Digital Twin- A Key Driver to Transform North American Railroad

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Digital twins are virtual representations of real-world objects or systems that use data, simulation, and machine learning to help decision making. They can be applied to various domains, such as manufacturing, healthcare, and transportation. In this paper, we focus on the use of digital twin for the North American rail network, which is one of the largest and most complex in the world. We discuss how digital twins can help improve the efficiency, safety, and sustainability of rail operations, by enabling real-time monitoring, predictive maintenance, and scenario analysis. We also present some of the challenges and opportunities for implementing digital twins in the rail industry, such as data integration, security, and interoperability. We conclude by highlighting the potential benefits and impacts of digital twin for the future of rail transportation in North America.

Additional Keywords and Phrases: IoT, Artificial Intelligence, Digital Twin

1 INTRODUCTION

North America has a vast and diverse railroad network that spans across three countries: the United States, Canada, and Mexico. The network is composed of different classes of railroads, based on their operating revenue and size. The largest and most dominant class is Class I, which includes six freight railroads and one passenger railroad. These railroads own their own tracks and operate over long distances with minimal stops. They account for most of the freight rail mileage and revenue in North America. Class I railroads are followed by Class II and short line railroads, which are smaller and serve regional or local markets. Together, these railroads cover more than 200,000 miles of track in North America [2][3], with the majority in the United States. Railroads are an essential part of the North American economy, as they provide a fuel-efficient and cost-effective way to transport goods and people. Railroads are more environmentally friendly than trucks, as they consume less fuel and emit less greenhouse gases per ton-mile. Railroads also handle a large share of the long-distance freight volume in North America, more than any other transportation mode. In the United States alone, railroads ship around 61 tons of goods per person every year, ranging from raw materials to finished products. Railroads are therefore a vital and valuable component of the North American transportation system [4].

The current US administration has shown a strong commitment to improving and expanding the rail transportation system in the country. In the past few months, the administration has made two major announcements that will provide billions of dollars in funding for rail projects across 35 states. The first announcement was in September 2023 [7], when the administration awarded $1.4 billion to improve rail safety and boost capacity. The funds will be used for various purposes, such as upgrading signals, bridges, tracks, and stations, as well as enhancing passenger and freight services. The second announcement was in December 2023 [5][6], when the administration announced $8.2 billion in new grants for high-speed rail and pipeline projects. The grants will support the development of new high-speed rail corridors that will connect major cities and regions, as well as the construction of pipelines that will transport natural gas and other fuels. These projects will not only create jobs and stimulate the economy, but also reduce greenhouse gas emissions and

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dependence on foreign oil. By investing in rail transportation, the administration is demonstrating its vision for a modern, efficient, and sustainable transportation system.

Digital twins are not a new concept, but they are becoming more relevant and powerful in the era of big data, cloud computing, and artificial intelligence. A digital twin is a virtual representation of a physical object, person, or process, contextualized in a digital version of its environment. By using real-time data streams from sensors, cameras, and other sources, a digital twin can simulate the behavior and performance of its physical counterpart, as well as test various scenarios and outcomes. McKinsey research in a recent study indicates that 70 percent of C-suite technology executives at large enterprises are already exploring and investing in digital twins [8].

Research towards the application of Digital Twins is limited to railroad especially in freight transportation. This paper will explore the current and future applications of Digital Twins in the transportation industry, with a focus on the railroad sector, especially for freight transport. This paper will explore the current and future applications of Digital Twins in the railroad industry, with a focus on freight transport, which is a vital and valuable component of the North American economy. The paper will also investigate how Digital Twins can help the railroad industry achieve higher levels of safety, reliability, and economic growth, by improving the efficiency and resiliency of rail operations and maintenance, as well as enabling smart and sustainable mobility solutions.

2 CONCEPT AND CHARACTERIZATION

The idea of creating a digital replica of a physical entity can be traced back to the Apollo space program, where NASA used a 'twins' concept to monitor and control the spacecrafts in orbit. By having a duplicate of the space vehicle on earth, NASA could simulate and predict the behavior and status of the real one in space and perform troubleshooting and maintenance accordingly. The term 'digital twins' was coined by Michael Grieves at the University of Michigan in 2003, to describe the digital equivalent of a physical product that can be used for design, testing, and optimization purposes. Since then, digital twins have evolved and expanded to various domains, such as manufacturing, healthcare, and transportation, where they can help improve the performance and efficiency of physical systems and processes.

