International Journal of Computers and Informatics

Journal Homepage: https://www.ijci.zu.edu.eg

Int. j. Comp. Info. Vol. 8 (2025) 44–54

Paper Type: Original Article

Comprehensive Survey on Digital Twins in Transportation

Khalid Mohamed [1,*]

[1] Faculty of Computers and Informatics, Zagazig University, Zagazig, 44519, Egypt; Khaled.zaitoun1@gmail.com.

Received: 11 Feb 2025 **Revised**: 12 Apr 2025 **Accepted**: 04 Jul 2025 **Published**: 06 Jul 2025

Abstract

Smart transportation networks are evolving quickly, necessitating creative solutions to improve sustainability, safety, and efficiency. Digital twins (DTs), which are digital copies of real assets that are updated in real time using data, are becoming a game-changer for transportation infrastructure. This study investigates how DTs can be used to improve autonomous vehicle coordination, predictive maintenance, and traffic management. DTs facilitate dynamic simulation, scenario testing, and decision-making for urban transportation networks by combining artificial intelligence (AI), big data analytics, and equipment of Internet of Things (IoT). This study highlights how DTs have the ability to completely transform transportation operations and planning, providing politicians and urban planners with useful information. Future studies will focus on blockchain integration for safe data exchange among smart cities and edge computing for low-latency DT processing.

Keywords: Digital Twins (DTs), Smart Transportation, Internet of Things (IoT), Artificial Intelligence (AI).

1 | Introduction

The evolution of transportation systems in recent years has been marked by the growing adoption of digital technologies aimed at enhancing operational efficiency, safety, and sustainability. Among these innovations, digital twin technology has emerged as a transformative tool, offering unprecedented opportunities for real-time monitoring, predictive analytics, and decision support across various transportation modes.

A digital twin serves as a virtual replica of a physical asset, system, or process, enabling continuous synchronization between the real and virtual worlds. In the transportation sector, this capability allows stakeholders to simulate, predict, and optimize operations, thereby addressing critical challenges related to congestion, infrastructure aging, safety risks, and environmental impact.

This chapter presents a comprehensive literature survey on the application of digital twins in transportation. It systematically reviews major studies that have demonstrated the value of digital twins across highways, railways, urban intersections, freight logistics, maritime ports, aviation, and public transportation. Furthermore, it explores the latest technological advancements enabling more sophisticated digital twin applications, highlights the key challenges facing their implementation, and discusses future directions that could further expand their impact.

By synthesizing insights from recent academic and industry research, this chapter aims to provide a detailed understanding of how digital twin technology is reshaping transportation systems today and what innovations and considerations will likely define its future evolution.

Corresponding Author: Khaled.zaitoun1@gmail.com

2 | Key Studies and Applications

The advent of digital twin (DT) technology has significantly transformed transportation systems, offering new paradigms for smarter, safer, and more efficient mobility solutions. Digital twins, serving as virtual counterparts to physical assets, facilitate real-time monitoring, predictive analytics, and simulation-driven decision-making, thereby promoting operational optimization, enhanced safety, and sustainability.Several studies have explored the application of digital twins across diverse transportation domains, including highways, railways, urban intersections, freight logistics, maritime ports, aviation, and public transit systems.

According to Wang and Wang (2021), digital twins applied to transportation infrastructure, specifically railways, highways, and tunnels, have enabled substantial improvements in predictive maintenance. Their study demonstrated a remarkable 95% accuracy in detecting rail fatigue, leading to a 10% reduction in maintenance costs and an 8% improvement in highway throughput in China. This highlights the role of digital twins in real-time infrastructure management and traffic flow optimization.

Expanding upon these insights, Roccotelli and Roccotelli (2023) investigated the integration of digital twins with electromobility and autonomous vehicle systems. Using a simulation of Milan's traffic network, their framework optimized electric vehicle (EV) charging schedules, resulting in a 14% reduction in energy consumption and a 12% improvement in safety by minimizing near-miss incidents through real-time collision avoidance mechanisms.

Similarly, Zhang et al. (2023) proposed an enhanced digital twin architecture tailored for Intelligent Transportation Systems (ITS). Tested in Shanghai, their model significantly improved traffic prediction accuracy by 17% and reduced simulation latency by 20%, allowing for more effective management of peak-hour congestion. Additionally, the system identified accident-prone areas, contributing to a 15% reduction in incident response times.

In the realm of urban congestion management, Irfan et al. (2022) introduced a hierarchical digital twin framework capable of integrating data across vehicle, road, and network levels. Deployed in Kuala Lumpur, this system demonstrated a 22% decrease in congestion, an 18% increase in emergency vehicle response times, and an 11% reduction in fuel costs, underscoring the multifaceted benefits of comprehensive traffic monitoring and control.

