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Intelligent Technologies for Urban Rail Transit Emergency Management

Zeyuan Zhao

Joint Jiaotong College of Beijing Union University & Russian University of Transport, Beijing Union University, Beijing, China
z532346629@gmail.com

Abstract. With the increasing urban rail transit network and the closer connection among operational subsystems, the potential influence range and management difficulty of emergencies have greatly increased. The current emergency management based on traditional methods has some shortcomings in real-time risk recognition, integration of multi-source information and cross-departmental collaborative decision-making. By integrating a comprehensive literature survey with typical case analyses, this paper investigates the use of Internet of Things (IoT), big data, artificial intelligence (AI) and digital twins (DTs) in urban rail transit emergency management. The research is carried out from three main aspects: risk monitoring and early warning, emergency decision-making and collaborative response, and passenger evacuation and operation recovery. The results show that intelligent techniques offer assistance in the monitoring of operational status, anomaly detection, emergency information exchange and evaluation of evacuation plans, which can effectively improve the processing efficiency of information and the supportive ability in decision-making. However, at present, the actual implementations are limited by insufficient data sharing between different systems, restricted model generalization, lack of validation in practical operational situations, and network and data security risks. In the future, more efforts should be made to standardize multi-source data and sharing mechanisms, strengthen the validation of intelligent models and DT systems under real operational conditions, and optimize human-in-the-loop collaborative decision-making to improve the reliability and practicability of intelligent technologies in urban rail transit emergency management.

Keywords: urban rail transit, intelligent emergency management, risk monitoring and early warning, collaborative response, digital twin

1. Introduction

Due to the continuous development of urbanization and the increasing public transportation needs, urban rail transit systems have changed from single line operations to large network operations. The train operations, station services, communication and signaling, and power systems are closely connected; therefore, events like equipment failure, fire, sudden increase in passengers, heavy rain, flooding and service interruption may affect the stations, lines and even the whole transit network.

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The traditional emergency management in urban rail transit mainly relies on manual inspection, fixed threshold alarms and step-by-step reporting at different levels. In complicated emergencies, this method generally has problems such as late collection of operational data, lack of effective information exchange between different systems, insufficient ability to identify dynamic risks and low collaborative response efficiency. Thus, it is an important research field to use intelligent technology to improve the awareness of operational status, risk identification and emergency response abilities in urban rail transit operation safety management.

In recent years, the Internet of Things (IoT), big data, artificial intelligence (AI) and digital twins (DTs) have been extensively used in the operation and safety management of urban rail transit. The IoT and multi-source sensing techniques can acquire the train operation data, equipment status, station environment and passenger flow dynamics, thereby forming a reliable data foundation for the anomaly detection. Some previous work has adopted IoT sensing and image recognition algorithms to automatically recognize the abnormal behaviors and emergencies in the transfer area of urban rail transit stations [1]. By extending these sensing functions, big data analysis and AI methods can also be used for identifying operational anomalies, forecasting risks and assisting in decision-making. Moreover, by integrating WebGIS, building information modeling and real-time monitoring streams, virtual operation environments can be set up to support the infrastructure condition monitoring, fire dynamic simulation and evaluation of emergency evacuation plans [2]. This progress indicates that many intelligent technologies have been applied at various stages of urban rail transit emergency management, offering new techniques for the real-time monitoring, risk analysis and plan evaluation. Nevertheless, the current research focuses mainly on individual problems, such as the detection of particular equipment failures, local passenger flow prediction, fire simulation and single-station evacuations. The connections among these technologies and their comprehensive impacts during each emergency process are not clearly known. Especially, systematic investigations and integrations concerning cross-system data exchange, joint decisions made by multiple organizations and long-term verifications in practical operating conditions are still lacking.

This paper gives a systematic study on the applications of intelligent technologies in urban rail transit emergency management. Firstly, the usual emergency situations and their related managing needs are introduced, then an introduction to the main technologies such as IoT, multi-source sensing, big data, AI and DTs is given. Afterwards, the detailed applications of these intelligent technologies are examined in three main stages: risk observation and early warning, emergency decision-making and cooperative handling, and passenger evacuation and service recovery, by examining some typical engineering examples to evaluate their practicality and operational limitations. Finally, the main problems concerning data interchangeability, model reliability, field operation verification and cyber-physical security are summarized, and possible developments of intelligent technologies in urban rail transit emergency management are discussed.

