

Mirroring Reality: The Rise of Digital Twins in Vehicle Development

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Abstract. Facing complex vehicle systems and the need for efficient development, the automotive industry increasingly adopts digital twin technology – virtual replicas of physical vehicles – as a solution. This paper explores this adoption, investigating how digital twins improve design, accelerate testing and validation, and contribute to overall vehicle development. It aims to demonstrate the value of digital twins in reducing costs, improving quality, and accelerating innovation. The paper highlights challenges, future directions in vehicle engineering, practical applications for automotive engineers, and impacts on traditional methodologies. Synthesizing trends and best practices, it provides an overview of digital twins' impact across the entire vehicle development lifecycle, highlighting their potential to transform processes and unlock innovation for automotive engineering, research, and technology development communities.

Keywords: digital twin, virtual testing, automotive engineering, vehicle development.

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Introduction

The automotive industry is undergoing a transformative shift, driven by the rapid adoption of digital technologies that are reshaping traditional development processes. Among these innovations, the concept of Digital Twins has emerged as a vital tool in vehicle development, offering unprecedented capabilities to simulate, analyze, and optimize real-world systems in a virtual environment. A Digital Twin is a dynamic, digital replica of a physical asset or system that mirrors its behavior in real-time, enabling engineers to predict performance, diagnose issues, and enhance design efficiency (Grieves & Vickers, 2017). This technology has gained significant attention in recent years, particularly in the automotive sector, where the complexity of vehicle systems demands advanced solutions for design, testing, and maintenance.

The rise of Digital Twins in vehicle development is not a technological trend but a response to the growing demands for innovation, sustainability, and cost-effectiveness in the automotive industry. As vehicles become increasingly complex, with the integration of electric powertrains, autonomous driving systems, and connected technologies, traditional development methods are proving inadequate and are slowly being replaced (Cvetkov, Zhilenkova, & Zhilenkov, 2021).

This article explores the research question: How are Digital Twins revolutionizing vehicle development, and what are the key benefits and challenges associated with their implementation? The study investigates the hypotheses that Digital Twins can significantly enhance vehicle design and testing processes, reduce development costs, and improve predictive maintenance capabilities. By analyzing case studies and industry practices, the research aims to provide a comprehensive understanding of the role of Digital Twins in modern automotive engineering and their potential to shape the future of vehicle development.

Methodology

A concise literature review was conducted on the evolution of digital twins in vehicle development, searching the databases from IEEE, Elsevier, Springer and Dimensions Research using keywords such as "digital twin," "virtual testing," "automotive engineering," "vehicle development," "electric vehicles," and "predictive maintenance." Selected studies were screened for relevance and synthesized to identify applications, benefits, challenges, trends, and best practices. Main research questions: (1) How do digital twins improve virtual testing and validation in vehicle development? (2) What is the impact of digital twins on lifecycle cost and predictive maintenance for electric vehicles? Research hypotheses: (H1) Digital twins significantly reduce physical testing time and costs; (H2) Integration of real-time data in digital twins improves predictive maintenance accuracy for electrical vehicles.

Case studies: areas of implementation of digital twins in the automotive industry

Vehicle design and testing

A key advantage of digital twins is their ability to replace or supplement expensive physical prototypes with virtual validation. For example, digital test benches can simulate suspension, braking, and cooling systems, letting engineers evaluate safety and comfort features without risk or the cost of building multiple physical models. This approach speeds development, cuts costs, and helps engineering teams identify problems earlier in the design process (Cvetkov, Zhilenkova, & Zhilenkov, 2021). In Formula 1 and general automotive development, digital twins have been shown to shorten design cycles (Nikita, Smolyaninov, Deniskin, Polity, & Mangushev, 2023).

Another study by Katzorke et al. emphasized the role of digital twins in virtual proving grounds, which replicate real-world track and environmental conditions such as adverse weather. Mercedes-Benz has started implementing a digital proving ground twin, demonstrating the research's practical relevance and its potential for reducing road accidents and emissions (Katzorke, Vinçon, Kolar, & Lasi, 2023).