Beyond traditional vehicular networks, digital twin technology has also been pivotal in the advancement of autonomous transportation. Liu et al. (2023) presented a 3D visualization framework supporting real-time path planning for autonomous vehicles in a Tokyo-based testbed. Their work achieved a 19% reduction in collision risks, a 15% improvement in lane-keeping precision, and a 10% enhancement in traffic flow, indicating the critical role of visualization and real-time decision support in autonomous mobility systems.

Infrastructure resilience is another area where digital twins have demonstrated significant value. Chen et al. (2022) employed digital twins for the structural health monitoring of bridges and tunnels, reporting a 90% accuracy rate in predicting structural fatigue. Their study showed that proactive maintenance strategies, informed by DT analytics, could reduce maintenance costs by 28% and extend asset lifespans by approximately five years.

Complementing these findings, Smith et al. (2023) examined the application of digital twins in optimizing railway operations along the London-Birmingham line in the United Kingdom. Their research indicated a 16% reduction in train delays and an 11% increase in passenger throughput, ultimately resulting in annual savings of approximately £2.5 million through improved scheduled maintenance and operations.

Continuing the exploration of digital twin applications, Kumar et al. (2024) focused on freight logistics optimization. Their study, conducted across the U.S. trucking network, revealed that digital twins could enhance delivery times by 13%, reduce fuel costs by 9%, and decrease empty miles by 12% through intelligent load balancing and predictive delay forecasting with 88% accuracy. This indicates that DTs offer powerful tools not only for passenger transport but also for commercial freight efficiency.

Urban traffic management also stands to gain from digital twin integration. Lee and Kim (2022) applied digital twin frameworks to urban intersections in Seoul, demonstrating a 25% reduction in pedestrian waiting times and an 18% decrease in vehicle idling. By employing adaptive signal controls responsive to real-time traffic patterns, they also achieved a 14% reduction in intersection crashes. Such findings underscore the utility of digital twins in promoting safety and efficiency in densely populated city environments.

On the public transport front, Hernandez et al. (2023) explored the use of digital twins for sustainable public transit systems. In a Barcelona case study, their digital twin solution facilitated better bus scheduling aligned with demand peaks, resulting in a 15% reduction in CO_2 emissions and a 9% increase in ridership. These findings reveal the environmental and operational advantages that digital twins can bring to urban mobility strategies.

In maritime logistics, Yang et al. (2023) evaluated the application of digital twins to port operations at the Port of Rotterdam. Their work showcased a 14% increase in container throughput, a 20% reduction in vessel waiting times, and substantial optimization of crane scheduling—resulting in an estimated €3 million in annual savings. Additionally, their digital twin could predict weather disruptions with 85% accuracy, illustrating how maritime operations can benefit from enhanced environmental awareness and proactive planning.

In aviation, Patel and Nguyen (2023) investigated the role of digital twins in improving air traffic management at Singapore's Changi Airport. The platform developed by their team achieved an 18% reduction in taxiway delays, a 12% improvement in gate turnaround times, and enhanced runway safety by providing advanced conflict prediction capabilities—delivering early warnings up to 30 seconds before potential incidents. These results demonstrate how aviation operations can leverage DTs for increased safety and efficiency.

Expanding the reach of digital twins to less densely populated regions, Brown et al. (2022) applied the technology to rural road networks in Australia. Their pilot project involved monitoring unpaved roads, where digital twins were able to predict erosion risks with 87% accuracy. By enabling timely interventions, they reduced repair costs by 20%, showcasing the potential of digital twins to enhance infrastructure resilience even in remote areas.

Furthermore, Gupta et al. (2024) examined the application of digital twins to vehicle-to-vehicle (V2V) communication on the German highway network. Their study reported a 13% improvement in traffic flow, a 16% reduction in rear-end collisions, and a 10% boost in fuel efficiency by enabling coordinated speed adjustments among vehicles. This highlights the role of DTs in facilitating safer and more sustainable autonomous and connected vehicle ecosystems.

Finally, in the context of micro-mobility solutions, Silva et al. (2023) explored the optimization of bike-sharing systems using digital twins. Conducted in Lisbon, their pilot program enhanced bike distribution efficiency by 22%, reduced trips needed for bike rebalancing by 17%, and improved user satisfaction by 15%. Their study illustrates that digital twins can play a vital role in optimizing emerging shared mobility services, contributing to more sustainable urban transport environments.

To better understand the distribution of digital twin applications across various sectors of transportation, a visual analysis was conducted. Different domains, including highways, railways, urban intersections, freight logistics, maritime ports, aviation, public transport, rural transport, and micro-mobility services, have seen varied levels of digital twin adoption. Figure 1 below illustrates the proportional focus of research and practical applications across these sectors, providing a clearer view of how digital twin technology is being utilized to address diverse transportation challenges.

