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DIGITAL TWINNING FOR RAIL TRACK COMPONENTS – FROM MONITORING TO REPORTING

Charitini Tsolaki[1, 2], Spyridon Arsenis[2], Konstantinos Gkiotsalitis[3], Savvas Triantafyllou[1]
[1]National Technical University of Athens, School of Civil Engineering, Laboratory of Structural Analysis and Aseismic Research, Greece
[2]AR.DE.CO. Technical Company, Greece
[3]National Technical University of Athens, School of Civil Engineering, Railways and Transport Laboratory, Greece

Abstract

Railway systems generate extensive and diverse datasets that often reach the scale of a big-data problem, yet much of this information remains underexploited due to limited integration between monitoring outputs, simulation tools, and visualization methods. Conventional approaches record local anomalies yet offer limited capacity to explain why these emerge or how they interact with broader network dynamics. Within this setting, we present a dedicated Digital Twin (DT) environment to capture the evolving condition of rail tracks. Detailed data from laser scanning, encoders, and inclinometers are analyzed and fused so that the digital representation reflects the current, “as-is”, state of the track. Next, network-wide diagnostic diagrams are developed, which condense extensive corridor information into a single visual output, enabling engineers to detect correlations, recurring behaviors, and system-level trends, while also revealing the unique characteristics and inherent particularities of each network. The workflow is complemented by holistic reporting, combining measurements, interpretations, and simulation insights into structured documentation that supports clear and transparent decision-making. The results show that the combined use of DT technologies and network-scale visualization techniques significantly enhances the capacity to analyze and interpret the performance of railway infrastructure.

Keywords: digital twin, railway assets, rail defects, monitoring, network-scale diagnostics

1 Introduction

Railway infrastructure monitoring is rapidly evolving, driven by the increasing availability and deployment of high-resolution sensing technologies over extended network lengths [1]. Modern monitoring campaigns routinely produce large and heterogeneous datasets, including three-dimensional geometric information, track geometry parameters, and localized defect indicators. While these data provide unprecedented insight into the physical state of the infrastructure, their growing volume, variety, and spatial density have effectively introduced a big-data challenge for railway operators and infrastructure managers [2-4].

In current practice, track condition assessment requires more than raw monitoring measurements. Operational conditions, including train speed profiles (with acceleration and braking phases), traffic load per interstation, and alignment features such as curves and gradients together with asset installation and maintenance history strongly influence the behavior of the track and the evolution of defects [5].

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Network studies show that degradation patterns may significantly vary between sections depending on local geometric and operational factors [6]. However, this contextual information is often scattered across different tools, datasets, and reports, creating a fragmented picture [7]. As a result, engineers must manually reconcile disparate sources to assess the condition of individual track sections; this hinders effective networklevel management and prioritization.

Within this context, DT concepts have emerged as a promising means of linking physical infrastructure assets with their digital representations [8, 9]. When applied to railway tracks, a DT can provide a structured framework for integrating monitoring data and derived condition information into a coherent representation of the current "as-is" state of the network. Nevertheless, the practical value of such representations depends not only on data integration, but also on the ability to interpret and communicate complex information in a manner that supports engineering judgement both at the corridor but also the network scales.

To address these challenges, we present a DT based workflow for rail track components that bridge monitoring, diagnostic visualization, and reporting. A trolley-based measurement system is used to capture high-resolution geometric and condition-related data. Data is then integrated into a three-dimensional "as-is" DT of the track. Based on this representation, section-based diagnostic diagrams are developed by condensing heterogeneous information into unified visual outputs for each station-to-station segment. These diagnostics are then incorporated into a structured reporting framework that supports transparent decision-making and targeted investigation of critical network sections.

2 Digital twinning

2.1 Monitoring data

The monitoring data used in this study is captured by a dedicated trolley-based measurement system operating along the railway track. The trolley integrates multiple sensing modalities, including a laser scanner and mechanical subsystems equipped with encoders and inertial sensors; combined, they enable the acquisition of high-resolution geometric and positional information. More specifically, the laser scanning system acquires transverse rail profiles at scanning rates of up to 5 kHz, allowing profile sampling at intervals as small as 1 mm along the track, with a measurement resolution on the order of 60 µm. Hence, dense three-dimensional representations of the rail track and its immediate surroundings are generated, capturing the physical state of the infrastructure [10]. These are compounded by the measurements from the encoders and inclination sensors, which provide the necessary input for the calculation of the track's geometry parameters, i.e. track gauge, track cant, and alignment, with resolutions of up to 0.138 mm. Despite these rich datasets, their size and heterogeneity challenge conventional assessment workflows, which do not systematically relate the measured data to alignment characteristics and network parameters.