2. Fundamentals of intelligent emergency management

2.1. Types of emergencies and management requirements

Urban rail transit includes several subsystems such as rolling stock, traction power supply, communication and signaling, and station operations. These subsystems are mutually related; therefore, emergencies may cause a series of disturbances in line operations and affect the safety of passengers. The common emergencies mainly include failures of equipment and systems, public safety accidents like fires, sudden increases in passenger traffic, natural disasters such as heavy rainstorms and floods, and resulting disruptions in operation.

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Traditional emergency management in urban rail transit mainly depends on manual checks, fixed threshold alarms and step-by-step reporting systems. In complicated emergencies, this method usually experiences the delay of data acquisition, the shortage of interdepartmental information exchange and the restriction of decision-making speed [3]. With the expansion of rail transit networks and the increase of operating environment complexity, emergency management should further improve its abilities in recognizing operational status, identifying risks, making quick decisions and cooperative responses, and should also balance the passenger evacuation and operational recovery in a systematic way. Therefore, the use of intelligent techniques to enhance the efficiency of data collection and processing has become an important development trend for urban rail transit emergency management.

2.2. Key intelligent technologies

Intelligent emergency management for urban rail transit is mainly based on the technologies like the Internet of Things (IoT), multi-source sensing, big data analysis, AI and DTs and simulation. The IoT and multi-source sensing technologies collect data from roadside sensors, onboard inspection units, video monitoring and automatic fare collection systems to continuously observe the trains, machinery, station conditions and passenger flow changes. Moreover, the progress in relevant communication techniques enhances the transmission rate among various devices and systems, providing a strong data basis for prompt identification of emergencies [4].

Big data analysis is used to combine the operation information from different business systems, which is beneficial for a thorough investigation of the equipment failures, changes in the passenger numbers and past accident records. In this situation, artificial intelligence methods can be applied to identify the abnormal conditions, predict the risks, classify the accidents and give decision support. By processing the various data sources, intelligent models assist the operation personnel in finding the concealed risk patterns from a great amount of real-time telemetry data, thus increasing the speed of the emergency evaluation and decision-making. Moreover, the joint use of resources at several levels such as the end user, edge and cloud can allocate the adjustable computing power according to the different latency requirements, offering technical help for the urgent emergency operations [5].

Digital twin and simulation techniques are mainly applied to build virtual operational copies of stations, lines or transit networks, simulating emergency situations and their subsequent effects in virtual environments. For instance, crowd simulation can assess the passenger evacuation processes under various operating methods, and network-level traffic simulation can depict the spreading influences of train adjustment schemes during line disturbances. Consequently, these techniques offer quantitative analysis assistance for emergency plan assessment, scheme comparison and operational recovery.

2.3. Intelligent emergency management framework

Intelligent technologies can be used throughout the whole lifecycle of urban rail transit emergency management. Before an incident occurs, multi-source sensing and artificial intelligence algorithms monitor the status of the equipment, the surrounding conditions and the passenger density to detect possible abnormal situations and early risks. After an incident, big data analysis, intelligent models and DT platforms help the operation staff with the incident evaluation, scenario choice and joint response. During and after the emergency, simulation and optimization techniques assist in passenger evacuation, train re-scheduling and the overall restoration of operations. Instead of

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working separately, these technologies are connected by continuous data exchange and closed-loop feedback, cooperating to support the whole process of urban rail transit emergency management.

3. Applications of intelligent technologies and case studies

3.1. Risk monitoring and early warning

Risk monitoring and early warning are important parts of the emergency management in urban rail transit, mainly dealing with the rapid identification of risks like equipment failures, fires, crowds and rainstorms and floods. In complicated operational situations, the traditional manual inspections and the fixed threshold alarms usually have a narrow monitoring range, late anomaly discovery and a hard time recognizing the changing risks. With the progress of the Internet of Things (IoT), multi-source sensing and artificial intelligence (AI), information about the equipment condition, station environment, passenger numbers and weather conditions can be collected and analyzed continuously, which gives strong information assistance for anomaly detection and risk early warning. Some previous works have used data diffusion models and spiking neural networks to forecast the fire conditions in rail transit systems, obtaining high recognition accuracy on experimental data sets and showing the feasibility of AI algorithms in assisting the dynamic fire monitoring and early warning [6].

