Growth and Intelligent Transportation Systems

DIGITAL TWINS AND ITS APPLICATION IN TRANSPORTATION INFRASTRUCTURE

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Executive Summary

A digital twin is a virtual representation of a physical system that integrates sensor data, simulations, and historical insights to enable real-time monitoring, analysis, and optimization. Widely used in industries such as manufacturing, healthcare, transportation, and energy, digital twins bridge the gap between the physical and digital worlds, creating dynamic replicas of physical objects, systems, or processes. In transportation, this technology is transforming infrastructure planning, construction, and maintenance, enabling smarter, safer, and more sustainable systems while improving decision-making and operational efficiency.

This report proposes adopting digital twins across the lifecycle of transportation infrastructure, supported by a comprehensive policy framework to maximize accessibility, functionality, and impact. We analyze current challenges in transportation infrastructure and demonstrate how digital twins address these issues, focusing on improved efficiency, predictive maintenance, and enhanced safety. Our qualitative analysis draws from journal publications, industry reports, and case studies from cities like Singapore, Boston, and Barcelona, showcasing the tangible benefits of digital twin integration in ongoing and completed projects.

Building on these findings, we recommend a strategic roadmap for adopting digital twins, emphasizing the need for collaboration between stakeholders, investment in technological infrastructure, and policy initiatives to ensure seamless and effective implementation across all levels of the transportation sector.

Background

Modern systems' growing complexity makes predicting failures, optimizing performance, and ensuring efficiency challenging. Current tools often lack integration and real-time adaptability, leading to downtime, resource wastage, and poor decision-making. Digital Twins address these issues by creating real-time virtual counterparts of physical systems. This framework enhances decision-making, enables predictive maintenance, and optimizes performance through real-time insights and simulations. Key priorities include scalability for expanding systems, interoperability across platforms, and leveraging AI and IoT for smarter operations.

The first digital twin was brought to life by NASA in the 1960s where they used simulators to model the spacecraft and analyze potential failures, particularly during the Apollo 13 crisis where they needed to troubleshoot issues in real-time using a virtual representation of the spacecraft. According to Gene Kranz, NASA Chief Flight Director for Apollo 13,[1] “The simulators were some of the most complex technology of the entire space program: the only real things in the simulation training were the crew, cockpit, and the mission control consoles, everything else was make-believe created by a bunch of computers, lots of formulas, and skilled technicians.

This concept gained traction due to the rapid advancements in IoT, cloud computing, artificial intelligence (AI), and simulation technologies. These innovations transformed the way physical systems are monitored and managed. As systems grow more interconnected and data-driven, an integrated virtual model becomes essential to address the increasing complexity. Digital twins offer a dynamic solution, enabling organizations to simulate "what-if" scenarios, reduce downtime, optimize resource allocation, and unlock new opportunities for innovation. Their growing adoption highlights their transformative potential across industries, from manufacturing and healthcare to smart cities and beyond.

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[1] *Ferguson, Stephen. “Apollo 13: The First Digital Twin - Simcenter.” Simcenter, 28 Aug. 2024,* blogs.sw.siemens.com/simcenter/apollo-13-the-first-digital-twin.

Digital twins have found remarkable applications across various sectors, with several standout examples demonstrating their transformative potential. General Electric stands as a pioneer, using digital twins to monitor over 1.2 million jet engines, enabling predictive maintenance and extending engine life by up to 25%. [2]In healthcare, Siemens Healthineers employs digital twins of human organs, particularly the heart, to assist surgeons in procedure planning and patient care optimization. NASA continues its long-standing use of digital twins, notably in mission planning and spacecraft monitoring, building upon their original digital twin concept from the Apollo missions. In urban development, Singapore's Virtual Singapore project represents one of the most ambitious digital twin implementations, creating a comprehensive 3D model of the entire city-state to improve urban planning, emergency response, and public services.[3]. In the automotive sector, Tesla utilizes digital twins for each vehicle they produce, enabling remote diagnostics, over-the-air updates, and performance optimization. The Port of Rotterdam stands as another noteworthy example, employing digital twins to manage shipping traffic, optimize berthing times, and reduce vessel waiting times by up to 20%. These implementations showcase how digital twins are moving beyond theoretical concepts to deliver tangible benefits in real-world applications.

GE electric's jet engine digital twin

[2] *Griffin, Matthew. "GE's Revolutionary Industrial Machines Can Have Conversations With Engineers – Matthew Griffin | Keynote Speaker &Amp; Master Futurist." Matthew Griffin | Keynote Speaker & Master Futurist, 28 June 2019,* www.fanaticalfuturist.com/2016/11/ges-new-industrial-machines-are-speaking-to-engineers-about-their-problems.