Automated and Autonomous Driving

In automated driving systems, DTs reduce the "reality gap" between simulations and real-world testing. Low-fidelity digital twins are simplified virtual recreations (approximate vehicle dynamics and trajectories, simplified sensors) and can be automatically generated from recorded vehicle data, allowing repeatable and scalable scenario testing for autonomous driving software (Vlasak, Klapálek, Kollarčík, Sojka, & Hanzálek, 2024).



Figure 1. SAE J3016: Levels of driving automation.

Source: (SAE, 2021)

Another recent study published by K. Ling in 2023 approaches another interesting subject: acquiring vast amount of data directly from customer fleets.

Ling's research proposes a decision support system (DSS) framework that utilizes vehicle usage data, combined with specific data from testing fleets, physical vehicle models, and designed evaluation models. This framework enables the creation of digital twins that reflect real-world customer behavior without compromising individual privacy. The digital twinning process involves a structured four-step methodology: pre-processing, profiling, simulation, and post-processing. A key element is the aggregation of customer fleet data into usage statistics, which are then used to parameterize simulations.

To validate the approach, Ling conducted a proof-of-concept study involving a fleet of over 57,000 vehicles. The results showed that the resulting DTs were able to cover 99% of the defined evaluation metrics with an average fleet twinning accuracy of 91.09%, demonstrating the feasibility and potential of the proposed framework (Ling, 2023). In Figure 2 it is shown the Decision Support System presented in this paper.

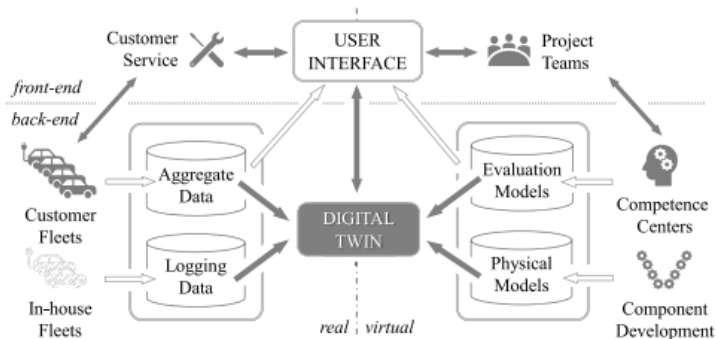


Figure 2. An overview of the Decision Support System.
Source: (Ling, 2023)

Electric Vehicles and Powertrains

The number of electric and hybrid vehicles (EVs, HEVs) is rapidly increasing. According to a study published by Xiaokang Li, Wenxu Niu and Haobin Tian in 2024, the sales for the electrical vehicles are predicted to equal the sales for the ICE (internal combustion engine) vehicles by 2040 and to make up to 80% of the total vehicle sales by 2050 (Li, Niu, & Tian, 2024).

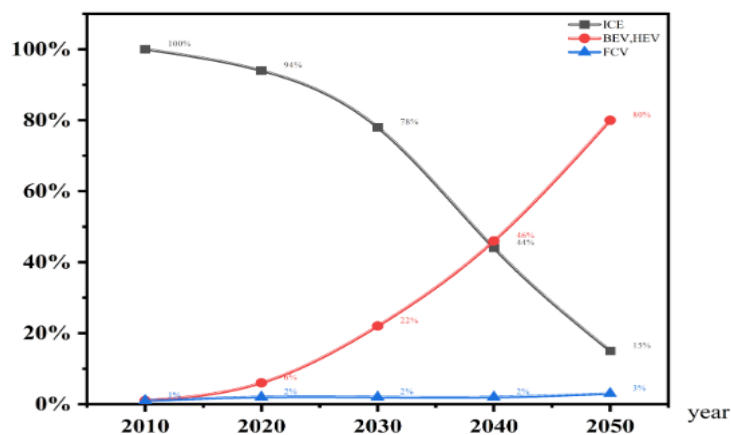


Figure 3. Global trends of EV, ICE and FCV markets.
Source: (Li, Niu, & Tian, 2024)

