Advances in
Mechanical
Engineering

Advances in Mechanical Engineering
2026, Vol. 18(2) 1–3

DOI: 10.1177/16878132261426614
journals.sagepub.com/home/ade
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Advances in railway vehicles and infrastructure engineering

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Keywords
rolling stock, railway track, simulations, testing, efficiency, environmental impact

The present Special Collection is devoted to current advances in railway vehicles and infrastructure engineering, a field that has gained renewed strategic importance in the context of sustainable mobility, climate goals, and the rapid development of transportation systems. Rail transport is increasingly expected to combine high levels of safety, energy efficiency, environmental performance, and operational reliability, while simultaneously responding to growing demands for capacity and speed. The Special Collection brings together 11 contributions that reflect these challenges and offer an interesting overview of recent methodological, technological, and applied research directions that shape contemporary railway engineering.

One of the most important topics in contemporary railway transportation is safety and the associated maintenance and condition monitoring, as it directly influences operational reliability, public trust, and the long-term sustainability of rail systems. With increasing traffic density, higher operating speeds, and the integration of advanced digital technologies, ensuring a high level of safety has become more complex and more critical. Modern safety approaches encompass not only robust infrastructure and rolling stock design, but also sophisticated signalling systems, real-time monitoring, human–machine interaction, and comprehensive risk management frameworks. Effective safety management reduces the likelihood of accidents, minimizes their potential consequences, and supports the resilience of railway networks in the face of technical failures, human error, and external threats. Consequently, safety is not only a regulatory requirement but a fundamental prerequisite for the competitiveness and societal acceptance of railway transport in contemporary mobility systems. The topic of safety is addressed in various ways in the seven papers of our Special Collection.

Bianchi et al.[1] provide a comprehensive systematic review of railway infrastructure monitoring techniques, tracing the evolution from traditional inspection methods to modern predictive maintenance strategies. Their review establishes a unifying framework for structural health monitoring (SHM) of railway tracks and clearly identifies future research directions, concluding that SHM will lead to an increase in the resilience and efficiency of mobility systems.

Bernardin et al.[2] are also involved in infrastructure monitoring focusing on damage detection for railway bridges. Using continuous wavelet transform and sparse autoencoders applied to bogie vertical acceleration measurements, the authors demonstrate how passing trains can be exploited as moving sensors for infrastructure condition assessment. A promising damage detection performance was obtained, even in the

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presence of measurement noise and speed estimation inaccuracies. This contribution exemplifies the shift towards cost-efficient, non-intrusive monitoring solutions that reduce the need for dedicated sensor installations on structures.

A vehicle derailment as one of the most serious incidents from a safety perspective is further addressed by Santelia et al.,[3] who present a detailed multibody numerical investigation of post-derailment dynamics, comparing guard rails, and derailment containment walls. By modelling the entire trainset rather than a single vehicle, this study provides more realistic predictions of impact forces and containment effectiveness. The results offer valuable guidance for the design of mitigation measures in high-risk sections of the railway network.

Fault detection and condition monitoring represent a key area of interest not only in the context of railway infrastructure but also with respect to railway vehicles. Cui et al.[4] investigate wheel flat detection combining advanced machine learning methods and vibration data acquired from a 1:10 scale railway test rig with the aim of developing highly accurate diagnostic tools. The performance of long short-term memory (LSTM) and Transformer models for wheel flat detection is evaluated. The study also confirms the effectiveness of scaled experimental test rigs for data generation and demonstrates the strong potential of Transformer-based approaches for reliable wheel condition monitoring, contributing to improved safety and maintenance efficiency in modern railway systems.

From a different perspective, Li et al.[5] are concerned with the safety of rail vehicles. Their work aims to develop a device that can accelerate the test vehicle during crash tests using a set of air springs. A numerical framework for predicting the ejection performance of series–parallel air spring systems used in high-energy railway collision testing is presented and a coupled fluid–structure finite element model is developed to analyse the effects of air spring configuration, pressure, and geometry on ejection parameters. The study confirms the effectiveness of series–parallel air spring systems as a controllable ejection mechanism while maintaining a safe wheel–rail interaction without derailment.

From a safety perspective, it is also essential to reliably stop the vehicle within the prescribed braking distance. Wheel–rail adhesion and braking performance are examined in the contribution of Zhou et al.,[6] which analyses the effectiveness of sanding and its impact on the braking of a subway vehicle under low-adhesion conditions. Through laboratory tests and simulations, the authors provide quantitative evidence supporting the installation of sanding devices on metro vehicles, thus linking detailed tribological analysis with practical safety recommendations.