2.2 "As-is" track representation

Using the monitoring data, a three-dimensional digital representation of the rail track is generated. Within this context, the DT is defined as a synchronized digital replica of the physical asset yet enriched with condition information obtained from the measurements. This interpretation is consistent with recent applications of DTs in railway engineering, where emphasis is placed on coupling measured asset conditions with their digital counterparts to support analysis and engineering decision-making [11].

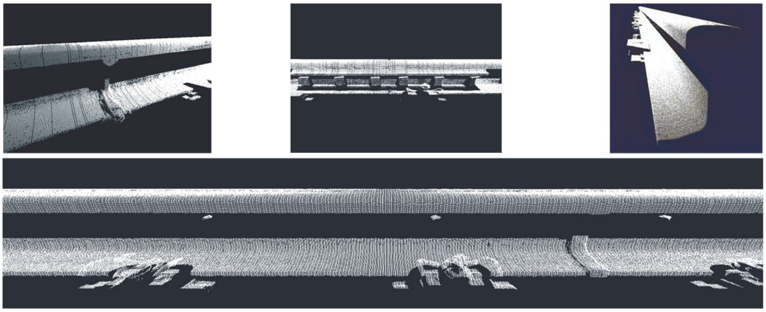

Figure 1 Three-dimensional point-cloud representation of the rail acquired by the trolley-based monitoring system

To construct the three-dimensional “as-is” track representation, the data gathered from multiple sensing sources are integrated within a common spatial reference framework. First, point clouds are generated from laser scanning providing the geometric basis of the DT. These are then fused with measurements derived from the mechanical subsystems. The integrated dataset supports the derivation of condition indicators, including rail wear metrics and the detection of localized surface defects such as squats [12]. This data fusion process aligns heterogeneous datasets and preserves their spatial relationships, allowing the DT to represent track condition as a coherent and continuous entity. Crucially, the DT aggregates geometric and condition information into a unified representation. This enables a purely automated workflow for the signposting of critical sections.

3 Network-scale diagnostic visualization

3.1 Diagnostic visualization framework

The diagnostic visualization framework developed in this work integrates geometric, condition-related, and contextual information derived from the DT into unified visual representations for network-level assessment. In addition to the track geometry and condition indicators provided by the DT, network-related features, i.e. alignment characteristics, station locations, and section-level operational context are incorporated within the same visual representation to support interpretation. The visualization logic is applied uniformly along the corridor, enabling comparable representations across the network while preserving spatial continuity. Hence, complex and heterogeneous information is condensed into interpretable diagnostic views that support qualitative assessment and form the basis for subsequent reporting. An overview of the proposed DT workflow, illustrating the transition from the physical asset to data acquisition, digital representation, diagnostic analysis, and feedback to the physical system, is shown in figure 2.