Therefore, the same study emphasizes the need for Digital Twin (DT) introduction in the electric vehicle (EV) industry for several key reasons. First, the expanding EV market is bringing increased complexity in vehicle systems, especially the powertrain. Digital Twins offer a solution by enabling monitoring, simulations, and predictive capabilities, which are essential for managing and optimizing these systems. A crucial area for DT application is optimizing powertrain design and performance. By creating virtual representations of the power source, electronics, and motor, digital twins can simulate operating conditions to identify problems and improve

efficiency. Furthermore, digital twins are set to change Battery Management Systems (BMS). Since batteries are a major cost and performance factor for EVs, digital twins' ability to monitor battery health, predict lifespan, and optimize charging becomes crucial.

Another important study conducted by Arun Jose and Sonam Shrivastava, published in Elsevier, highlights the applications of digital twins in electric vehicles and analyzes possible future directions for further implementing toward Industry 5.0. It highlights how digital twins have transformed manufacturing processes by improving optimization, design, maintenance, and safety. The study conducts a bibliometric analysis of 328 papers to provide an overview of digital twin technology since 2003, exploring classifications, applications, and usage in the automotive industry, particularly for electric vehicles and battery management systems (BMS). A thorough critique of recent literature is presented, offering insights for practitioners and researchers to conceptualize digital twin applications. The article introduces a structure resembling an inverted pyramid divided into five sections and identifies research gaps in practical digital twin implementations, alignment with Industry 5.0, and domain-specific reviews. It also discusses digital twin's role in smart cities, construction, healthcare, and the oil and gas sector, as well as recent advances in battery management. The review concludes by emphasizing digital twin's significance in the automotive industry, particularly for electric vehicles, and its potential to improve efficiency and sustainability (Li, Niu, & Tian, 2024).

A third study published by Li et al. explores using digital twin technology to improve the testing and development of electric vehicle (EV) powertrains. It focuses on the potential of digital twins for optimization and improvement within the electric vehicles' powertrain, while also addressing the complexity of this technology and its benefits (Li, Lei, Yang, Xu, & You, 2024).

Digital Twins in Predictive Maintenance

There are several applications of Digital Twins in Predictive Maintenance which are being increasingly used by the development teams nowadays.

Brake systems: Rajesh et al. created a digital twin of an automotive brake pad. The authors create a digital twin model of a brake pad and rotor using a software, integrating real-time data collected from a physical brake system via an IoT platform. Brake pressure is measured at different vehicle speeds and this data is then used to simulate brake wear in the digital twin model. The simulated wear data is compared to analytically calculated wear, showing good correlation. The goal is to develop a system that can gather real-time data from vehicles in use, enabling big data analytics for prescriptive maintenance of brake pads. The paper demonstrates that digital twins can predict brake-pad wear and enable proactive maintenance—capabilities not yet adopted by OEMs in advanced solutions. It acts as a proof of concept and recommends future work to build full-vehicle digital twins with more sensors and subsystems (Rajesh, Manikandan, Ramshankar, Vishwanathan, & Sathishkumar, 2019).

Thermal management: Karkaria et al. (2024) developed a digital twin framework with transformer-based models for predicting tire degradation, providing confidence intervals around tire life estimates. By employing data reduction techniques, a Temporal Fusion Transformer (TFT) model is trained to predict future tire health, quantified as Remaining Casing Potential (RCP), while also assessing prediction uncertainty. The digital twin accurately predicts tire health, continually improves its digital representation, and supports informed maintenance decisions, leveraging big data and machine learning for enhanced outcomes (Karkaria, et al., 2025).

Production systems: a study conducted by F. Pohlkoeter et al. discusses developing a hybrid predictive maintenance system using digital twins. The five authors, BMW engineers, argue how these systems can significantly improve production processes. By predicting potential failures of the, maintenance can be scheduled proactively, minimizing unexpected downtime. This leads to better utilization of equipment, reduced maintenance expenses, and assurance of consistent product quality. The overall impact is a more efficient, reliable, and cost-effective production environment (Pohlkötter, Straubinger, Kuhn, Imgrund, & Tekouo, 2023).

