

Applying digital twin technology to the modeling, monitoring, and optimization of railway infrastructure

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OPEN ACCESS

Citation:

Anatolii Yatsiuk (2026). Applying digital twin technology to the modeling, monitoring, and optimization of railway infrastructure. *Am. Impact Rev.* e88628301. [10.66308/air.e88628301](https://doi.org/10.66308/air.e88628301)

Received: August 5, 2026

Accepted: September 10, 2026

Published: September 14, 2026

DOI:

[10.66308/air.e88628301](https://doi.org/10.66308/air.e88628301)

ISSN: 3071-124X

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Abstract

This article examines how digital twin technology can be used to model, monitor, and optimize railway infrastructure. It describes the technological basis of railway digital twins, including how information models are built and how diagnostic data are used to assess the condition of infrastructure assets. The article reviews methods for fault prediction, repair planning, and improving maintenance efficiency, and analyzes experience with digital twins deployed for railway track, bridges, and stations. It identifies the main constraints on the technology: data integration, software interoperability, and information security. The review shows that digital twins expand the possibilities for modeling, monitoring, and managing the condition of railway infrastructure, and the international experience examined confirms that they are practically applicable to individual assets and infrastructure systems. Their effectiveness, however, depends on the reliability of input data, the interoperability of information platforms, and the quality of the computational models used. Finally, the article outlines promising directions for developing digital twins within railway infrastructure management systems.

Keywords: digital twin, railway infrastructure, condition monitoring, fault prediction, maintenance optimization, infrastructure management

1 Background

This study is motivated by the need to improve how the condition of railway infrastructure is monitored, to make its operation more reliable, and to increase maintenance efficiency. Track, bridges, tunnels, and other infrastructure assets are exposed to operating loads and environmental effects, so defects must be detected and the condition of structures assessed in good time. This gives particular importance to digital technologies that bring diagnostic, modeling, and monitoring results together in a shared information environment.

One promising approach is the use of digital twins, virtual models of physical assets that are linked to those assets through data exchange. The technology makes it possible to track changes in infrastructure condition, simulate how the infrastructure behaves under different operating conditions, and use the resulting information to predict faults and plan repair work. In the literature, digital twins are seen as a tool for moving from interval-based maintenance to maintenance based on the actual and predicted condition of assets.

At the same time, putting digital twins into practice requires integrating data from different information systems, ensuring that the digital models are accurate, and maintaining a continuous flow of information

between physical assets and their virtual representations. Existing studies also point to software interoperability problems, high implementation costs, and the need for cybersecurity. The capabilities and limitations of digital twin technology for modeling, monitoring, and optimizing railway infrastructure therefore merit closer examination.

1.1 Objective

This study aims to analyze the technological features and practical potential of digital twins for modeling, monitoring, and optimizing railway infrastructure, and to identify the main ways in which digital technologies can make infrastructure operation and maintenance more efficient.

2 Materials and methods

The materials included scientific publications, research findings on the digital modeling of railway infrastructure, technical documentation, and documents from European projects on digital twin deployment.

The study used literature review and synthesis, comparative analysis of technological solutions, systematic organization of data, and examination of practical experience with digital twins.

3 Results

The technological basis of a railway infrastructure digital twin comprises an information model of the asset, a system for collecting operational data, components for data transmission and storage, and software tools for processing the data. When such a system is developed, the geometric characteristics of the infrastructure must be reconciled with data on its actual condition. An architecture described in [1] integrates information on rails, track geometry, the ballast layer, and the overhead contact line within a common digital twin structure.

Figure 1 shows the architecture of a railway infrastructure digital twin system.