3 PREVIOUS CASE STUDIES IN TRANSPORTATION INDUSTRY

3.1 DIGITAL TWIN TO INTEGRATE RAILWAY DATA

Railway infrastructure is composed of large complex systems that require data from various sources to operate and maintain efficiently. However, often the data exists in numerous siloed places, making it difficult to access, integrate, and analyze. This challenge can be overcome by using digital twins, which are virtual representations of physical entities that can simulate and optimize their behavior and performance using real-time data. A case study by G.C. Doubell [14] demonstrated how Passenger Rail Agency of South Africa (PRASA) used digital twins to integrate data from different sources, such as track geometry, train location, and passenger information. The digital twin system architecture utilized a layer with various “wrapper” components that provided specific interfaces to each of the data sources to be included in the system. This enabled PRASA to improve the efficiency and reliability of its rail operations and maintenance. In a similar study [18], Uber, a firm with more than $30 billion in annual revenue, planned to build future enterprise data apps leveraging real-time digital twins for their businesses. The digital twins would create virtual models of their customers, drivers, vehicles, and network, based on their real-time data streams, to provide personalized and seamless travel experiences, as well as to optimize the performance and profitability of their platform. These studies show how digital twins can help transform the railway industry by enabling data integration and analysis, as well as delivering enormous customer value.

3.2 RAILROAD BRIDGES MAINTENANCE

Railroad bridges are critical infrastructure that require constant monitoring and maintenance to ensure their safety and performance. Parker [9] conducted research on the application of structural health monitoring (SHM) for railroad bridges, and argued that a digital model, which is a simplified representation of the bridge geometry and properties, is more suitable than a digital twin, which is a comprehensive and dynamic simulation of the bridge behavior and environment. However, in the last two years, there have been significant developments in artificial intelligence (AI), which can enhance the capabilities and benefits of digital twins for railroad bridges. For instance, AI can detect and alert any deviation between the physical bridge and the digital twin, such as a frozen bearing, and notify the engineers immediately. AI can also generate an impact report and a possible solution, based on the data and analysis from the digital twin. Therefore, AI can complement and improve the digital twinning concept for railroad bridges, by enabling faster and better decision making, optimizing processes and resources, and reducing risks and costs.

3.3 RAILWAY FACILITIES WITH TUNNEL

Kim et al., 2023 [10] conducted a study on the Osong Railway Test track, which is a 13 km long railway line in South Korea. The main objective of the study was to scan a 4 km section of tunnel using a 3D lidar device and create a digital twin space. A digital twin is a virtual representation of a physical asset, process, or system that can be used for monitoring, analysis, and optimization. The study aimed to demonstrate how digital twin technology can benefit the railroad industry by enabling preemptive maintenance, efficient operation, and effective management of the test track. The study also compared and analyzed the current state-of-the-art lidar technology and presented the future plan for expanding the digital twin space to cover the entire test track. The study used a Leica BLK360 device, which is a compact and portable 3D lidar scanner. The device was connected to a tablet or a mobile device via Wi-Fi, and the scan results were evaluated in real time using the Matterport Capture software. The study suggested that this technique can be applied to various railway tunnels for continuous maintenance and inspection.

3.4 RAILWAY BUILDINGS

Kaewunruen et al., 2023 [11] conducted research on the design and construction processes of an intermediate railway station, as well as its maintenance management, using BIM (Building Information Modeling) techniques aka digital twin and Revit software. Revit is a software application that supports BIM workflows for architecture, engineering, and construction. The research used King's Cross station, one of the busiest railway stations in the UK, as a case study. The research simulated the construction work of the station using BIM and Revit and evaluated the benefits and challenges of this approach. The research also explored how BIM and Revit can facilitate the maintenance management of the station, by providing real-time data, analysis, and optimization of the station's performance and condition.