[3] *Prime, Gw. "Virtual Singapore – Building a 3D-Empowered Smart Nation." Geospatial World, 28 Oct. 2022,* geospatialworld.net/prime/case-study/national-mapping/virtual-singapore-building-a-3d-empowered-smart-nation.

Apollo Simulators at Mission Control in Houston. The Lunar Module Simulator is in the foreground in green, the Command Module Simulator is at the rear of the photo in brown. Image credit: NASA

Case Studies

Digital twins have emerged as powerful tools for infrastructure management, as demonstrated by two notable implementations. In Singapore, a comprehensive city-scale digital twin integrates real-time data from sensors, cameras, and IoT devices to simulate urban dynamics, enabling efficient management of traffic, energy consumption, and emergency responses. Meanwhile, in Minnesota, digital twins of critical bridge infrastructure provide continuous structural health monitoring, allowing engineers to predict maintenance needs and prevent potential failures through advanced simulation models.

Case Study 1: Virtual Singapore

Virtual Singapore is a digital twin platform developed by the Singapore government to model and simulate the city's physical and social environments. It serves as an advanced 3D city model and collaborative platform integrating data and applications to support urban planning, resource management, disaster response, and smart city initiatives. It was launched in 2014 as a $73 million collaborative project between the National Research Foundation (NRF) and Dassault Systèmes, representing one of the world's most ambitious urban digital twin initiatives. The project aimed to create a dynamic 3D model of Singapore that would serve multiple stakeholders including government agencies, businesses, and researchers.

Key Features

1. **High-Fidelity 3D Model:** Photorealistic representation of Singapore's environment, integrating data layers like traffic and population via advanced mapping technologies.
2. **Data Integration:** Combines geospatial, IoT, and real-time data for dynamic simulations and big data analytics.
3. **Collaborative Platform:** Enables government, businesses, and researchers to test urban development scenarios collaboratively.
4. **Simulation Capabilities:** Models urban phenomena and simulates disasters to enhance resilience and planning.

Applications

1. ***Urban Planning and Development:*** Visualize land-use plans, optimize urban layouts, and assess the impact of new developments.
2. ***Sustainability and Energy Management:*** Evaluate energy efficiency, monitor environmental conditions, and address urban heat islands.
3. ***Disaster Management:*** Simulates evacuation routes, improves emergency responses, and manages flood or fire risks.
4. ***Transport and Mobility:*** Analyze traffic patterns, optimize public transportation, and plan infrastructure projects.
5. ***Public Engagement:*** Enables citizen participation in urban planning and enhances transparency with interactive models.

Technologies Used

1. ***GIS (Geographical Information Systems):*** For mapping and spatial analysis.
2. ***IoT (Internet of Things):*** To gather real-time data from sensors across the city.
3. ***AI and ML*****:** For predictive analytics and decision-making.
4. ***Cloud Computing:*** To store and process large datasets efficiently.
5. ***AR/VR:*** To provide immersive experiences for stakeholders and citizens.

Impacts

1. **Enhanced Decision-Making:** Provides detailed simulations and real-time data to improve urban planning and proactively address future challenges.
2. **Economic Development:** Positions Singapore as a leader in smart city innovation, attracting investments and fostering a thriving ecosystem for startups and enterprises.
3. **Environmental Benefits:** Supports sustainability goals by analyzing energy use, air quality, and urban heat, reducing carbon footprints, and enhancing climate resilience.
4. **Citizen Engagement:** Promotes transparency and inclusivity by enabling public access to urban visualizations and fostering participation in planning through AR/VR tools.

Challenges

1. **Data Integration and Accuracy:** Ensuring compatibility, consistency, and regular updates of diverse datasets is complex; inaccuracies can undermine trust in the platform.
2. **Privacy and Security:** Safeguarding sensitive, real-time data while enabling open collaboration requires stringent security measures and compliance with data protection regulations.
3. **Cost and Resource Allocation:** High initial and ongoing expenses for data acquisition, infrastructure, and personnel demand efficient budgeting and sustainable funding.
4. **Stakeholder Coordination:** Aligning priorities among diverse stakeholders requires effective communication, project management, and a unified vision to avoid delays and inefficiencies.

Virtual Singapore exemplifies how advanced digital twin technologies can revolutionize urban management and planning. Its integration of data, collaboration, and simulation creates a robust tool for addressing modern urban challenges. As a pioneering initiative, it sets a benchmark for smart cities globally, showcasing how technology can enhance livability, sustainability, and resilience in urban environments[4].