By taking the development of the digitized and intelligent subway safety emergency assurance system in Ningbo Rail Transit as an instance, this platform combines various kinds of data, such as hydrological, meteorological and field sensor information, with DTs, geographic information systems and building information modeling to deal with the operational conditions and safety risks of the subway [7]. The system includes functions like daily safety inspection, emergency resources management, emergency plans formulation and command dispatch, concentrating mainly on three emergency situations: fire, flood prevention and passenger crowding [7]. This research shows that integrating the heterogeneous operational and environmental data onto one unified digital platform enables the operation managers to have a clear knowledge of the risk conditions and provides strong information assistance for the emergency alarms and the following responses.

However, the trustworthiness of the intelligent monitoring and early warning systems is still restricted by the accuracy of the sensor data, the stability of the devices and the degree of information exchange between various business systems. Especially, the low probability emergencies offer little historical data for the model training and verification. Therefore, it is necessary to concentrate on strengthening the integration of multi-source data, verifying the models in practical operations and improving the coordination of data among different monitoring systems in order to increase the stability and reliability of the risk early-warning results.

3.2. Emergency decision-making and collaborative response

When an emergency happens, the attention of emergency management changes from the surveillance of risks to the evaluation of the incident, the formulation of plans and cooperative responses. The urban rail transit consists of several special subsystems such as operation, rolling stock, traction power supply, communication and stations; complicated incidents usually need different departments to exchange information and take joint actions in a short time. Some technologies like AI, Bayesian networks and DTs can combine the equipment telemetry, incident logs and historical records to give quantitative basis for emergency decision-making through risk analysis and scenario simulation. Previous studies have applied Copula Bayesian networks to assess

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the relationships among various risk factors and, by integrating the forecasting and diagnostic analyses, found out the main risks influencing the safety of rail transit operations, thus providing quantitative assistance for risk evaluation and operational measures [6].

Concerning the emergency decision-making assisted by DTs, a study has established a decision support system including DTs of nearby subway stations, by means of collecting operation data from surveillance cameras, acoustic sensors and environmental monitors [8]. During abnormal situations like fire or flood, the relevant information can be exchanged between adjacent stations and the positions and conditions of the events are shown to the staff via a mobile intelligent assistant, which helps to improve the situational awareness and cooperative response among the stations [8]. In the experiment which simulated the emergency situations, this system reduced the response time of the staff to unexpected accidents by 17.4% compared with the control platform [8]. This example indicates that the advantages of DTs are not only in three-dimensional display but also in enhancing the efficiency of emergency information acquisition and decision-making support through the connection of information from multiple sites [8].

It is important to mention that this case study was mainly carried out in simulated emergency situations; therefore, the empirical results cannot be directly compared with the actual effectiveness in real urban rail transit emergencies. Moreover, the rail transit system has strict safety regulations, which indicate that intelligent models are more appropriate as auxiliary aids at present. In practical engineering work, model-based suggestions should be integrated with the experience of dispatchers, and the reliability of the system should also be verified by real operational data and extensive emergency drills.

3.3. Passenger evacuation and operational recovery

Emergencies like station fires, sudden passenger increases and faulty equipment may cause rapid crowding in limited space and possibly make some important facilities and exit routes inaccessible; thus, the safe removal of passengers is an important issue in the urban rail transit emergency management. Virtual Reality, DTs and microscopic crowd simulation techniques can simulate the movement of passengers according to the spatial arrangement of the station, the distribution of the crowd and the development of the incident, so as to compare different evacuation routes and crowd control methods. Up to now, some studies have applied virtual reality, computer simulations and field investigations to assess the fire evacuation capacity in urban rail transit stations, showing that digital simulation can give quantitative analysis for evacuation planning [9].

Based on the Lumu Station of Suzhou Rail Transit, the researchers have developed a coupled simulation model of fire dynamics and passenger evacuation by using PyroSim, Python and AnyLogic to build an interactive simulation system which integrates human behavior, fire spread and autonomous agents [10]. They combined the fire development, pedestrian behavior and the geometric structure of the underground station to study the passenger evacuation dynamics under various emergency organization methods, such as evaluating the reverse opening schemes of the automatic gates [10]. This example shows that, in comparison with the contingency plans relying only on fixed egress routes, the dynamic simulation can reflect the effects of changing fire conditions and passenger behaviors on the evacuation process, thus providing an empirical foundation for finding possible bottlenecks and improving the station evacuation procedures [10].

