Proceedings of the 4th International Conference on Mechatronics and Smart Systems
DOI: 10.54254/2755-2721/2026.32836

# *Digital Twin Applications in Metro Systems: Infrastructure Monitoring and Operational Management*

**Yufei Cheng**

*SWJTU-Leeds Joint School, Southwest Jiaotong University, Chengdu, China*
*cn233yc@leeds.ac.uk*

***Abstract.*** Recently, more and more digital twin technologies are getting attention in managing and operating urban metros. The fact that integrating time-monitor data like a metro digital twin right now has chances to improve its operation and dependability. This essay is mostly about the applications of digital twins for the metro system: infrastructure monitoring and operation management. Digital twin, at the infrastructure level, can be utilized in observing the structure inside the metro tunnel to see if there is a dangerous situation. For example, a swelling on Earth. After applying our collected data to a predictive analysis, this will offer us an early warning and allow preventive maintenance. In terms of operation, a digital twin system would help people to monitor the operation of metro network, which means smoother passenger flow. Although the metro system's digital twin technology has great benefits, problems like data integration, reliability of the whole system and its security still need to be solved. More studies and practices need to take place to make sure that digital twin tech is employed safely and correctly on future metros.

***Keywords:*** Digital Twin, Metro Systems, Infrastructure Monitoring, Predictive Maintenance, Operational Management.

## 1. Introduction

Because of the ever-growing number of urban inhabitants, Metro systems are an important part of modern city transportation. In comparison to roads, metros can take a considerable number of passengers at a time without clogging up city streets and putting extra stress on the environment. As more and more major cities build their own metro systems, these lines are getting larger and more complex. However, it also brings new problems of maintaining infrastructure and operational management.

Most of the metro lines are built underground and pass through crowded parts of town. In the long term, the structure may be affected by changes in the ground, buildings being uneven, and aging problems. As for civil engineers, it is vital to monitor the condition of underground infrastructure and identify any problems at an early stage. Traditional monitoring ways mainly depend on the occasional examination or limited sensor information, so it's difficult to know continuously about the structural status of metro systems. Moreover, metros have to manage considerable numbers of passengers at once and swiftly deal with accidents like broken train parts or service delays.

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Recently, more and more people have paid attention to digital twin technology as a possible approach for managing complicated infrastructure systems. A digital twin, so to speak, is a sort of virtual version of a physical asset in the real world, always getting changed up with current data from all kinds of sensors [1,2]. To integrate physical Structure, sensor network and data Model for digital twin, engineers would not only check the overall situation at the moment, but also predict the near future. And it is also stated in other studies that when combined with technologies like IoT, artificial intelligence, etc., digital twins could greatly enhance predictive maintenance and operations efficiency in transport. For example, Sarp and Kuzlu state that it was advantageous to have an AI-driven digital platform regarding the railway system [3].

Among metro lines, digital twin tech has been mostly tried out on 2 things: monitoring infrastructure and handling operations. As for underground buildings, it can monitor the building's health of metro tunnel in real time and provide alerts to people when there is going to be a deformation or settlement at an early stage [4]. Taking Zhou's experiment for example, it demonstrated the application of a digital twin platform in metro tunnel monitoring and maintenance, making it a practical idea to further take advantage of a potential AI assistant [5].. Apart from the infrastructure part, digital twin models have also been utilized in metro operation system, passenger flow prediction and operational decision making [6]..

## 2. Infrastructure digital twin

### 2.1. Structural monitoring of metro tunnels and surrounding ground

The structural status of metro Tunnels is very important to the long-term safety of urban railways. The tunnel is in constant operation and it will be impacted by many factors such as ground pressure, train vibration, groundwater level change and material degradation. After a while, it will lead to some problems like wrinkles, cracks, lines breaking, water leakage, etc., which also affect the stable surroundings. For that reason, it is common now to monitor both the tunnel structure as well as geology nearby.

Structural monitoring systems have always relied on rich sensors for tunnels and around the soil: These machines collect data including displacement, strain and shakes and send that along to the control center so the engineers can see whether the structure holds up or not. Actually, there are systems out now that can continuously update real-time info on the behavior of tunnels for engineers to see and monitor structure changes while operating.

Digital twin technology is no replacement for such monitoring systems; rather, it just extends their abilities. With instant sensor data and digital model of tunnels and ground around, engineers can actually visualize the structure behaving in a much more integrated digital world. This also offers us to better organize and monitor the information and analyze the structural responses systemically. Furthermore, as demonstrated by Afrazie, combining digital twin and AI will find how the structure is irregular inside the tunnel and give advice on early maintenance [7]. Besides, integrating what has been monitored with the digital equivalent of a structure gives engineers a much better understanding of how it behaves over time, enhancing its utility [8].

### 2.2. Prediction and early warning

While monitoring can tell the current situation, it's equally crucial to know whether they will get better or worse later for safety issues. In many big cities, metros are arranged in densely built-up places. Factors including soil conditions, groundwater level and trains overloading slowly make the

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land sink. If don't get noticed, these potential risks could eventually change structures nearby or compromise tunnel stability.

Digital twin systems could be suitable to identify these sorts of problems using today's monitoring data along with the computational model of the tunnel. Then designers can visualize real-time changes and make predictions for nearly future. It'll help spot odd changes even when not supervised by human.