Case Study 2: Digital Twins of Bridges in US Bridges, Minnesota

The United States alone has over 617,000 bridges with roughly 7% classified as "poor" condition and 44% classified as "fair" condition.[5] Bridge quality is steadily decreasing over time, showing a 1.3% decrease in "good" condition bridges and a 3.8% increase in "fair" condition since 2020. Current methods of bridge inspection are highly stagnant and time consuming. In 2007, the I-35W bridge failure into the Mississippi river resulted in 14 deaths and 145 injuries.[6] This was attributed to a design flaw accumulated from bridge deterioration as well as lack of inspection. The Minnesota Department of Transportation immediately integrated a new bridge inspection system. Additionally, centralized companies such as Bently have also since then adopted modernized technology to replace current outdated and inefficient inspection methods as previously mentioned. This technology revolves around drone-based inspections which is then used to create a digital twin of the bridge itself for further analysis.

Snooper Truck used for traditional bridge inspections(Pre-Drone)

[4] *Virtual Singapore - a 3D City Model Platform for Knowledge Sharing and Community Collaboration*. www.sla.gov.sg/articles/press-releases/2014/virtual-singapore-a-3d-city-model-platform-for-knowledge-sharing-and-community-collaboration.

[5] *Thorpe, Ben. "Number of U.S. Bridges in 'Fair' Condition Continues to Rise." Equipment World, 2 Dec. 2024, www.equipmentworld.com/roadbuilding/article/15709108/number-of-us-bridges-in-fair-condition-continues-to-rise#:~:text=Data%20from%20the%20Federal%20Highway,44.36%25%20and%20274%2C675%20in%202023.*

[6] *Tara, Roopinder. "Digital Twin Makes Bridge Inspection Safer, Cheaper and Accessible." Engineering.Com, 13 Apr. 2021,* *www.engineering.com/digital-twin-makes-bridge-inspection-safer-cheaper-and-accessible/.*

Key Features & Specific Softwares[7]

1. ***Advanced Drone Technology:*** Utilizes unmanned aerial vehicles (UAVs) programmed to follow precise, predetermined flight paths for consistent and comprehensive coverage.
2. ***High-Resolution Visual Data Collection:*** Captures an extensive array of high-quality images and videos, ensuring every aspect of the bridge is documented with exceptional detail.
3. ***Photogrammetry Innovation:*** Powered by advanced photogrammetry technology, originally acquired from France-based Acute3D in 2015. This technology enables the real-time stitching of images without requiring registration marks or manual intervention.
4. ***ContextCapture Software:*** Transforms thousands of photos into an at-scale reality mesh, providing an immersive, realistic model that reflects the bridge's current state with precision.
5. ***Augmented LiDAR Integration:*** Offers the flexibility to enhance the model with LiDAR technology for additional layers of data and depth perception when necessary.
6. ***Life Cycle Analysis and Maintenance Planning:*** Utilizes historical and real-time data from the Digital Twin to conduct life cycle assessments and implement proactive maintenance strategies, ensuring structural longevity and safety.

Digital Twin of Stone Arch Bridge Minneapolis, MN(Bentley Systems)

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[7] *Fonceca, Christopher. "Digital Twins: Revolutionizing Inspection Reports: Article." MFE Inspection Solutions, 4 Nov. 2024,* mfe-is.com/en/digital-twins-revolutionizing-inspection-reports/#:~:text=Time%2DSaving%3A%20Creating%20a%20Virtual,be%20physically%20present%20on%2Dsite.

Real World Application and Impact

1. ***Operator Safety:*** Drones enable thorough and safe assessments of difficult-to-reach locations, reducing risks to personnel.
2. ***Good Quality Data:*** Drone footage produces high-quality images and detailed 3D Digital Twins for accurate bridge condition documentation.
3. ***Better Maintenance:*** Digital Twins streamline maintenance design, repair planning, and load rating calculations, significantly reducing processing time.
4. ***Taxpayer Benefits:*** Benefits of drone inspections include cost efficiency, improved data quality, enhanced safety, taxpayer savings, and reduced traffic disruptions.

Challenges

1. ***System Integration:*** These systems were not originally designed to interface with contemporary technologies, creating compatibility barriers.
2. ***Technical Expertise:*** Operating and maintaining drone inspection systems and digital modeling requires specialized skills.
3. ***High Initial Costs:*** The upfront investment in equipment, software, and training can be prohibitive, especially for smaller businesses or organizations with limited budgets
4. ***Cultural Resistance:*** Some companies remain reliant on traditional inspection methods, showing resistance to change. The reluctance to adopt modern technologies can come from a combination of familiarity with existing processes and skepticism about the benefits of modernization.
5. ***Regulatory Compliance:*** Navigating legislative and regulatory frameworks can complicate implementation, particularly concerning the use, storage, and confidentiality of data captured during inspections. Compliance with evolving laws must be considered for widespread adoption.

