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Assessing the maturity of digital twins in global transportation engineering with a focus on Brazil

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ABSTRACT

This study evaluates the maturity of digital twin technologies in global transportation engineering, with a specific focus on Brazil. Digital twins worldwide integrate real-time data and predictive modelling to optimise infrastructure, reaching high maturity levels. In contrast, Brazilian applications remain mostly at Level 2 maturity, relying on static data and limited integration. Using the Maturity Model for Digital Twins, this research compares global and Brazilian implementations through a systematic literature review and case study analysis. The findings highlight both technical and socio-technical challenges: limited IoT infrastructure, uneven digital capacity, and the need for inclusive governance. By incorporating a Science, Technology, and Society (STS) perspective, the study emphasises that digital maturity extends beyond technical readiness to encompass ethical, institutional, and cultural dimensions. The results underscore the need for coordinated policies, investment in data analytics, and participatory frameworks to ensure that Digital Twins support sustainable, equitable, and resilient transportation systems in Brazil.

KEYWORDS: Digital Twins. Transportation Engineering. Maturity Model. Brazil. Science, Technology, and Society.

INTRODUCTION

In the ever-evolving landscape of transportation engineering, the integration of advanced technologies has become pivotal for shaping sustainable and efficient mobility solutions. Among these technologies, Digital Twins stand out as transformative tools, enabling the creation of digital replicas through the integration of historical and real-time data (Grieves, 2005).

The increasing demands on transportation systems, aggravated by factors such as urbanisation and population growth, demand innovative approaches for infrastructure optimisation. Digital Twins, as conceptualised by Grieves (2005) and further expounded upon by researchers like Botín-Sanabria et al., (2022) and Fu et al., (2023), offer a promising path for a comprehensive understanding and management of transportation assets. The utilisation of Digital Twins in transportation engineering encompasses a range of applications, from optimising urban traffic to supporting autonomous driving.

However, from a Science, Technology, and Society (STS) perspective, technological maturity cannot be seen as a purely technical evolution. Technologies such as Digital Twins are socio-technical constructs shaped by human decisions, institutional contexts, and cultural values (Bijker, 2008; Feenberg, 2002). Their impact depends not only on engineering excellence but also on governance, inclusivity, and ethical alignment (Lenzi, 2019).

Moreover, most previous studies have focused exclusively on the technical dimension of Digital Twin development, overlooking the broader socio-technical conditions that influence their implementation. As highlighted by Turbay and Firmino (2023), technological innovation in transport must be understood in relation to issues of governance, inclusion, and social impact, especially in emerging economies.

This study highlights the increasing global implementation of Digital Twins as crucial tools for enhancing the management, optimisation, and resilience of transportation systems. Digital Twins have the potential to revolutionise how infrastructure is developed, maintained, and monitored, especially considering the rapid technological advancements in the transportation sector. Brazil's unique challenges, such as geographical diversity and varying levels of urban development, make Digital Twins particularly beneficial. This research uses the Maturity Model for Digital Twins by Evans et al., (2019) to assess and compare the implementation levels of Digital Twins globally and in Brazil, emphasising the need for detailed analysis in the Brazilian context.

This paper is structured as follows: Section 2 overlays the methodology adopted by this study, Section 3 presents the science, technology, and society (STS) perspective on Digital Twins, Section 4 the definition of Digital Twins, Section 5 explains the Maturity Model proposed by Evans et al., (2019), Section 6 describes the importance of Digital Twins within the transportation sector and summarizes the current state of the Brazilian transportation infrastructure, Sections 7 and 8 are composed of the analysis made utilizing the Maturity Model on global and Brazilian case studies, respectively, Section 9 is comprised of the comparative analysis between the international and Brazilian case studies and Section 10 is the chapter that concludes this study.

METHODOLOGY

The methodology for this study was crafted to align with the PRISMA-P guidelines, ensuring a structured, transparent, and replicable framework for the systematic review of the literature (Moher; et al., 2016). The primary research question was: "What is the current state of maturity of Digital Twins technology in the transportation engineering sector, both in Brazil and other countries, and how is it being implemented?"

A comprehensive literature review was conducted to gather insights from articles published in both English and Portuguese, reflecting the global and Brazilian perspectives. Peer-reviewed articles were primarily targeted; however, due to the scarcity of Brazilian publications on the topic, master's theses, doctoral dissertations, and conference proceedings were also considered for the Brazilian sector. The databases utilized included Scopus and Web of Science, accessed on April 21, 2024, along with Google Scholar, which was accessed on April 26, 2024, to capture Brazilian-specific studies.

The global literature search was refined using a combination of keywords and filters. In Scopus, the initial search using "digital AND twin AND transportation", based only on words contained in the article's title, abstract, and keywords, returned 750 results, which were narrowed down by results only in English, publication date starting in 2019, and document type, featuring only peer-reviewed articles, resulting in 290 articles. The same keywords were used in the Web of Science database, also considering only words contained in the title, abstract, and keywords, which returned 335 results, and after applying the same filters as the ones in the Scopus database, only 215 results persisted.