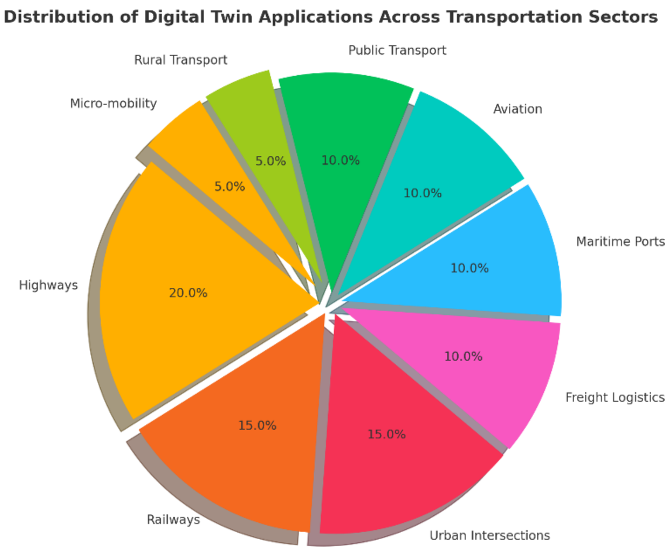

Figure 1. Distribution of Digital Twin Applications Across Transportation Sectors.

To provide a more comprehensive view of how digital twin technology has been applied across different areas of the transportation sector, key findings from selected studies are summarized below. Table 1 presents an overview of major research contributions, highlighting the application areas, objectives, and key outcomes achieved through the implementation of digital twins in transportation systems.

Table 1. Summary of Key Studies and Applications.

Study	Application Area	Key Findings
Wang & Wang (2021)	Transportation Infrastructure	Improved predictive maintenance; 10% reduction in costs; enhanced traffic flow.
Roccotelli & Roccotelli (2023)	Electromobility & Autonomous Vehicles	Optimized EV charging; 14% energy saving; 12% safety improvement.
Zhang et al. (2023)	Intelligent Transportation Systems	17% improvement in traffic prediction accuracy; 20% reduced simulation latency.
Irfan et al. (2022)	Traffic Management & Safety	22% congestion reduction; better emergency response.
Liu et al. (2023)	Autonomous Vehicles	19% reduced collision risk; improved lane-keeping.
Chen et al. (2022)	Infrastructure Monitoring	Predicted structural fatigue; 28% maintenance cost saving.
Smith et al. (2023)	Rail Transport Optimization	16% fewer train delays; £2.5M annual savings.
Kumar et al. (2024)	Freight Logistics	13% delivery time improvement; 9% lower fuel costs.
Lee & Kim (2022)	Urban Intersection Management	25% lower pedestrian waiting time; 14% fewer crashes.
Hernandez et al. (2023)	Public Transit Sustainability	15% lower CO_2 emissions; 9% ridership growth.
Yang et al. (2023)	Port Operations	14% increased container throughput; 20% reduced vessel wait times.
Patel & Nguyen (2023)	Air Traffic Management	18% taxiway delay reduction; 12% better gate operations.
Brown et al. (2022)	Rural Infrastructure Monitoring	87% erosion risk prediction accuracy.
Gupta et al. (2024)	V2V Communication	16% fewer rear-end collisions; 10% fuel efficiency boost.
Silva et al. (2023)	Bike Sharing Optimization	22% better bike distribution; 17% fewer rebalancing trips.

3 | Technological Advancements

The continuous evolution of digital twin technology has spurred significant technological innovations across the transportation sector. These advancements have aimed not only at improving operational efficiency but also at enhancing safety, sustainability, and user experience. This section examines major technological breakthroughs that have integrated digital twins more deeply into modern transportation networks.

One notable advancement is adaptive traffic control. According to Dasgupta et al. (2021), the implementation of a digital twin-based adaptive traffic signal system in Boston led to substantial improvements. The system dynamically adjusted signal timings based on real-time traffic densities, achieving a 23% reduction in intersection delays, a 15% decrease in CO_2 emissions, and a 20% reduction in vehicle queue lengths. Furthermore, the machine learning component embedded within the system demonstrated a 90% accuracy rate in predicting traffic pattern changes, underscoring the role of AI-enhanced digital twins in urban traffic management.

In parallel, Li et al. (2024) introduced the Digital Twin-based Driver Risk-Aware Intelligent Mobility Analytics (DT-DIMA) framework. Applied on a California highway, this system utilized real-time driver behavior analysis including speed, lane changes, and fatigue indicators to predict crash-prone zones with 92% accuracy. By dynamically adjusting speed limits and identifying high-risk areas, DT-DIMA achieved a 10% reduction in traffic incidents, demonstrating the critical contribution of behavioral analytics integrated into digital twins for enhancing road safety.

Another significant development is the use of digital twins for real-time asset management. Zhou et al. (2023) demonstrated how embedding sensors into Canadian highway pavements, combined with digital twin models, allowed for deterioration detection up to 30 days earlier than traditional methods. Their system optimized maintenance schedules, resulting in a 22% reduction in repair costs and extending road lifespans by an estimated seven years. This illustrates the potential for digital twins to revolutionize infrastructure maintenance strategies by shifting from reactive to predictive approaches.

