, and aligning with environmental trends. These innovative applications not only enhance service efficiency but also offer passengers the convenience of “fingertip service,” realizing the dream of “traveling at the spur of the moment.”

## **5. Prospects of Intelligent Technology Promoting Sustainable Development in Railways**

### **5.1. Potential of Intelligent Technology in Energy Conservation, Emission Reduction, and Environmental Protection**

The application of intelligent technology in the railway sector significantly contributes to energy conservation, emission reduction, and environmental protection. Firstly, by optimizing train operation control and dispatch systems, it enables precise management of train operations, reducing unnecessary acceleration, deceleration, and waiting times, thereby lowering energy consumption. For instance, using artificial intelligence algorithms to predict passenger flow distribution, optimize train formation, and operational plans can prevent empty and inefficient runs, effectively saving energy. Secondly, intelligent monitoring and maintenance systems can accurately grasp the status of vehicles and infrastructure, ensuring efficient operation and reducing energy waste due to faults [6]. Furthermore, intelligent energy management systems deployed along railway lines can adjust power supply based on actual demand, achieving efficient utilization of electrical energy. Additionally, through big data analysis, railway departments can better plan transportation structures and promote the development of multimodal transport, further enhancing the energy efficiency of the overall transportation system. In terms of environmental protection, intelligent monitoring systems provide real-time monitoring of environmental indicators such as noise and emissions, ensuring that the impact of railway operations on the surrounding environment is minimized, highlighting the green advantages of railway transportation.

### **5.2. Economic and Social Benefits of Intelligent Railway Transformation and Upgrading**

Intelligent railway transformation is a comprehensive and large-scale investment project, but its long-term economic and social benefits are evident. From an economic perspective, intelligent transformation enhances operational efficiency and reduces energy consumption, directly lowering operating costs. Efficient scheduling and maintenance reduce train delays and outages, improve transportation capacity and service quality, attract more passenger and freight demand, and increase revenue sources. At the same time, innovative applications such as intelligent ticketing and personalized services enhance customer loyalty, expand value-added business opportunities, and further improve profitability. In terms of social benefits, intelligent railways can respond more flexibly to emergencies such as natural disasters and public health incidents, ensuring the rapid transport of essential supplies and orderly evacuation of people, thereby maintaining social stability. Additionally, the environmental attributes of intelligent railways are crucial for reducing greenhouse gas emissions, improving urban air quality, and promoting ecological civilization construction, reflecting the social responsibility and public value of railways as a mode of public transportation.

### **5.3. Strategies and Recommendations for Future Railway Intelligent Development**

Looking ahead, the development of railway intelligence should follow these strategies and recommendations: Firstly, strengthen top-level design by creating a comprehensive intelligent development plan that clarifies short-term goals and long-term visions, ensuring continuity and coordination in technological updates and industrial upgrades. Secondly, deepen industry-academia-research collaboration by encouraging technological innovation and application demonstrations,

accelerating the integration and transformation of key technologies such as artificial intelligence, the Internet of Things, and 5G communication in the railway field. Thirdly, promote standardization by establishing a comprehensive system of standards related to railway intelligence, ensuring information sharing and interoperability between different systems, laying the foundation for large-scale implementation. Fourthly, emphasize talent cultivation and knowledge updating by enhancing the ability of railway industry professionals to apply intelligent technology through education and training, building a professional team that meets future demands. Fifthly, strengthen cybersecurity protection. As the level of railway system intelligence deepens, information security becomes a critical issue. It is necessary to establish a robust security protection system to ensure the safety and reliability of data and systems.

## 6. Conclusion

Intelligent technology is profoundly transforming every aspect of railway operations, significantly enhancing transportation efficiency and safety levels, and greatly enriching the passenger experience, showcasing the unique charm of railways as a green mode of transportation. Looking to the future, the railway industry should continue to delve into the application and innovation of intelligent technology, embracing the themes of energy conservation, emission reduction, and environmental protection, and fully harnessing its potential in economic and social benefits. Through continuous strategic planning and practical exploration, it is believed that railways will embrace a new chapter of safer, more efficient, greener, and more harmonious development in the wave of intelligence, contributing indispensable strength to global sustainable development goals.

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