Policy Review/Framework

Implementing digital twins for transportation infrastructure faces several challenges, including ensuring up-to-date and compliant data integration and accuracy, protecting sensitive infrastructure information, and managing the high costs of technology and training, particularly for smaller organizations. A lack of skilled personnel limits technical expertise, while scalability remains an issue as supply chains grow more complex. Integrating digital twin solutions with existing legacy systems can lead to disruptions, and cultural resistance in traditional industries slows the adoption of new technologies.

A cost-benefit analysis of digital twin implementation in transportation infrastructure examples previously mentioned reveals significant potential returns. The Department for Transport in the UK estimates that integrated network management digital twins could provide benefits of approximately £850 million across a ten-year period.[8] These benefits stem from improved efficiency, reduced congestion, and enhanced safety in transportation systems. However, this involves significant initial investments, encompassing the procurement of drones, IoT devices, advanced software platforms like ContextCapture, and specialized training for personnel. Affordability remains a challenge, especially for smaller municipalities or developing regions. The high initial costs of data collection, software development, and personnel training can be prohibitive.

To address this, policymakers should consider the following alleviation methods:

1. Phased implementation approaches
2. Public-private partnerships to share costs and expertise
3. Grants and funding programs to support adoption
4. Open-source solutions to reduce software costs.

A detailed cost-benefit analysis reveals that the long-term savings and operational efficiencies provided by digital twins outweigh the initial investment, particularly when considering the avoided costs of infrastructure failures, such as the tragic I-35W bridge collapse. Moreover, the economic benefits extend to enhanced productivity, reduced downtime, and improved public safety, further justifying the financial commitment required for digital twin implementation.

The justification for spending on digital twin technology lies in their long-term benefits such as cost savings through predictive maintenance and optimized

[8] *Condie, Catherine. "Research on the Economic Benefits of Digital Twins for Integrated Transport Network Management - Digital Twin Hub." Digital Twin Hub, 13 Nov. 2024, digitaltwinhub.co.uk/research-on-the-economic-benefits-of-digital-twins-for-integrated-transport-network-management.*

resource allocation, enhanced safety for infrastructure users and maintenance personnel. They provide for improved decision-making capabilities for urban planning and infrastructure management, increased sustainability and environmental benefits, and economic growth through innovation. They are great exhibits to attract investments in smart city technologies for urban governments.

Results & Implications

The deployment of digital twins in transportation infrastructure has yielded significant, measurable benefits, as evidenced by pioneering projects like Virtual Singapore and Minnesota's bridge inspections. In the Singapore example, the implementation of a comprehensive smart mobility system leveraging digital twins has enhanced urban planning and resource management through its high-fidelity 3D city model, enabling real-time simulations that optimize traffic flows and energy consumption.enhanced safety and security via incident detection, and reduced environmental impact[9]. It's comprehensive data integration and real-time monitoring capabilities have improved operational efficiencies, leading to a 30% reduction in machine downtime for Siemens' manufacturing facilities.Minnesota's use of drone-based inspections for bridge monitoring has resulted in reduced operational costs, improved data accuracy, and enhanced safety by minimizing the need for manual inspections.

Similarly, Los Angeles has utilized big data analytics and real-time data for transportation planning and infrastructure investments. This data-driven approach has enabled city officials to identify areas for improvement, optimize transportation networks, and allocate resources effectively.[10]

The implications of these results extend beyond immediate operational gains; widespread adoption of digital twins promises to revolutionize infrastructure management by enabling predictive maintenance, extending the lifespan of assets, and preventing catastrophic failures such as the I-35W bridge collapse in 2007.

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[9] *Faliagka, Evanthia, et al. "Trends in Digital Twin Framework Architectures for Smart Cities: A Case Study in Smart Mobility." Sensors, vol. 24, no. 5, Mar. 2024, p. 1665, doi:10.3390/s24051665.*

[10] *Faliagka, Evanthia, et al. "Trends in Digital Twin Framework Architectures for Smart Cities: A Case Study in Smart Mobility." Sensors, vol. 24, no. 5, Mar. 2024, p. 1665, doi:10.3390/s24051665.*

Furthermore, the integration of digital twins necessitates a transformation in workforce skills, emphasizing the need for training programs to equip personnel with expertise in digital technologies, data analytics, and system interoperability. This shift underscores the broader impact of digital twins on organizational structures and operational paradigms within the transportation sector.