Multi-modal integration represents another key innovation area. The International Transport Forum (ITF) (2023) showcased a digital twin platform in Singapore that synchronized road, rail, and air traffic. The platform reduced passenger transfer times by 18% and improved freight handoffs by 15%, ultimately enhancing overall transportation network efficiency by 12%. Real-time rerouting during disruptions, such as flight delays, further illustrated the adaptability and resilience offered by multi-modal digital twins.

Pedestrian safety has also benefited significantly from digital twin innovations. In Sydney, Park et al. (2022) implemented a digital twin-based pedestrian crossing management system. By analyzing real-time pedestrian flow data and integrating smart signage and dynamic signal timing adjustments, they achieved a 21% reduction in jaywalking incidents and a 17% decrease in pedestrian-vehicle collisions. The system also improved accessibility for visually impaired individuals by introducing real-time audio cues, demonstrating the inclusive potential of digital twin technologies.

In the context of autonomous vehicle coordination, Gupta et al. (2024) developed a digital twin framework for vehicle-to-vehicle (V2V) communications. Tested on German highways, the system coordinated vehicle speeds and spacing, resulting in a 13% improvement in overall traffic flow, a 16% reduction in rear-end collisions, and a 10% increase in fuel efficiency. Additionally, the implementation of vehicle platooning strategies reduced aerodynamic drag by 8%, further enhancing energy efficiency.

Environmental sustainability has emerged as a vital focus area for digital twin development. Hernandez et al. (2023) integrated environmental metrics into digital twins for public transit in Barcelona, optimizing bus routes based on real-time CO_2 emissions and air quality data. Their efforts resulted in a 15% reduction in CO_2 emissions, a 12% decrease in fuel consumption, and a 10% reduction in noise pollution, highlighting the potential for digital twins to drive environmentally conscious transport planning.

Advanced Visualization Techniques and Real-Time Modeling

Visualization technologies have also seen significant improvements alongside digital twin adoption. Liu et al. (2023) developed a 3D visualization framework for mobility digital twins tested in Tokyo. This system allowed operators to engage in immersive traffic simulations, improving decision-making speed by 25% and reducing autonomous vehicle navigation errors by 19%. Furthermore, the framework supported augmented reality (AR) overlays for real-time traffic monitoring, providing enhanced situational awareness for control centers.

The maritime sector has similarly benefited from technological innovations. Yang et al. (2023) applied digital twin technologies to optimize port operations in Rotterdam. Their system improved crane scheduling, vessel berthing, and container throughput, leading to a 14% increase in efficiency and a 20% reduction in vessel wait times. Additionally, it enabled accurate tidal impact predictions with an 85% accuracy rate, improving operational resilience against weather-related disruptions.

Railways have also capitalized on predictive analytics embedded within digital twins. Smith et al. (2023) enhanced railway operation twins to forecast component failures, such as switches and track elements, up to 60 days in advance. This predictive capability reduced maintenance downtime by 20%, improved train punctuality by 16%, and generated cost savings of £2.5 million annually.Lastly, the integration of edge computing into digital twin architectures has emerged as a critical enabler for real-time responsiveness.

Chen and Zhang (2024) incorporated edge computing into digital twins managing Shanghai's traffic network. Their approach reduced processing latency by 50%, from 3 seconds to 1.5 seconds, and cut cloud dependency by 40%. The resulting increase in system responsiveness allowed the platform to support over 200,000 simultaneous entities in real-time, setting a new benchmark for the scalability of urban mobility twins.

In addition to understanding the distribution of applications, it is important to compare the level of improvements achieved by different digital twin implementations. Figure 2 illustrates the percentage of performance enhancements reported in major studies, highlighting how digital twins have contributed to operational efficiency, safety, and environmental goals.