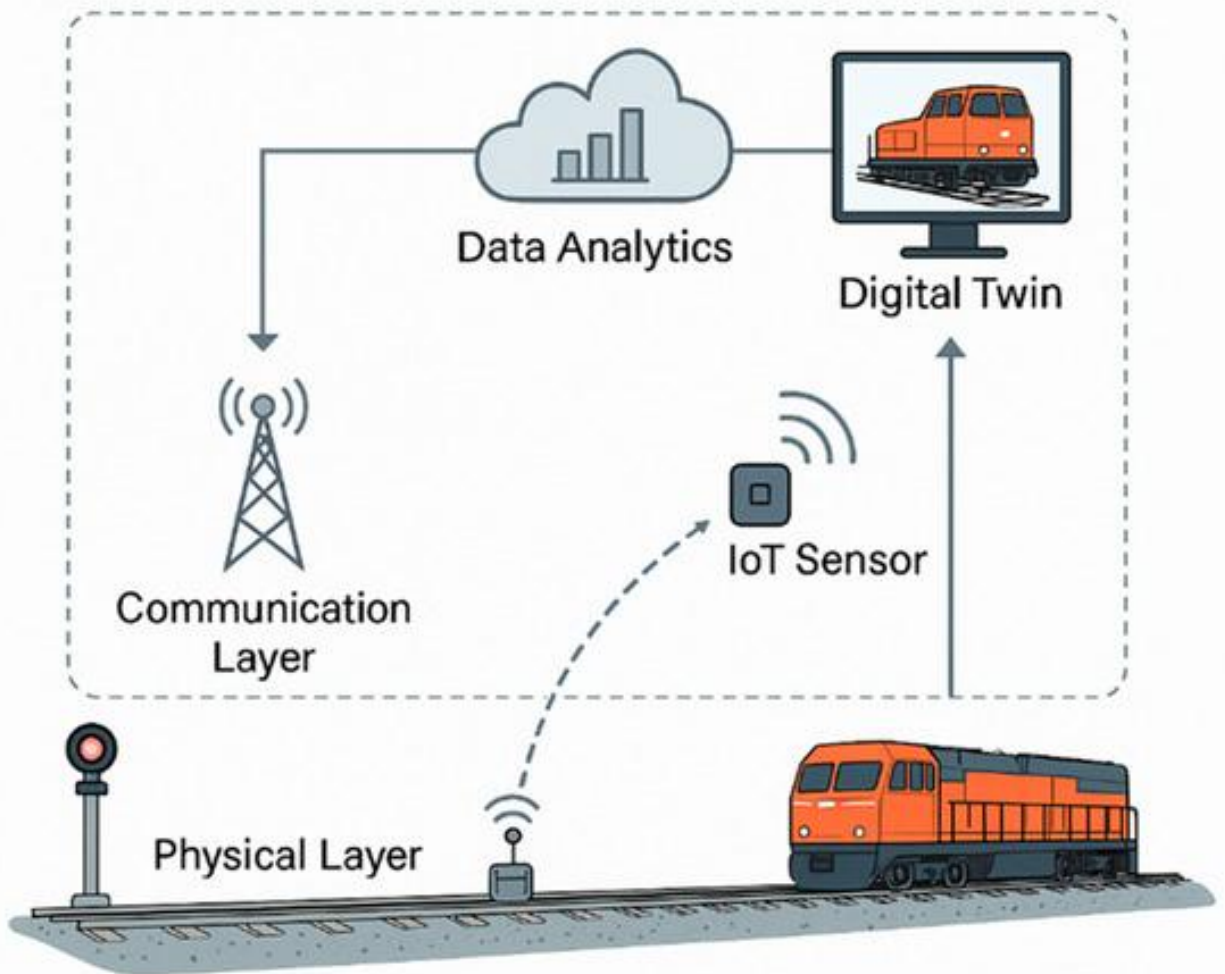


Figure 1. Architecture of a railway infrastructure digital twin system [4]

Spatial models are built using building information modeling (BIM), geographic information systems (GIS), geodetic survey data, and laser scanning. Data interoperability is supported, among other means, by the IFC 4.3 standard developed by buildingSMART International. Its railway extensions cover track, signaling, telecommunications, and power supply. Linear referencing mechanisms are particularly important, as they allow assets to be located relative to the track centerline [5].