After the successful evacuation of the crowd, the emergency management should concentrate on the comprehensive restoration of the station and line transportation services. Intelligent simulation and optimization algorithms can assist in evaluating the passenger flow control, facility rebuilding and train rescheduling plans as well. However, the present research is mainly based on simulation,

DOI: 10.54254/2755-2721/2026.37717

which may lead to discrepancies when compared to the actual emergency conditions. Hence, it is important to integrate the simulation results with the actual station telemetry, emergency exercises and operational experiences to enhance the practicability of the intelligent techniques in crowd evacuation and service recovery.

4. Challenges and future development directions

The current application of intelligent techniques in urban rail transit emergency management encounters several problems. The dissimilarity in the fundamental data standards and communication interfaces results in the formation of different independent information systems such as those for rolling stock, power supply, signaling and station operations. This obstacle prevents the integrated operational information from being obtained, transmitted and shared promptly during emergencies. The existing intelligent algorithms mainly rely on particular training data and routine operational conditions. They have poor adaptability and generalization in handling unforeseen disturbances and complicated or extreme environments. Many technical models are still in the stage of off-line simulation and laboratory tests. There is a lack of long-term verification under actual working conditions. The establishment and continuous maintenance of high-fidelity digital twins and extensive sensor networks need a large amount of expenditure. Therefore, this expenditure limits their widespread application.

At the intelligent decision-making and practical application levels, the system reliability and security are still restricted by various operating limits. AI and DTs can enhance the speed of situation change simulation and contingency plan assessment. Nevertheless, the results of their analyses are limited by the accuracy of the primary sensing data, the settings of parameters and the varying on-site conditions. The railway transportation environment has stringent safety regulations with a zero-error tolerance. The intelligent models cannot completely take the empirical judgement and definite decisions of the operation managers away. Furthermore, the unclear 'black-box' nature of the algorithms leads to low decision-making interpretability. A large number of edge terminals may bring about operational risks to the on-board and wayside networks, such as system instability, infringement of passengers' privacy and cyber attacks. Thus, the improvement of intelligent emergency management is not enough with only small gains in algorithm accuracy. It also needs to reinforce the comprehensive operational robustness and engineering practicability.

To solve these obstacles, the development of urban rail transit intelligent emergency management in the future requires improvements in the cooperation of multiple technologies and engineering implementations. The industry should speed up the establishment of common emergency data interfaces and data exchange standards. It is necessary to integrate multi-source heterogeneous data from depots, stations and railway lines in depth to eliminate the information barriers among different disciplines [11]. According to these interoperability standards, systematic engineering verification should be carried out continuously on the operating lines and passenger centers. This work enhances the bidirectional dynamic coordination between the data transmission systems and the real-time operational data flows. In addition, an integrated human-in-the-loop hybrid decision-making mechanism should be established to coordinate intelligent analysis with expert judgement. Moreover, a comprehensive cyber-physical protective system covering network security and data privacy protection should be constructed. In conclusion, the strategy of urban rail transit intelligent emergency management will change from the independent application of individual technologies to the intensive cooperation of multiple technologies and overall intelligent support throughout the process [12].

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5. Conclusion

This paper investigates the use of intelligent technologies in the emergency management of urban rail transit. By means of some particular engineering examples, the significant roles of the Internet of Things (IoT), big data, AI and DTs are analyzed in the areas of risk identification and early warning, emergency decision-making and collaborative response, passenger evacuation and system recovery. According to the previous research and practical implementations, multi-source sensing and intelligent analysis can improve the supervision of operational status and anomaly detection. DTs and simulation techniques offer substantial assistance for the assessment of contingency plans, information communication and passenger evacuation. However, the field implementations are still limited by several problems. These factors involve the lack of data exchange between different systems, the high reliance of models on certain operational conditions, the insufficient long-term testing during actual operation and the persistent presence of both physical and cyber security threats. In the future, it is crucial to optimize the data integration strategies among all subsystems in an integrated manner. Researchers and operators should carry out further operational validations on intelligent models and DT platforms in real operating conditions. Moreover, appropriate coordination between algorithmic analysis and human judgements is necessary. In addition, establishing unified data standards and compatible communication interfaces among the previously isolated subsystems, as well as carrying out long-term verification of intelligent models under actual working conditions, will be an important precondition for transforming the current laboratory-level achievements into reliable engineering practices. These measures can raise the credibility, adaptability and efficiency of intelligent technologies in urban rail transit emergency management.

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