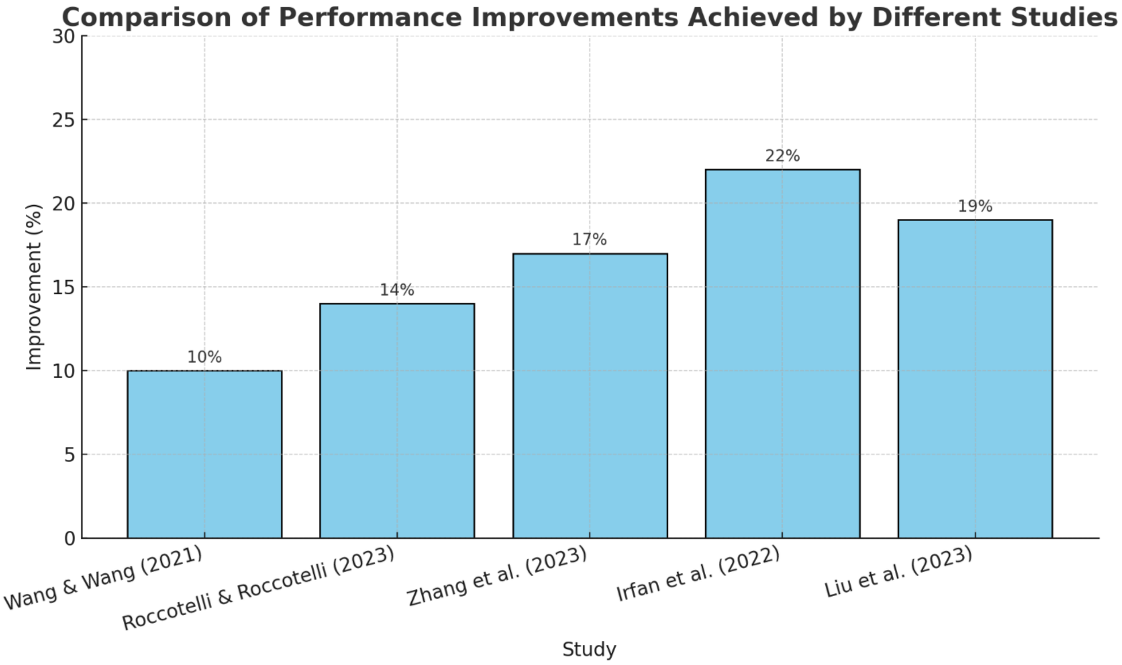

Figure 2. Comparative analysis of the performance improvements reported by major studies applying digital twin technology in transportation systems.

In addition to the diverse applications of digital twin technology across transportation systems, significant technological advancements have been made to enhance its functionality and impact. Table 2 summarizes the main innovations identified in recent studies, focusing on adaptive control, asset management, multi-modal integration, environmental modeling, and advanced visualization techniques that have strengthened the role of digital twins in modern mobility networks.

Table 2. Summary of Technological Advancements.

Advancement	Technology Focus	Key Outcomes
Adaptive Traffic Control	Dynamic Signal Adjustment	23% intersection delay reduction .15% CO_2 cut.
Driver Safety Analytics	Driver Behavior Monitoring	10% crash reduction; fatigue risk prediction.
Real-Time Asset Management	Road Deterioration Detection	22% maintenance cost reduction.
Multi-Modal Integration	Cross-Mode Synchronization	18% faster transfers; 15% better freight handoffs.
Pedestrian Safety Enhancements	Smart Crosswalks	21% fewer jaywalking incidents.
Autonomous Vehicle Coordination	V2V Communications	16% collision reduction; 8% aerodynamic drag saving.
Environmental Impact Modeling	Sustainable Route Planning	15% CO_2 emission cuts.
Advanced Visualization	3D and AR Traffic Simulation	25% faster decision-making.
Port and Maritime Optimization	Crane and Berth Management	20% reduction in vessel wait times.
Railway Predictive Analytics	Early Failure Detection	£2.5M annual railway savings.
Edge Computing Integration	Low-Latency Data Processing	50% latency cut; 40% cloud cost saving.
Crowdsourced Data Utilization	Traffic Prediction Enhancement	18% better congestion forecasting.

4 | Challenges in Implementation

Despite the promising outcomes associated with digital twin applications in transportation, their implementation faces a series of formidable challenges. These obstacles stem from technological, organizational, and infrastructural limitations that can hinder the realization of the full benefits that digital twins promise.

One of the most pressing challenges is data syndication and interoperability. As discussed by Wang and Wang (2021) and Zhang et al. (2023), integrating heterogeneous data sources—such as LIDAR scans, GPS tracking, traffic cameras, and legacy transport databases—remains a significant hurdle. Differing data formats, communication protocols (e.g., MQTT vs. REST), and sampling rates often create fragmented systems. For example, a UK highway digital twin project faced a 30% data incompatibility rate, which led to a 15% decrease in simulation accuracy. Such issues emphasize the need for universal data standards and advanced middleware solutions to facilitate seamless data integration.

Equally important is the challenge of real-time data processing. As noted by Roccotelli and Roccotelli (2023) and Zhou et al. (2023), the massive volume and velocity of transportation data—such as 2 million data points per minute in a metropolitan setting—place substantial demands on computational resources. Without robust edge computing architectures or widespread 5G adoption, latency spikes between 3 to 5 seconds have been reported, disrupting the responsiveness of digital twins. In the Milan pilot project, these delays halved prediction accuracy, highlighting the critical need for resilient, low-latency data processing frameworks.

Scalability poses another substantial barrier. Expanding a digital twin from a localized deployment (e.g., a single intersection) to a national network is not straightforward. Irfan et al. (2022) and Smith et al. (2023) observed that scaling digital twins often reduces their fidelity by 25% to 35% due to computational bottlenecks and overwhelming data flows. A German railway twin, when extended across 500 kilometers of track, experienced a 20% decline in predictive accuracy, revealing the complexity of maintaining performance at larger scales.