Information is exchanged between the physical infrastructure and the digital model through measurement equipment and network interfaces. Depending on the asset under study, data sources may include accelerometers, strain gauges, temperature sensors, and diagnostic systems. The measurements are preprocessed and then used to update the model parameters. Machine learning methods can be applied to detect patterns in the accumulated data, while computational models can reproduce the mechanical behavior of structures.

Implementing a digital twin in practice requires standardized descriptions of infrastructure asset properties. The IFC 4.3.2.0 documentation provides dedicated classes for describing railways and their geometry. For example, the `IfcAlignment` class is used to define the alignment and the linear referencing of elements, and `IfcRailway` represents a railway as a spatial element [11].

Modular design is an important technological feature of digital twins. G. C. Doubell et al. show how separate digital representations of infrastructure elements can be combined through software services. Heterogeneous

data sources are connected through dedicated software interfaces that access the source databases without changing their structure. This approach allows the system to be extended by adding further assets and data sources [4].

Using digital twins to model railway track involves analyzing changes in track geometry parameters and in the condition of individual components. In a study published in Scientific Reports, J. Sresakoolchai and S. Kaewunruen examined a model that accounts for track geometry deviations and component defects. These data make it possible to study how faults develop on individual track sections and to evaluate changes in infrastructure condition during service [9].

In modeling railway bridges, it is important to determine the stresses and strains in structures under moving loads. In a study of high-speed railway bridges in the Spanish region of Extremadura, digital models were developed using the results of field load tests. Calculated and measured characteristics were compared to verify the initial design assumptions and to produce a model of the structure validated against measurements [3].

Digital twin-based monitoring of bridges can rely on analysis of structural vibrations as trains pass (Figure 2). In a 2024 study, A. Armijo and D. Zamora-Sánchez presented a system that uses wireless accelerometers to record vibrations of an operational railway bridge. The signals were analyzed in the frequency domain, and machine learning algorithms identified deviations from the characteristic vibration parameters. Such deviations are treated as signs of a possible change in the condition of the structure and call for further inspection [2].

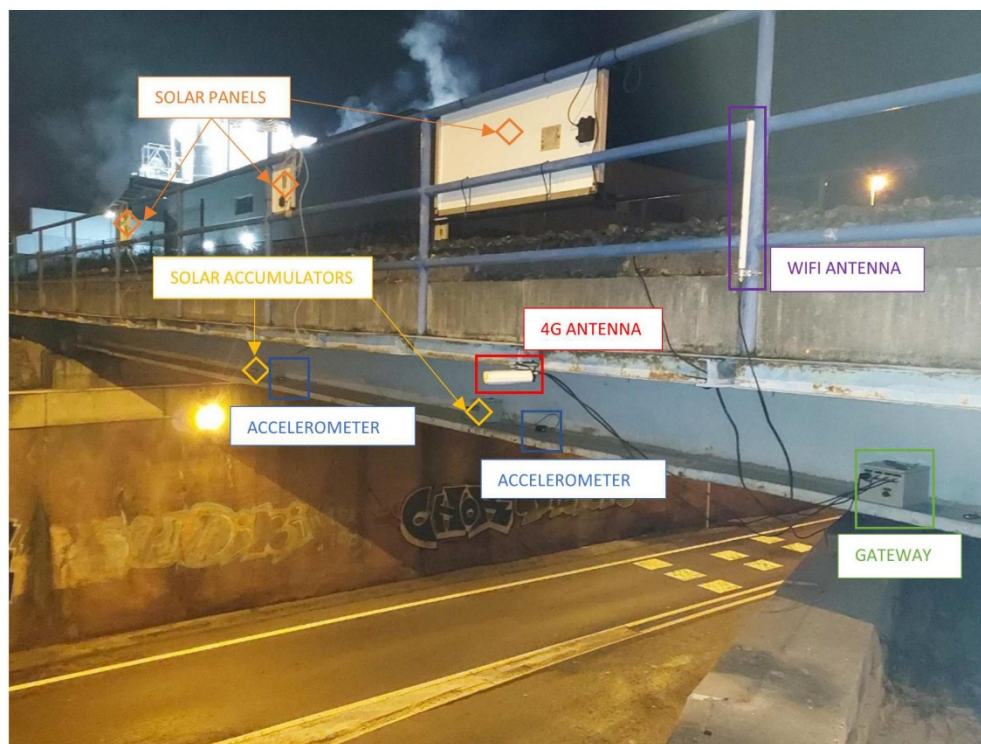


Figure 2. Example of instrumented monitoring of a railway bridge [2]