3.5 RAILWAY STATION SIGNALS

Ma et al., 2023 [13] presented a novel software for creating a digital twin of a railway station, using a computer chain system. A digital twin is a virtual representation of a physical asset, process, or system that can be used for monitoring, analysis, and optimization. A computer chain system is a distributed ledger that securely records and verifies transactions using cryptographic hashes [19][20]. The software developed by Ma et al., 2023 can monitor the railway signal in real time and display it intuitively on a graphical user interface. The software can also demonstrate the working process and working principle of the station signal equipment in detail, such as the types, aspects, and meanings of the signals, the logic and rules of the signaling system, and the interaction between the signals and the trains. The software can achieve the effect of three station redisplay, which means that the software can show the same signal information as the actual station, the control center, and the train cab. This feature can help the station staff and the students studying railway signal system to compare and verify the signal information from different perspectives, and to improve their understanding and skills of the railway signal system. The software can also simulate various scenarios and situations that may occur in the railway station, such as signal failures, train delays, track changes, and emergencies. The software can help the users to test and evaluate the performance and reliability of the railway signal system, and to find and solve potential problems and risks. The software can also provide feedback and suggestions for optimizing the railway signal system, and for enhancing the safety and efficiency of the railway station. Ma et al., 2023 claimed that their software can be a useful tool for railway station design, operation, maintenance, and training, and that their software can be applied to various railway stations with different signaling systems and configurations.

4 FUTURE SCOPE AND POSSIBLE CASE STUDIES FOR NORTH AMERICAN RAILROAD

4.1 INTERMODAL OPERATION – INTERMODAL YARD

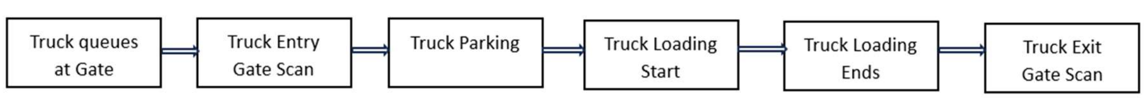
Intermodal transportation [22] is a key factor in the success of North America's trade, as it allows goods to be moved across long distances using different modes of transportation, such as truck, rail, sea, and air. Instead of operating separately, these modes work together under a coordinated system that optimizes the efficiency and reliability of freight movement. Intermodal transportation can span across continents, such as the service provided by Canadian Pacific Kansas City (CPKC) that connects the northern Canada and southern Mexico and all points in between [24]. One of the main advantages of intermodal transportation is the use of standardized steel containers that can be easily transferred from one mode to another without requiring additional handling or repackaging. The use of containers has increased significantly over the years, from 47% of the total intermodal volume in 1990 to 92% in 2019 [21]. Containers also offer the possibility of "double stacking", which means placing one container on top of another on a rail car. This reduces the space and fuel consumption of rail intermodal, making it more cost competitive than other modes [23].

Intermodal rail terminal facilities provide an interface between the rail and road systems of circulation. They handle containers and trailers that are transferred between railcars and trucks. Some rail terminals are also connected to port terminals or airports by rail shuttle or truck drayage services.

Intermodal terminals composed of few key elements – Intermodal yard, storage area, classification (hump) yard, gate, chassis storage, repair/maintenance.

A Digital Twin solution can play an important role manage freight parking at the yard along with Artificial Intelligence. A rail intermodal facility is a place where trucks can come and go with or without containers. Usually, a truck has one container, but sometimes it can have two 20-foot containers or two bigger ones on a double trailer. Table 2 describes typical truck movement in the yard.

Table 1: Truck movement in the yard



All or few of these data, typically available such as gate scanning, loading start time, loading end time, truck make and model, engine type, fuel type etc. (table 2).

Table 2: Available data

Data to be collected
Gate Scanning timestamp
Loading start timestamp
Loading end timestamp
Truck make
Truck model
Engine Type
Fuel Type

Using this data and data collected by advanced cameras and sensor, a digital twin space can be developed. When combined with advanced cameras and sensors lidar can collect high accuracy data and real time monitoring. It provides vehicle classification, real time monitoring, license plate recognition and advanced AI capabilities. Based on this digital twin space, model such as graph neural network [30] or a spatio-temporal convolutional [31] can generate a traffic overview. YOLOv5 model [32] can detect and classify trucks and their bounding boxes. Then those bounding boxes can be mapped to the predefined parking regions and assign a designated parking spot. Similarly, a survival analysis model or time series forecasting model [33] can be applied from real time and historical data to predict wait time for trucker and assign an arrival window.

Lindhjem [26] found that the main sources of carbon emissions at Port of Oakland were truck idling in the entry line and driving in the yard (table 3). A successful implementation of digital twin at intermodal yard will reduce carbon emissions by 40%.