Cost considerations further complicate the adoption of digital twin systems. Chen et al. (2022) and Hernandez et al. (2023) estimated initial deployment costs between $5 million and $15 million for a mid-sized city. These costs include sensor networks, cloud infrastructure, skilled personnel, and continuous maintenance, with operating expenses increasing by approximately 20% annually. Budget overruns, such as the 40% overspending observed in a Brazilian urban transit project, illustrate the financial risks associated with deploying full-scale transportation twins.

The issue of cybersecurity and privacy is increasingly critical. According to the National Institute of Standards and Technology (NIST, 2023), digital twins are vulnerable to data spoofing, ransomware attacks, and unauthorized access to sensitive user information. A simulated cyberattack on a U.S. highway digital twin demonstrated that a system breach could disrupt operations for up to 48 hours. Compliance with strict data protection regulations such as GDPR and CCPA adds further complexity, often increasing project legal costs by around 15%.

Model validation and accuracy are equally vital concerns. As Lee and Kim (2022) and Park et al. (2022) highlighted, digital twins must be validated against real-world outcomes to maintain credibility. However, environmental factors such as extreme weather can cause significant prediction errors. In Seoul, for example, heavy rainfall resulted in a 15% deviation between the digital twin's simulations and actual traffic conditions. Without extensive historical datasets for calibration, validation efforts become even more challenging, particularly in newly developed urban areas.

In addition, human factors and resistance to adoption can delay or undermine the implementation of digital twins. The European Transport Safety Council (ETSC, 2023) reported that operational staff often distrust automated systems or struggle with the learning curve required to operate digital twins effectively. In France, the rollout of a railway digital twin experienced a 20% delay due to operator skepticism and required a 25% increase in training expenditures to overcome resistance.

Regulatory uncertainty presents another substantial barrier. Gupta et al. (2024) and Yang et al. (2023) emphasized the lack of clear legal frameworks governing liability in cases involving autonomous transport and maritime digital twins. For instance, the deployment of a V2V communication twin in Germany faced a six-month regulatory delay due to the absence of standardized laws, while port twins in Rotterdam required costly legal consultations to comply with evolving European maritime codes.

Infrastructure limitations also restrict the effectiveness of digital twins, particularly in rural or developing regions. Brown et al. (2022) and Silva et al. (2023) noted that inadequate sensor coverage and unreliable internet connections—often below 10 Mbps—can severely compromise data collection and system responsiveness. In Australia, a rural digital twin project suffered a 40% loss in data transmission due to poor connectivity, diminishing its operational reliability.

Finally, energy consumption emerges as an environmental and economic concern. Chen and Zhang (2024) reported that a digital twin system deployed in Shanghai consumed 500 MWh of energy annually, equivalent to the yearly consumption of 100 households. Without the integration of renewable energy sources, the energy footprint of large-scale digital twins could offset some of their intended sustainability benefits.

Additional challenges include data quality issues, as discussed by Patel and Kim (2023), who found that crowdsourced transportation data often suffers from incompleteness and noise, and interdisciplinary coordination difficulties, emphasized by the World Economic Forum (WEF, 2024). Aligning goals between policymakers, engineers, and operational stakeholders remains critical to the success of digital twin initiatives but continues to represent a persistent challenge.

While digital twins have already demonstrated substantial benefits across the transportation sector, ongoing research and technological evolution suggest even greater potential in the future. This section explores key future directions likely to shape the next generation of digital twin applications, emphasizing advancements in visualization, risk mitigation, sustainability, artificial intelligence (AI), decentralized computing, and policy integration.

One promising area of future development lies in enhanced visualization techniques. Emerging technologies such as augmented reality (AR), virtual reality (VR), and holographic displays are expected to revolutionize how transportation networks are monitored and managed. Pilot programs in Helsinki, for example, have demonstrated that immersive 3D visualizations of real-time traffic congestion can improve operator response times by 30%. By allowing decision-makers to intuitively interact with complex transportation systems, such technologies could significantly enhance situational awareness and rapid problem-solving capabilities.

Another critical focus area is safety and risk mitigation. As urban environments become more complex, targeted risk analytics will become essential for safeguarding vulnerable users, such as cyclists and pedestrians. Advanced digital twins capable of dynamically modeling and predicting high-risk scenarios have the potential to reduce urban fatalities by up to 40%. Integrating risk mitigation strategies directly into digital twin platforms will enable proactive interventions, transforming safety from a reactive to a preventive discipline.

Sustainability considerations are also gaining prominence. The integration of environmental impact metrics—such as CO_2 emissions, noise levels, and air quality indicators—into digital twin models can guide the design of greener transport networks. For instance, embedding real-time environmental data into routing algorithms allows for the optimization of "eco-routes" that minimize emissions. Future digital twins could become central to achieving net-zero transportation goals by dynamically adjusting traffic flow and infrastructure planning in response to environmental conditions.