The table below summarizes the results of practical studies on the use of digital twins for railway infrastructure monitoring.

Table 1. Results of practical studies on the use of digital twins for railway infrastructure monitoring

Asset studied	Verified data	Outcome
Operational railway bridge, study by Armijo and Zamora-Sánchez (2024)	Vibration monitoring over 2 years	Training a model to recognize normal vibrations and automatically detect anomalies
Same bridge	On average, 2 train passages every 18 minutes	Building a dataset of vibration measurements under regular train traffic
Railway bridges in Extremadura, Spain (2024)	Field load tests of the structures	Verification of design assumptions and refinement of digital models

Source: [2], [3].

Accumulating successive measurements is especially important for monitoring, because a single deviation in a diagnostic parameter does not necessarily indicate damage. Comparing current data with previously recorded characteristics makes it possible to detect persistent changes in the dynamic behavior of a structure. Detecting an anomaly, however, is not the same as identifying a specific defect: further diagnostic investigation is needed to determine its nature.

Digital twins can improve maintenance planning for railway infrastructure by taking into account how quickly its components deteriorate, the cost of repair work, and operational constraints. The study reported in [8] proposes combining degradation models, the Weibull distribution, and a semi-Markov model to determine the cost-effective time for preventive intervention. With this approach, maintenance can be scheduled according to the calculated condition of the asset and the expected costs, rather than solely according to fixed intervals.

Another important area is the optimization of repair schedules with regard to infrastructure availability. A study of the French infrastructure manager SNCF Réseau examined the use of a digital twin to coordinate the parties involved in maintenance planning. The system integrates asset data and makes them available to departments for coordinating work. Its main purpose is to support better decision-making when maintenance and repair schedules are drawn up [10].

Figure 3 shows how a digital twin is used in railway infrastructure maintenance management.