Table 3: Styles available in the Word template

Activity	Idling Time (hours)	Distance (miles)	Speed (mph)
Entrance Queue	0.17	N/A	N/A
Movements in Yard	0.34	1.39	10
Exit Queues	0.05	N/A	N/A
Local Streets	N/A	1 – 5	20 – 30
Long Haul	N/A	<500	50 – 65+

4.2 HUMP (CLASSIFICATION) YARD

A hump yard or classification yard is where trains are sorted and classified. Hump yard plays a significant role in streamlining operations and enhancing efficiency [34]. Some of the critical tasks involved in hump yards are – build trains, cleaning and lubricating hump lead, monitoring and adjusting the terminal process control that integrates the data and processes of the hump yard operations, inspect and repair classification and departure tracks. Some of the common problem in hump yards are car damage, inefficiency and delays due to weather conditions, workers, and equipment safety due to the complex and fast-moving operations. A digital twin system of the hump yard can address most of these issues, by creating a virtual model that reflects the real world in real time and using advanced data analysis and artificial intelligence to monitor, predict, and optimize the hump yard performance. This can be achieved by a multi-dimensional and multi-level DT model from elements, behavior, and rule [35]. Then those models are analyzed and are dynamically updated based on real time data. DT along with 3D cameras and sensor can track equipment and immediately alert control center if an equipment positioned in a wrong place and can possibly cause a safety issue. It also can improve workers safety and prevent yard injury. Realtime DT along with artificial intelligence can predict behavior based on weather conditions and other external factors. A digital twin system can thus improve the safety, reliability, and sustainability of the hump yard facilities, which play a key role in the transportation of various goods across the country.

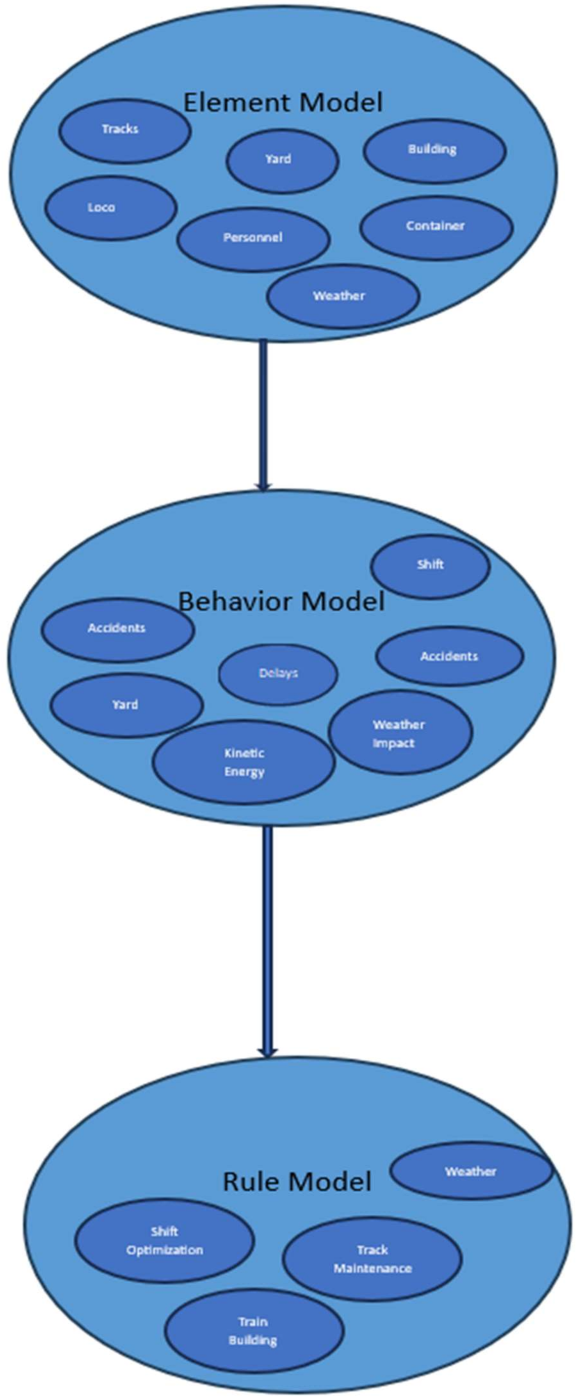
One of the challenges in designing and operating a hump yard is to create a realistic and accurate digital representation of the physical system. This can be achieved by using a multi-level approach that consists of three steps: element model, behavior model, and rule model.