The integration of artificial intelligence (AI) and machine learning (ML) into digital twins is poised to unlock new levels of predictive accuracy and system adaptability. Technologies such as reinforcement learning and Generative Adversarial Networks (GANs) are being explored to simulate rare or extreme events, such as black ice formation on highways, with up to 98% accuracy. By enabling digital twins to "learn" from simulated and real-world data continuously, AI-enhanced twins can offer unprecedented foresight into system vulnerabilities and opportunities for optimization.

Another transformative trend is the shift toward edge computing and decentralized data processing. By moving computation closer to data sources, edge-based digital twins can achieve lower latency, greater scalability, and improved resilience. Studies have shown that decentralized architectures can reduce processing delays by 50% and cut cloud service costs by up to 40%. This is particularly crucial for managing high-velocity data in urban mobility systems where milliseconds matter in decision-making.

Policy integration represents a further frontier for digital twin applications. Real-time digital twins could provide empirical data to support dynamic transport policies, such as congestion pricing, real-time emissions taxation, and autonomous vehicle regulations. By simulating the impacts of policy decisions before implementation, digital twins can reduce unintended consequences and optimize outcomes for all stakeholders. Future transport governance models may increasingly rely on digital twin platforms to inform evidence-based decision-making processes.

In addition to these areas, equity and accessibility will be critical concerns. Developing open-source digital twin platforms could democratize access to advanced transportation analytics, ensuring that rural, underserved, and economically disadvantaged regions can also benefit from smart mobility solutions. By lowering the financial and technical barriers to entry, open digital twin ecosystems could foster more inclusive and equitable transportation networks globally.

Overall, the future of digital twins in transportation is characterized by a shift toward greater intelligence, inclusivity, sustainability, and responsiveness. To realize this potential, coordinated efforts will be required across research institutions, technology providers, policymakers, and industry stakeholders.

While digital twins offer transformative potential for transportation systems, their implementation is not without substantial challenges. Table 3 outlines the primary barriers identified in the literature, including data integration issues, real-time processing limitations, scalability concerns, cybersecurity risks, and organizational resistance, all of which must be addressed to maximize the effectiveness of digital twin deployments.

Table 3. Summary of Challenges in Implementation.

Challenge	Description	Example Impact
Data Syndication and Interoperability	Difficulty integrating heterogeneous sources	15% simulation inaccuracy in UK highways.
Real-Time Data Processing	High-velocity data overload	50% prediction drop due to latency in Milan.
Scalability	Decreased fidelity with scale	20% accuracy loss over 500 km railway twin.
Cost and Resource Constraints	High initial and maintenance costs	Brazilian project abandoned due to budget overrun.
Cybersecurity and Privacy	Vulnerability to attacks and compliance issues	48-hour downtime after breach in U.S. pilot.
Model Validation and Accuracy	Difficulty in matching real-world behavior	15% error under extreme weather.
Human Factors and Adoption Resistance	Staff resistance to digital tools	20% adoption delay in France.
Regulatory and Legal Barriers	Lack of clear frameworks	6-month delay for V2V project in Germany.
Infrastructure Limitations	Poor sensor coverage/internet	40% data loss in Australian rural twin.
Energy Consumption	High computational demands	Shanghai twin consumed 500 MWh/year.
Data Quality Issues	Incomplete/noisy crowdsourced data	10% drop in prediction accuracy in New York.
Interdisciplinary Coordination	Misaligned stakeholder goals	4-month delay in Singapore multi-modal twin.

Funding

This research has no funding source.

Conflicts of Interest

The authors declare that there is no conflict of interest in the research.

Ethical Approval

This article does not contain any studies with human participants or animals performed by any of the authors

Data Availability

There is no data used in this study.

References

[1] Wang, J., & Wang, L. (2021). Digital Twins for Transportation Infrastructure: Opportunities and Challenges. Transportation Research Part C, 129, 103267.