The system should be able to utilize data for analytical techniques as well. Studying the metro system data has proved that deep learning models can capture complex spatiotemporal patterns in large datasets and reveal hidden trends in system behavior [9]. Combining all those techniques would allow the monitored data to be used for both observing the current infrastructure conditions and detecting risks. Then the corresponding actions would be taken.

Therefore, the digital twin system offers early warning as well as predictive maintenance. Engineers are capable of preventing problems from getting worse as they notice unusual patterns in the information being detected. In this way, predictive advice will change metro infrastructure management, moving from being reactive to a more proactive, with-data repairing approach, which is vital for guaranteeing the reliability of these complex rails system [10].

## 3. Operational digital twin

### 3.1. Real-time monitoring of metro operation

In addition to infrastructure management, digital twins could also be employed to monitor the operation of metros. Modern metros are about interactions among the trains, signals and passengers. Therefore, maintaining stable operation refers to continuously monitoring the operating conditions of trains, service intervals and passenger volumes. Traditional monitoring system primarily rely on control center, operation data platform, and so on. However, they usually present information in an isolated way. As metro networks are growing and becoming more complicated, more combined monitoring methods are required.

A digital twin platform gives engineers a virtual copy of metro system, which will be updated with actual info continuously. Through integration with data obtained from the train control system, sensors and passenger information system, engineers would have a better idea of what the current state of the metro network is. This can help operators visualize the current state of their networks and spot possible issues.

The latest study on smart transportation indicates that putting live info into digital plans could really help with figuring out how things work in city train lines. Some operational ideas are mentioned by Dai et al. that once AI receives the data, predictions are expected to be made which would help with alerting accident possibilities to subway drivers during operation [11].

### 3.2. Ai-based train scheduling and disruption management

Ensuring train operations maintain efficiency is also one of the important difficulties for metro systems, particularly for big cities with frequent train running 24 hours a day. Minor disruptions like equipment breakdown or crowded passengers can make things go wrong rapidly and cause delays in timetable across the whole line. For some early-built metro systems, trains will be scheduled mostly by the control center operators who have rich experience and available data. Although this kind of approach is mostly reliable, it sometimes struggles to react quickly if the situation gets more complicated.

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Digital Twin technology brings another perspective to making wise decisions since there's a real-time digital representation of our metro system. The digital twin working with AI would analyze all sorts of operational information, which would simulate imaginary scenarios before they really take place. This would make operators evaluate potential options for problems beforehand and pick the best answer.

Artificial intelligence technologies have already been applied in Railway operations management. Machine learning models can analyze huge amounts of operational data and find certain patterns regarded as delay, passenger demand, or system performance. He et al. mentioned in their paper that this kind of information could create more adaptive train schedules and generally improve the metro system efficiency [12]. Assistance from the applied digital twins can possibly enable such sorts of evaluation instruments to give us metro operators a flexible and information-rich method to monitor enormous metropolis railroad systems.

### 3.3. Passenger flow prediction and decision support

Passenger demand is also an important factor affecting the operation of metro. In metropolitan areas, people flow is usually quite variable at different stations throughout the day, especially around rush hours in the morning and evening. There could be overcrowding at the station and late trains when there's a sudden influx of people. Metro operators need to understand these patterns too in order to keep their service delivered smoothly.

Digital twin technology is a suitable platform to observe how passengers move around on metro networks. A digital twin system consists of individual stations and railway lines in the model- bring them all together, so the control center is allowed to have an overview of the network and the passengers inside. Making it practical for operators to see changes in the amount of people and stations where might be crowded.

Wang et al. employed digital twinning of a rail transit system in order to integrate diverse operational data into a single system. They found out that using a digital model with the present information was much more efficient for visualizing passenger demand and system work. And with this information, the metro operator might adjust the frequency of trains, distribute passengers in the stations, and implement some temporary operations during peak times [13].

Digital Twin systems could also be helpful for routine flow plans and emergency evacuations. By creating digital models of stations and tunnels, engineers would find the best elevation for emergency routes. Besides, they should also support for making decisions, facilitating the evacuation in various conditions.

Therefore, a digital-twin system that aids us in making decisions to bring the metro more effective and reliable has great necessity to be integrated in the metro system and continuously advancing in the near future.

## 4. Conclusion

Digital twin technology offers a promising future to make infrastructure administration and operation better in metro system. Through linking the real-time monitor data to the model, a digital twin can provide deep insights into the surface situation, permitting engineers to have an overview of the whole system in a comprehensive way. It is especially vital in cities with complex railway networks, which need to keep their infrastructure safe and operations stable for a very long time.

When looking at infrastructure, digital twin does not replace traditional methods like monitoring. Even though there is a fact that the traditional sensor networks can provide constant streams of

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information, the model simply makes things easier. Therefore, operators can find abnormal situations sooner and implement corresponding plans for keeping everything working well. Possible dangers like deformation and settling would be detected ahead of time, which reduces the probability of structures failing, improving the long-term trustworthiness of subway facilities.

From an operational perspective, digital twin platforms are integrated with supervising current situations and AI decision-making. The passenger flow and the train operation information would assist operator too. Even if there is nothing out of order, the system could help make some adjustments to make the metro run more flexibly.

However, several issues still can not be ignored. These include data quality, system integration, cybersecurity, etc. Therefore, digital twin system may not be achieved instantly. Furthermore, even if AI-based analysis could make decisions, human judgments shouldn't be completely abandoned, especially when it comes to safety issues. To make a balance, future research has to focus on improving the dependability and robustness of the digital twin systems to guarantee that it could still be implemented properly with caution in real-world metro operations.

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