The element model is the first step that defines the physical assets involved in the hump yard, such as tracks, locomotives, cars, yard, personnel, containers, goods, etc. The element model also establishes the relationship between each component using a tree structure, which helps to organize and manage the data. To build the element model, various types of 3D data sets are used, such as 3D building data, spatial data, sensor data, PLC and RFID data. These data sets provide the necessary information about the geometry, location, status, and identity of the physical assets. Some researchers call this the 3D connectivity of digital twins [36], as it links the real and virtual worlds. Conceptual data model can be used to build this [37].

The behavior model is the second step that determines the dynamic aspects of the hump yard, such as the container loads, locomotives position, behavior while building a train, weather related behavior, etc. The behavior model uses mathematical equations, algorithms, and rules to describe how the physical assets interact with each other and with the environment. The behavior model also considers the uncertainties and variations that may occur in the real system, such as delays, breakdowns, accidents, etc. The behavior model enables the simulation and analysis of different scenarios and outcomes. One type of behavior model is a state transition diagram, which uses a graphical notation to show the states, events, and transitions of a system or an object [38].

The rule model is the third and final step that correlates the elements and behaviors to achieve the desired objectives and performance of the hump yard. The rule model defines the policies, procedures, and constraints that govern the operation and management of the hump yard, such as the yard optimization, scheduling of the personnel, track maintenance, safety enhancement, building trains, etc. Then use AI to predict the rule based on changed scenario. Like impact of changing weather to the kinetic energy. The rule model also allows the evaluation and optimization of the hump yard, as well as the detection and resolution of potential problems and conflicts. DT ontology can help to build this model [39].

Figure 1: DT modelling



By using this multi-level approach (Figure 1), a hump yard can create a comprehensive and reliable digital twin that can help to improve its efficiency, productivity, and safety.

4.3 TUNNEL AND BRIDGE MAINTENANCE

Railroads are an essential part of the North American transportation system, carrying millions of passengers and tons of freight every year. However, maintaining the safety and efficiency of the railroad infrastructure, especially the tracks and bridges, is a challenging and costly task. According to the American Society of Civil Engineers, the U.S. rail network has a state of good repair backlog of $45.2 billion, and many bridges are over a century old and in need of replacement or rehabilitation [40].

To address this challenge, some railroads are turning to innovative technologies such as 3D LiDAR and digital twins. 3D LiDAR is a remote-sensing technology that uses laser beams to measure precise distances and movements in an environment, creating a high-resolution 3D map of the scanned terrain. By combining with digital twins, building information modeling (BIM) and structural health monitoring (SHM) [41] railroads can create digital representations of all their tunnels and bridges, and update them in real time with the data collected from sensors, inspections, and 3D LiDAR scans. These digital twins can then be used to monitor the condition and performance of the infrastructure, identify potential problems, and optimize maintenance and repair schedule.

For example, BNSF Railway, one of the one of the class-I railroads in North America, has been using 3D LiDAR and digital twins to inspect and manage its bridges since 2016. The company has deployed a fleet of drones equipped with 3D LiDAR sensors to scan its bridges, generating detailed 3D models that can be compared with the design specifications and historical data. The digital twins of the bridges can also be integrated with other data sources, such as weather, traffic, and load, to assess the impact of various factors on the bridge health. By using 3D LiDAR and digital twins, BNSF has been able to reduce the time and cost of bridge inspections, improve the accuracy and consistency of the data, and enhance the safety and reliability of its infrastructure. The company estimates that it has saved over $300 million in capital and maintenance expenses by using these technologies.

In another study, of an open deck bridge at Lyndhurst, NJ Nafaji A. et al. [42] showed that with the help of digital twins, bridge geometry can be extracted and then several scenarios such as bearing settlement scenario and heuristic scenario to output the corrosion can be determined.

3D LiDAR and digital twins are not only beneficial for railroads, but also for other stakeholders, such as regulators, customers, and the public. By providing a transparent and objective view of the infrastructure condition, these technologies can help improve the compliance and accountability of the railroads, increase the confidence and satisfaction of the customers, and reduce the environmental and social impacts of the infrastructure.