Applications & Implementations

Digital twins have many applications in transportation infrastructure:

1. ***Dynamic Traffic Management:*** Real-time monitoring and adjustment of traffic conditions, including signal timing and lane management.
2. ***Integrated Public Transportation:*** Seamless coordination of schedules, optimized route planning, and efficient resource allocation across various modes of public transport.
3. ***Multi-modal Trip Planning:*** Comprehensive platforms that integrate real-time data from various transportation modes to suggest efficient and sustainable routes.
4. ***Predictive Maintenance:*** Analysis of sensor data to identify potential issues in infrastructure before they occur, preventing disruptions and ensuring safety.
5. ***Parking Optimization:*** Integration of data on parking availability and occupancy to reduce congestion and improve urban accessibility.
6. ***Mobility Planning and Simulation:*** Evaluation of different mobility scenarios to assess the impact of proposed infrastructure changes or policy interventions.
7. ***Urban Planning:*** Virtual Singapore demonstrates how digital twins can be used to visualize land-use plans, optimize urban layouts, and assess the impact of new developments.
8. ***Infrastructure Maintenance:*** The Minnesota bridge inspection case study showcases the use of digital twins for structural health monitoring and predictive maintenance.
9. ***Disaster Management:*** Virtual Singapore's capabilities in simulating disaster scenarios highlight the potential for improving emergency response strategies.
10. ***Sustainability:*** Digital twins enable the evaluation of energy efficiency and environmental impact of transportation infrastructure.

Digital twins represent a transformative technology for transportation infrastructure management, offering substantial improvements in efficiency, safety, and sustainability. As digital twin technology continues to evolve, it promises to play an increasingly vital role in shaping the future of transportation infrastructure management. The integration of AI, machine learning, and blockchain technology is expected to further enhance the capabilities of digital twins,[11] leading to more accurate predictions, automated decision-making, and improved supply chain transparency.

Limitations and Future Directions

As outlined in the case studies above, despite their potential, implementing digital twins for transportation infrastructure faces several challenges:

1. ***Data Integration and Accuracy:*** Ensuring consistent, up-to-date data from diverse sources, alongside regulatory compliance.
2. ***Privacy and Security:*** Protecting sensitive infrastructure data.
3. ***High Initial Costs:*** Significant investment in technology and training, especially for smaller organizations.
4. ***Technical Expertise:*** Limited availability of skilled personnel to manage digital twin systems.
5. ***Scalability:*** Adapting solutions for growing organizations and complex supply chains.
6. ***Integration with Legacy Systems:*** Aligning new technologies with existing infrastructure without disruptions.
7. ***Cultural Resistance:*** Hesitancy to adopt new technologies in traditional industries.

As a future direction of work, we believe that digital twins should be integrated into the larger urban planning ecosystem. To address some of the current limitations that digital twins present, there are other steps that can help mitigate the issues of data integration and accuracy. Developing advanced sensor networks and technology will ensure accuracy and quality in data collection. Making guidelines

[11] *Digital Twins: Navigate Complexities, Capitalize on the Technology.* lingarogroup.com/blog/digital-twins-navigating-complexities-and-capitalizing-on-the-technology

and practice shift to standardized data sharing between governments and agencies. Developing frameworks via academic insight and industry collaboration to ensure seamless integration of data systems to apply to digital twins in various public goods.

As a method for advancing the technology to improve its scale, frameworks need to be developed to promote trust in the ecosystem. Liability planning, robust cybersecurity and open resource sharing need to be promoted to accommodate the privacy, safety and independence of every stakeholder. Securing viability funding using innovative local government funding approaches, study grants by industry and public-private partnerships will steer the development of this technology towards scale and improved value creation capacity.

Addressing limitations in today's technology through policy considerations will be crucial for the widespread adoption and success of digital twins in transportation infrastructure management.

Conclusion

Digital twins are transforming transportation infrastructure by creating virtual models of physical systems. These models help improve decision-making, enable predictive maintenance, and optimize how infrastructure is managed. Real-world examples like Singapore's smart city platform and Minnesota's bridge inspections show how digital twins can reduce costs, increase safety, and prevent infrastructure failures.

However, challenges like high costs, data accuracy issues, and a shortage of skilled workers need to be addressed. Policymakers can help by supporting public-private partnerships, funding programs, and phased rollouts to ease adoption. Clear rules for data sharing, privacy protection, and technical standards will also be essential.

As technology advances, digital twins will become even more powerful, helping cities plan better, run more efficiently, and stay safer. With the right policies and investments, digital twins can reshape how transportation systems are built and maintained for the future.