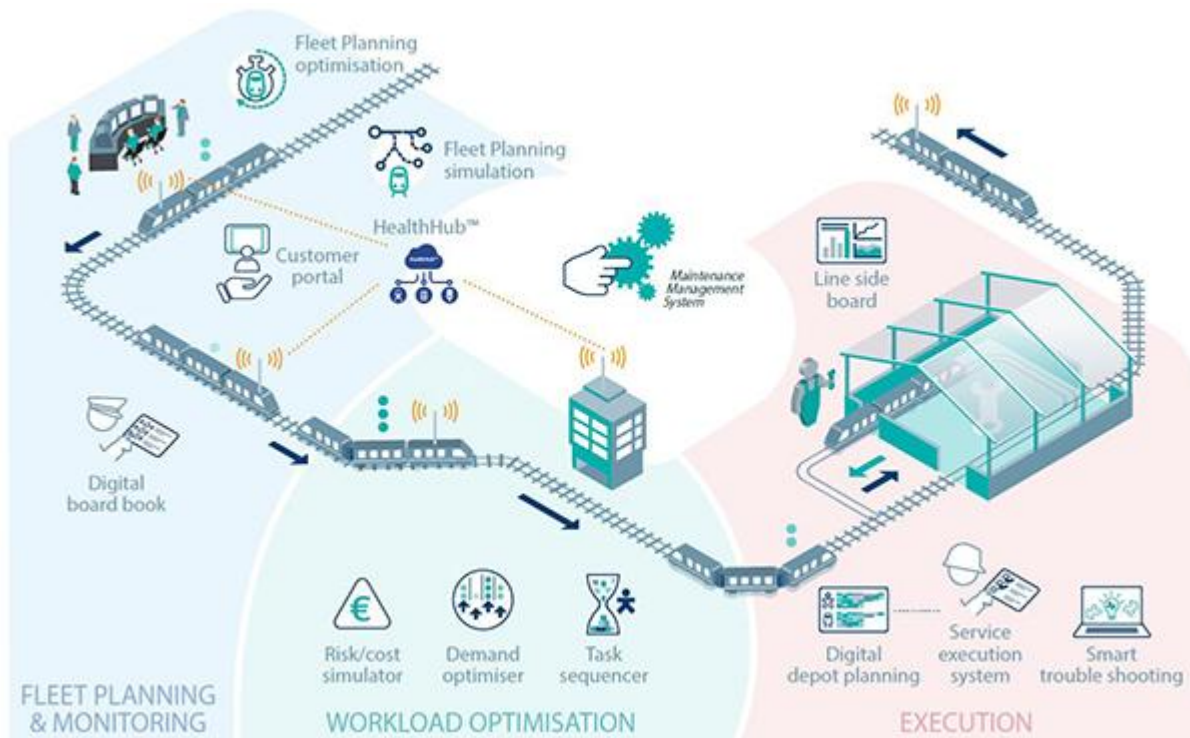


Figure 3. Use of a digital twin in railway infrastructure maintenance management [6]

Practical results have been obtained in European research on condition management for track and overhead contact lines. Within projects of Europe's Rail Joint Undertaking, tools have been developed for the digital representation of infrastructure assets, maintenance planning, and wear prediction. In particular, AVATAR, a software tool designed to support maintenance planning, has been deployed in ten maintenance units in France. This confirms that digital twins can be used not only for research purposes but also in the day-to-day operations of an infrastructure manager [6].

Gains in operational efficiency depend not only on lower maintenance costs but also on shorter traffic restrictions during repair work. Decisions should be evaluated in terms of intervention cost, probability of failure, duration of work, and consequences for train services. A study from Chalmers University of Technology on turnout maintenance proposes combining wear models with life cycle cost calculations to compare possible maintenance actions [7].

Optimizing railway infrastructure operation with digital twins therefore involves making well-founded choices about the timing and scope of repair work, coordinating work schedules, and comparing alternative solutions against technical and economic criteria. Published studies confirm that the approach is promising, but the size of the benefit depends on the characteristics of specific assets and their operating conditions.

Practical deployment of railway infrastructure digital twins is advancing in a number of European countries. Under Europe's Rail Joint Undertaking, projects have developed digital twins of railway track and overhead contact lines in France and Spain. The resulting solutions bring together data on asset condition, diagnostic inspection results, and wear prediction tools. The technology has reached technology readiness level 7 (TRL 7), meaning that a prototype has been demonstrated in an operational environment [6].

Railway station management is another potential area of application. Digital twins are among the topics addressed in the FP3-IAM4RAIL project, and solutions for stations are also being explored, for example, three-dimensional models that display the status of station equipment. Such solutions could help detect faults

more quickly and support operating staff, although published evidence of their effectiveness remains limited. Despite these results, wider adoption of digital twins is constrained by the difficulty of integrating heterogeneous data, limited interoperability between software platforms, high initial costs, and information security requirements. Prospects for the technology lie in standardized information exchange, better methods for predicting asset condition, and the combination of digital models of individual assets into integrated railway infrastructure management systems.

4 Conclusions

Overall, digital twins expand the possibilities for modeling, monitoring, and managing the condition of railway infrastructure. The technology allows diagnostic inspection results to be taken into account when predicting faults, scheduling repair work, and evaluating alternative maintenance options. The international experience reviewed here confirms that digital twins are practically applicable to individual assets and infrastructure systems. At the same time, the effectiveness of their deployment depends on the reliability of input data, the interoperability of information platforms, and the quality of the computational models used. Further development of the technology involves integrating digital twins of different infrastructure assets, improving prediction methods, and creating unified management information systems.

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