In conclusion, 3D LiDAR and digital twins are powerful tools that can help railroads improve their infrastructure management and performance. By creating and updating digital representations of their tunnels and bridges, railroads can leverage the data and insights generated by these technologies to optimize their operations, maintenance, and planning. These technologies can also enhance the communication and collaboration among the railroads and other stakeholders, leading to a safer, more efficient, and more sustainable transportation system.

4.4 CAR AND LOCO MAINTENANCE

The railway system relies on wheels as a basic element, allowing trains to move with speed and accuracy [43]. Wheel sensors have improved railway operations in terms of safety, maintenance, and performance over the years. Similarly for distance measurement, Global Navigation Satellite System (GNSS) and balise are used [46]. For speed, wheel sensor, radar and GNSS are used.

Sensor data refers to the information collected from various sensors installed on locomotives, cars, tracks, and other infrastructure. These sensors can measure different parameters such as wheel speed, distance, position, temperature, vibration, and more. Sensor data can provide real-time feedback on the condition and performance of the railway system, as well as enable predictive and preventive maintenance. Digital twins are virtual models that replicate the physical assets and processes of the railway system, using sensor data, simulations, and machine learning. Digital twins can help railways to visualize, analyze, and optimize their operations, as well as to test and implement new solutions. Digital twins can also support decision making and collaboration among different stakeholders. One of the recent developments in the field of sensor data and digital twins for railways is the Open Sensor Data for Rail 2023 (OSDaR23) project. OSDaR23 [45] is a multi-sensor dataset of 21 sequences captured in Hamburg, Germany, in September 2021. The sensor setup consisted of multiple calibrated and synchronized IR/RGB cameras, lidars, a radar, and position and acceleration sensors front-mounted on a railway vehicle. The dataset also contains 204091 annotations for 20 different object classes, such as trains, wagons, bicycles, animals, signals, and tracks. OSDaR23 is a valuable resource for researchers and practitioners who want to develop and evaluate computer vision and machine learning algorithms for object detection, tracking, and classification in the railway context. OSDaR23 [47] can also be used for tasks beyond collision prediction, such as train localization, speed estimation, track recognition, signal identification, and more.

Another example of how sensor data and digital twins can benefit railways is the Digital Twin for Rail Infrastructure (DTRI) project. DTRI is a collaborative project between the University of Birmingham and Network Rail, the owner and operator of most of the rail infrastructure in Great Britain. DTRI aims to create a digital twin of the railway infrastructure, using sensor data, geospatial data, and artificial intelligence. DTRI can help Network Rail to monitor the health and performance of the infrastructure, as well as to plan and execute maintenance and renewal activities.

DTRI can also enable Network Rail to explore different scenarios and alternatives, such as the impact of climate change, extreme weather events, increased traffic demand, and new technologies. DTRI can support Network Rail to achieve its goals of improving safety, reliability, efficiency, and sustainability of the railway system.

In conclusion, sensor data and digital twins are powerful tools that can help railways to improve their operations and performance. By collecting and analyzing data from various sensors and creating and updating virtual models of the railway system, railways can gain valuable insights and recommendations for optimal maintenance and improvement strategies. Sensor data and digital twins can also enhance the communication and collaboration among the railway stakeholders, leading to a safer, more efficient, and more sustainable transportation system.

5 SUMMARY

The article explores how digital twin technology can benefit the North American railroad industry in various aspects. Digital twin is a virtual model that mirrors the physical asset or system, using real-time data, simulation, and machine learning. Digital twin can help railways to optimize their planning, design, and operations, as well as to test and implement new solutions.

The article reviews the current research on digital twin and its applications in the railway infrastructure domain. It also presents some use cases that illustrate the advantages of digital twin for the North American railroad industry. Some of the use cases are:

Planning: Digital twin can help railways to evaluate and understand the existing condition of the infrastructure, manage and mitigate risks, and optimize communication among different stakeholders.

Design: Digital twin can help railways to assess the project impact, risks, and costs, and to compare different design alternatives and scenarios.

Operations: Digital twin can help railways to inspect the assets virtually, reduce operation costs and unplanned downtime, and enhance the performance and reliability of the infrastructure.

The article also discusses how digital twin can be integrated with other emerging technologies, such as the Internet of Things (IoT) and artificial intelligence (AI), to improve the overall railroad infrastructure. IoT and AI can provide more data and insights for the digital twin, as well as enable more automation and intelligence for the railway system.

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