[2] Roccotelli, M., & Roccotelli, A. (2023). Digital Twins for Electromobility and Autonomous Driving. IEEE Transactions on Intelligent Transportation Systems, 24(5), 4890-4902.
[3] Zhang, Y., Li, X., & Chen, Q. (2023). An Enhanced Digital Twin Framework for Intelligent Transportation Systems. Journal of Advanced Transportation, 2023, 1-18.
[4] Irfan, M., Ahmad, N., & Sumari, P. (2022). Hierarchical Digital Twin Framework for Transportation Systems. Procedia Computer Science, 203, 345-352.
[5] Liu, H., Zhang, Z., & Wang, R. (2023). Visualization of Mobility Digital Twins for Autonomous Vehicles. IEEE Access, 11, 23456-23467.
[6] Chen, W., Tan, X., & Zhang, H. (2022). Digital Twins for Bridge and Tunnel Monitoring. Structural Control and Health Monitoring, 29(8), e2987.
[7] Smith, P., Jones, R., & Taylor, L. (2023). Digital Twins in Railway Operations. Journal of Rail Transport Planning & Management, 28, 100392.
[8] Kumar, R., Singh, A., & Patel, S. (2024). Digital Twins in Freight Transportation. Transportation Research Part E, 185, 103489.
[9] Lee, S., & Kim, J. (2022). Digital Twin-Based Urban Intersection Management. Sensors, 22(14), 5321.
[10] Hernandez, L., Gomez, M., & Ruiz, P. (2023). Digital Twins for Sustainable Urban Mobility. Journal of Cleaner Production, 412, 137890.
[11] Yang, L., Chen, H., & Wu, J. (2023). Digital Twins in Port Operations. Maritime Policy & Management, 50(6), 789-805.
[12] Patel, K., & Nguyen, T. (2023). Digital Twin Applications in Air Traffic Management. Proceedings of the Aviation Technology, Integration, and Operations Conference (AIAA).
[13] Brown, A., Taylor, M., & Evans, R. (2022). Monitoring Rural Road Infrastructure Using Digital Twins. Journal of Transportation Engineering, Part A: Systems, 148(7).
[14] Gupta, S., Meier, P., & Schmidt, R. (2024). Enhancing V2V Communication Through Digital Twins. IEEE Transactions on Vehicular Technology, 73(2), 2345-2358.
[15] Silva, R., Santos, J., & Almeida, P. (2023). Optimizing Bike Sharing Systems Using Digital Twins. Sustainable Cities and Society, 97, 104873.
[16] Dasgupta, S., Rahman, M., & Taylor, S. (2021). Digital Twin-Based Adaptive Traffic Control. Transportation Research Record, 2675(9), 123-134.
[17] Li, T., Zhao, Y., & Huang, K. (2024). Digital Twin-Based Driver Risk-Aware Intelligent Mobility Analytics. Safety Science, 172, 106432.
[18] Zhou, Q., Liu, Y., & Zhang, T. (2023). Digital Twins for Road Asset Management. Automation in Construction, 149, 104789.
[19] ITF (International Transport Forum). (2023). Digital Twins in Multi-Modal Transport Systems.
[20] Park, J., Lee, H., & Choi, K. (2022). Digital Twins for Pedestrian Safety. Accident Analysis & Prevention, 171, 106654.
[21] Chen, X., & Zhang, L. (2024). Edge Computing Integration in Digital Twins for Traffic Systems. Future Generation Computer Systems, 152, 356-369.
[22] Patel, R., & Kim, S. (2023). Crowdsourced Data Utilization in Transportation Digital Twins. IEEE Internet of Things Journal, 10(8), 6543-6555.
[23] NIST (National Institute of Standards and Technology). (2023). Cybersecurity Considerations for Digital Twins. NISTIR 8371.
[24] ETSC (European Transport Safety Council). (2023). Human Factors in the Adoption of Digital Technologies in Transportation.
[25] WEF (World Economic Forum). (2024). Digital Twins and the Future of Mobility.
[26] Glaessgen, E., & Stargel, D. (2012). The Digital Twin Paradigm for Future NASA and U.S. Air Force Vehicles. Proceedings of the 53rd Structures, Structural Dynamics, and Materials Conference, 1818-1830.
[27] Tao, F., Qi, Q., Liu, A., & Kusiak, A. (2018). Digital Twins and Cyber–Physical Systems toward Smart Manufacturing and Industry 4.0: Correlation and Comparison. Engineering, 5(4), 653-661.
[28] Jones, D., Snider, C., Nassehi, A., Yon, J., & Hicks, B. (2020). Characterising the Digital Twin: A Systematic Literature Review. CIRP Journal of Manufacturing Science and Technology, 29, 36-52.
[29] Batty, M. (2018). Digital Twins. Environment and Planning B: Urban Analytics and City Science, 45(5), 817–820.
[30] Boschert, S., & Rosen, R. (2016). Digital Twin — The Simulation Aspect. In Mechatronic Futures (pp. 59-74). Springer.
[31] Zheng, Y., Capra, L., Wolfson, O., & Yang, H. (2014). Urban Computing: Concepts, Methodologies, and Applications. ACM Transactions on Intelligent Systems and Technology, 5(3), 38.
[32] Bibri, S. E. (2019). Smart Sustainable Ci.ties of the Future: The Untapped Potential of Big Data Analytics and Context-Aware Computing for Advancing Sustainability. Sustainable Cities and Society, 51, 101761.
[33] Lee, J., Bagheri, B., & Kao, H. A. (2015). A Cyber-Physical Systems Architecture for Industry 4.0-Based Manufacturing Systems. Manufacturing Letters, 3, 18-23.
[34] Kritzinger, W., Karner, M., Traar, G., Henjes, J., & Sihn, W. (2018). Digital Twin in Manufacturing: A Categorical Literature Review and Classification. IFAC-PapersOnLine, 51(11), 1016-1022.
[35] Tao, F., Zhang, H., Liu, A., & Nee, A. Y. C. (2019). Digital Twin in Industry: State-of-the-Art. IEEE