The use of digital twin technology eases the integration of physical and virtual spaces, thus offering significant potential for the enhancement of train operational safety compared with traditional approaches. Dong et al.[7] presents a digital twin framework for simulating train dynamics during curved track passage using a model–data fusion approach based on extended Kalman filtering (MDF–EKF). The method combines physical modelling with real-time multi-sensor data to estimate train operating states under nonlinear and uncertain conditions. A three-dimensional virtual train and track model is developed and validated through a case study, showing that the proposed approach outperforms other methods in terms of accuracy while satisfying real-time requirements. The results demonstrate the potential of the MDF–EKF-based digital twin to support a safety assessment and operational reliability of trains on curved tracks.

However, rail transportation encompasses not only urban services and long-distance high-speed passenger travel; a substantial share of rail activity is still devoted to freight transport, which is addressed in three papers included in this special collection.

The behaviour of long freight trains is fundamentally influenced by longitudinal dynamics, which is addressed in the work by Lanzillo et al.[8] The authors introduce SIMTRAD, a modular Simulink-based framework to simulate the longitudinal dynamics of freight trains, capturing detailed interactions among locomotives, wagons, couplers, and adhesion. SIMTRAD enables the design of locomotive placement and payload distribution targeting the optimization of longitudinal tensile and compressive forces acting along the trainset. It represents a flexible and optimized tool for both research and industrial applications in the safe and efficient operation of long freight trains.

The contribution of He et al.[9] also targets on heavy-haul trains facing significant challenges from actuator saturation, which can compromise both tracking accuracy and operational safety. This study presents an unbounded anti-windup terminal sliding mode controller (UAW–TSMC) that enables each locomotive to track target displacement and velocity rapidly and precisely, even under input saturation. Simulation and semi-physical experiments confirm that the UAW–TSMC outperforms traditional approaches, in minimizing tracking errors, suppressing oscillations, and enhancing stability. This method offers a robust and practical solution for improving the safety, reliability, and efficiency of modern heavy-haul railway operations.

The behaviour of a freight railway bogie on a test bench is addressed by Bustos et al.[10] This study presents a dynamic model of 21-degrees of-freedom of a Y-25 freight bogie tested on a unique full-scale double roller rig at BOGLAB laboratory. Such a roller rig has specific configuration, where each wheel of the front wheelset is supported by two small rollers. Simulation results show motion transmission from the front to the rear wheelset due to the specific configuration of this test bench and reveal that vertical accelerations in the axle boxes increase with load, while speed effects are nonlinear, with a threshold above which accelerations significantly increase.

Finally, Goolak et al.[11] deal with traction drive system modelling. The authors propose an enhanced simulation model of an induction motor that enables the analysis of electromechanical processes in traction drive systems, considering the specific characteristics of electric transport operating modes.

Simulation-based analyses are becoming increasingly important in the research of rail vehicle behaviour and railway infrastructure due to their ability to efficiently investigate complex mechanical, dynamic, and electromechanical phenomena under a wide range of operating conditions. Advanced simulation models enable detailed studies of vehicle–track interaction, structural loads, energy consumption, and system reliability already in early design stages, significantly reducing development time and costs. In all papers presented within this special collection, mathematical modelling and simulations play a key role. However, despite continuous progress in modelling techniques and computational capabilities, experimental investigations remain indispensable for validating simulation results and capturing real-world effects, that still cannot be fully represented in numerical models. The importance of physical experiments is also reflected in the contributions to this special collection, where a substantial portion of the works goes beyond purely simulation-based results and incorporates experimental validation. Due to the organizational complexity, high costs, and occasional infeasibility of vehicle-level on-track testing, dedicated test benches tailored to specific testing goals are widely utilized. Li et al.[5] and Bustos et al.[10] contribute to the development of such testing facilities. In many cases, experiments on scaled models provide a practical and effective approach, as illustrated by the studies presented in Cui et al.[4] and Zhou et al.[6] The connection between the physical system and the simulated environment can be obtained by hardware in the Loop and related approaches, as presented in Lanzillo et al.[8] and He et al.[9]

The Guest Editors wish to extend their sincere gratitude to the publisher for the opportunity to serve as Guest Editors of this Special Collection and for their support throughout the editorial process. We also express our deep appreciation to all contributing authors for their exceptional submissions. The high quality and originality of the contributions have been instrumental in shaping this collection and advancing the state of the railway engineering field.

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