Challenges

One of the biggest challenges currently encountered is the Research-Practice Gap. Chen et al. identify a mismatch between academic advances in AI-enhanced DTs (deep learning, reinforcement learning) and industrial adoption,

citing barriers like scale, integration complexity, and workforce readiness. They highlight the gap between theoretical models and practical deployment in factories. This suggests digital twin progress risks remaining blocked in academia without translation into industry (Chen, Bekar, Bokrantz, & Skoogh, 2025).

Similarly, two other studies emphasize the idea that the technical challenges are yet to be overcome at a large scale. Najm Us Sama et al. argue that one of the most pressing challenges is the lack of clarity on the enabling technologies and architectural frameworks for digital twins, leading to inconsistent implementations across the automotive industry (Sama, Jhanjhi, Humayun, & Rahman, 2021). In addition, Müller et al. are pointing out the fact that system reliability engineering in Industry 4.0 faces difficulties in data handling, integration of complex cyber-physical systems, and the need for accurate, fast simulation models (Müller, et al., 2025).

Lastly, a critical challenge and a big question is related to ROI – Return of Investment. While the applications of digital twins are theoretically unlimited, there still needs to be clarity about the costs of implementation and the return of investment. A study by Kristof Banyai and Laszlo Kovacs argues that Digital Twins can yield measurable and considerable economic gains but they require high upfront investment (Banyai & Kovacs, 2023).

Results and further discussions

The literature review reveals that digital twins offer significant potential to revolutionize vehicle development processes. Digital twins enable faster design iterations, reduced development costs, and improved product quality.

The adoption of digital twins is most evident in areas like vehicle design and testing. For example, virtual test benches simulate suspension, braking, and cooling systems, allowing engineers to evaluate safety and comfort features without risk or the cost of building multiple physical models. Digital twins are also used for electric vehicle powertrain optimization. By creating virtual representations of the power source, electronics, and motor, digital twins can simulate operating conditions to identify problems and improve efficiency. Lastly, digital twins have several applications in predictive maintenance, allowing development teams to schedule maintenance proactively, minimizing unexpected downtime, leading to better utilization of equipment and reduced maintenance costs.

However, the research also emphasizes some notable challenges. The "Research-Practice Gap" refers to the disconnect between advanced AI-enhanced digital twin models developed in academic settings and their practical adoption in industrial environments, citing barriers like scale, integration complexity, and workforce readiness. This gap suggests that the theoretical benefits of digital twins may not always translate into tangible improvements in real-world applications.

Technical complexities also pose a significant challenge. Data handling and system integration are particularly problematic, as digital twins rely on vast amounts of data from various sources. Ensuring the accuracy and compatibility of this data requires sophisticated data management systems and integration strategies. This suggests a need for standardized architectural frameworks for digital twins, leading to consistent implementations across the automotive industry.

Finally, there is the issue of return on investment (ROI). While digital twins offer many potential benefits, implementing and maintaining them can be expensive. Therefore, it is essential to develop clear methodologies or practices for assessing the economic benefits of digital twin implementation.

Conclusion

Digital twin technology represents a transformative force in the automotive industry, enabling unprecedented capabilities for simulating, analyzing, and optimizing vehicle systems. By creating virtual replicas of physical vehicles, digital twins offer valuable insights into vehicle performance, enabling engineers to make informed decisions throughout the development lifecycle. While the adoption of digital twins is still in its early stages, the potential benefits are clear. As technology continues to evolve, it is expected that digital twins will play an increasingly important role in shaping the future of vehicle engineering, driving innovation, and improving the overall sustainability of the automotive industry.

The paper emphasizes the transformative potential of digital twins, especially in areas like electric vehicles and predictive maintenance. By combining findings from various sources, including in-depth academic studies,

industry reports and technical publications, this review provides an overview of the current state, challenges and future directions of this field.

Finally, it serves as a comprehensive overview for researchers and engineers in the field, consolidating knowledge and insights about the future of vehicle development.

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