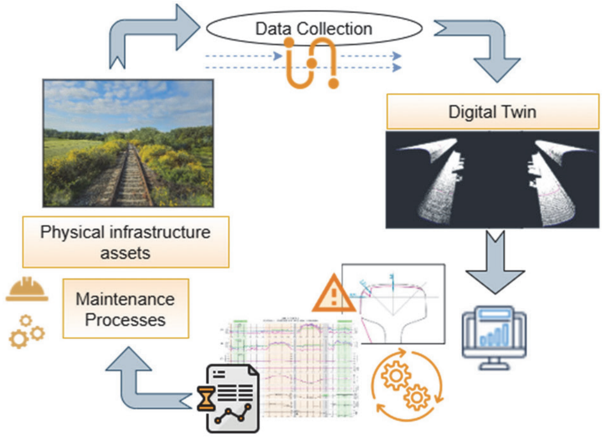

Figure 2 Digital Twin workflow

3.2 Integrated diagnostic diagrams

Based on the diagnostic visualization framework described in section 3.1, dedicated diagnostic diagrams are generated to present the integrated DT information in a compact and interpretable form. Each diagram corresponds to a discrete evaluation unit along the railway corridor, defined for practical and operational reasons between successive stations. This station-to-station organization provides a consistent spatial structure for presenting results while maintaining continuity along the network. Each diagnostic diagram consolidates multiple layers of information into a single visual output. Track geometry parameters are displayed together with condition indicators, i.e. rail wear metrics and localized surface defects. In addition, network-related features are incorporated within the same visual representation. The combination of these elements enables spatial correlations and contrasts to be observed across the network, supporting interpretation of track condition in relation to geometric and operational context without the need to consult separate sources. To support rapid overall assessment, selected indicators are additionally represented using consistent color scales. When viewed collectively, the set of diagnostic diagrams provides a holistic overview of track condition across the network. Presenting multiple sections within a common visual framework allows recurring behaviors, contrasts between sections, and network-specific characteristics to emerge naturally. An example of such a corridor-level overview is shown in figure 3, where multiple section-based diagnostic diagrams are arranged together. In this representation, diagrams (A) and (B) depict rail head wear values (side, vertical, and radial) along the interstation for each rail. Diagrams (C) and (D) present theoretical and measured track gauge together with gauge deviation on specific bases, while Diagram (E) illustrates theoretical and measured track cant (superelevation). Together, these diagrams provide a comprehensive, multi-parameter view of track geometry and condition for each interstation segment within a single, consistent visual framework.

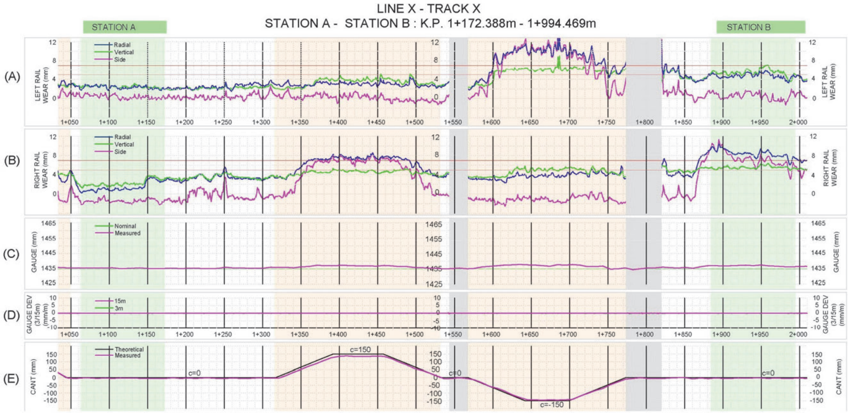

Figure 3 Overview of section-based diagnostic diagrams presented together for a railway corridor

4 Reporting framework for decision support

The diagnostic outputs produced by the DT based visualization framework are organized into a reporting structure aimed at supporting decision-making and strategic assessment at network level. More specifically, the diagnostic diagrams are incorporated into structured reports that provide operators with a clear and coherent overview of track condition along the corridor. Using consistent color-coded indicators within the diagrams enables rapid overall evaluation of track condition and facilitates identification of critical sections and priorities, as illustrated in figure 4. This organization supports understanding of the network as a whole and enables informed discussion of condition-related priorities among different stakeholders. When applied to consecutive monitoring campaigns, the reporting framework also supports the assessment of condition evolution over time. By consistently presenting diagnostic information across successive measurements, changes in defect severity, wear progression, or geometric response can be identified and tracked. While the present work focuses on diagnostic visualization and reporting, such longitudinal information provides a foundation for predictive maintenance strategies, enabling operators to anticipate when defects may approach critical thresholds and to plan interventions proactively. In this way, the reporting framework acts as a decision-support layer that bridges current condition assessment and longer-term maintenance planning.

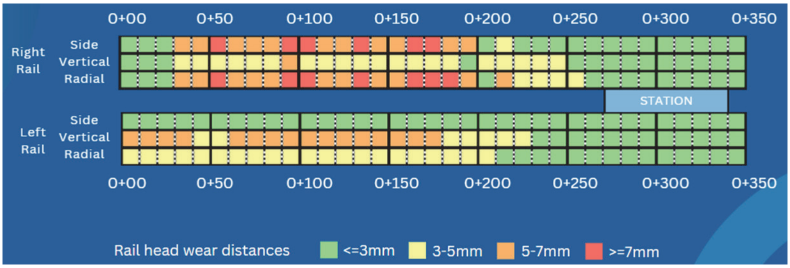

Figure 4 Example diagnostic diagram with color-coded indicators used to support rapid overall evaluation of track condition

5 Application

The proposed workflow was applied to a railway corridor monitored using the trolley-based measurement system described in section 2. The surveyed track included multiple consecutive interstation segments with varying alignment characteristics, including curves, gradients, and station approaches, providing a representative test case for network-level assessment.

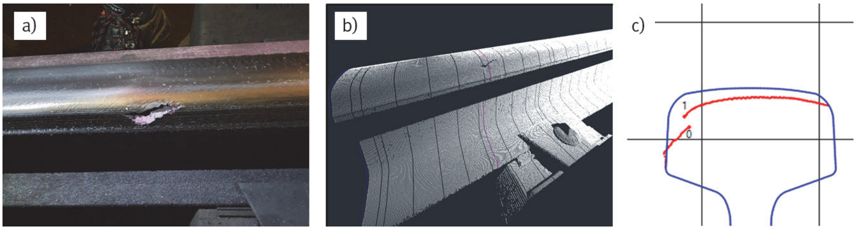

Figure 5 Localized rail surface defect (squat)(a) represented across different levels of the DT (b, c)

In figure 5, a localized rail surface defect (squat) is represented across different levels of the DT, from physical inspection (figure 5a) to its three-dimensional point cloud representation (figure 5b) and an extracted two-dimensional rail head profile (figure 5c). Together these representations illustrate how physical observations are linked to digital representations and measurable condition indicators within the proposed framework.
Following, diagnostic diagrams were generated for the surveyed sections based on the approach described in section 3 including also the two-dimensional rail head profiles corresponding to the most critical wear values as shown in figure 6. In figure 6 (left) a localized squat has been identified, and the pertinent geometric features such as depth and longitudinal extent are measured. In figure 6 (right) the dimensions of rail head wear are identified, including side wear, vertical wear, and radial wear, providing a concise quantitative reference that complements the visual diagnostics.

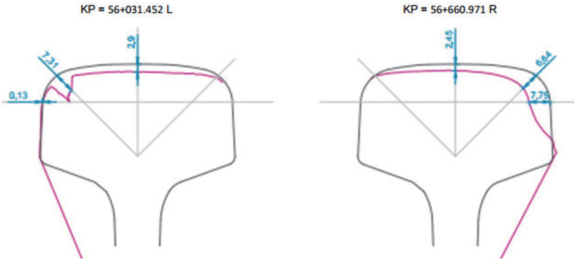

Figure 6 Extracted two-dimensional rail head profiles

Differences in relative rail wear patterns between two consecutive curved track sections become visually distinguishable when examined within the integrated diagnostic visualization framework (figure 7). By considering the diagrams together, contrasts in wear distribution can be related to curve direction, supporting interpretation of section-level behavior within its geometric and network context.

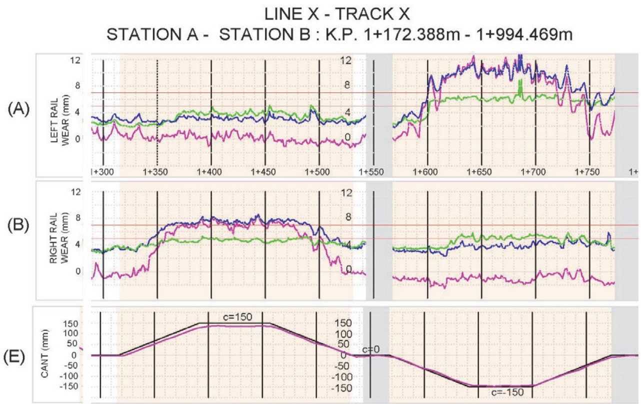

Figure 7 Diagnostic diagrams for two consecutive curved track sections

6 Conclusion

This work demonstrated how a DT–based approach can support holistic interpretation of railway track condition and contribute to more integrated railway asset management. By condensing heterogeneous information into unified visual representations, the proposed framework enables engineers and operators to understand track behavior in its spatial and operational context and to support informed decision-making. As a next step, future work will focus on exploiting consecutive monitoring campaigns to support predictive maintenance, with particular emphasis on the use of machine learning techniques for automated defect detection and assessment of condition evolution.

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