For Brazilian studies, a Scopus and Web of Science search were also conducted, using the advanced search "digital AND twin AND transportation AND Brazil", which yielded no results at the Web of Science database and Scopus, only 3 lecture notes, which were discarded. So, a Google Scholar search was tailored with the exact terms "brasil transporte* (gêmeo* digital*) OR (digital* twin*)" which initially yielded 1,430 results, refined further by date, only results dating from 2019, and organized by relevance, resulting in 708 studies. The Brazilian search was comprised of both English and Portuguese keywords due to the "Digital Twins" term being used regardless of the study's language.

For global research, articles were required to explicitly include phrases such as "Digital Twin", "Digital Twins", or "Digital Twinning" in the title, which returned 170 results in the Scopus database and 123 results in the Web of Science database, the .csv files containing the search database were then downloaded from both sources. A new search was conducted, based on the journals displayed by each article, the category and quartile of these journals were assessed, through the Scimago Journal & Country Rank database, to filter only journals that explicitly displayed the "transportation" category and, also, comprised a quality rating of Q2 or higher. The articles were then further filtered, based on the journals selected, which resulted in 23 articles. With those, 10 repeated articles were removed, and 5 articles also needed to be unconsidered, due to their not developing a Digital Twin model, only 8 articles persisted. The reason for this last removal lies in the fact that a model needs to be generated for its maturity spectrum to be implemented.

For the Brazilian research, the inclusion process involved a title assessment where articles that did not mention digital twins either in English or Portuguese were excluded, 12 articles persisted past this filter. A .csv database containing these 12 results was then created, the database was organized to display the result's author's names, title, year, document type, a "yes" or "no" field, to track whether results were further removed from this database, and an additional field that stated the reason for the study's removal. Abstract assessments followed; 10 results were removed because the studies analyzed were not related to transportation. Only 2 results persisted, a doctorate dissertation and a conference proceeding.

This methodological rigor, ensured by adherence to PRISMA-P guidelines, aimed to maintain the integrity and reproducibility of the literature review process. By providing a systematic and unbiased evaluation of the literature, this approach helped establish a comprehensive understanding of the implementation and maturity of digital twin technologies in transportation engineering.

SCIENCE, TECHNOLOGY, AND SOCIETY (STS) PERSPECTIVE ON DIGITAL TWINS

Digital Twin technology, like any complex innovation, must be understood as a socio-technical phenomenon rather than a neutral tool. Science and Technology Studies (STS) scholarship has long shown that technological artefacts are socially constructed and imbued with the values and context of their creation (Bijker, 2008). In other words, the development, adoption, and use of a technology depend on social groups' interpretations and interests, which means a "mature" Digital Twin is not defined solely by technical perfection but by alignment with social needs and practices. Technologies carry an ambiguous and contested character, exhibiting both empowering and problematic aspects depending on how they are designed and employed (Lenzi, 2019). Lenzi (2019) notes that while certain thinkers emphasise the emancipatory potential of technical rationality, others critique the destructive or inequitable dimensions of modern technology; this ambivalence reminds us that Digital Twins can simultaneously enable positive transformations (e.g. smarter infrastructure, enhanced decision-making) and raise new dilemmas (e.g. surveillance, dependency, inequality) if not critically guided by societal values.

From a critical theory standpoint, technology is not external to society but deeply intertwined with power relations (Feenberg, 2002). Feenberg argues that technological systems often reflect the interests of dominant groups, and without democratic intervention, they may reinforce existing inequalities or bureaucratic control. A Digital Twin in transportation, for example, could embody specific interests or biases – such as prioritising efficiency and profit over equity – unless diverse stakeholders participate in its design and governance (Feenberg, 2002). This perspective urges researchers to examine who gets to define the goals and parameters of Digital Twins in engineering projects, and who might be excluded. Indeed, even highly advanced digital models will fail to produce socially desirable outcomes if they are developed in a "depoliticised" vacuum detached from public oversight and ethical debate. Turbay and Firmino (2023), analysing a digital mobility platform, stress that such innovations must be aligned with principles of social inclusion – like the right to the city – rather than treated as purely technical fixes. They caution that when technological development is seen as value-neutral and left to market logic alone, undesirable consequences can result – for instance, new forms of exclusion or loss of accountability (Turbay and Firmino, 2023). By viewing Digital Twins through the STS lens, we acknowledge that their maturity involves institutional and cultural readiness – e.g. policies, skill sets, public acceptance – alongside technical sophistication.

Furthermore, the Digital Twin can be seen as part of a broader trend in which data-driven tools shape how decisions are made and justified in society. Borbach et al. (2025) argue that digital twins represent a technocratic paradigm aimed at “making everything count”: they continuously datafy and model aspects of the world in real time to predict and optimise outcomes. In their analysis, a Digital Twin is not a passive mirror of reality, but a performative agent intertwined with humans, infrastructures, and algorithms in feedback loops (Borbach et al., 2025). This means the technology actively influences organisational practices and even public policy by foregrounding certain metrics and simulations as the basis for action. Such power to redefine problems and solutions brings great responsibility. As STS scholars highlight, there are always choices about what data to collect, what models to build, and what purposes to pursue – choices that reflect particular social and political priorities (Duarte and Álvarez, 2019). A Digital Twin of a transportation network, for example, might prioritise congestion and vehicular flow, or instead prioritise accessibility for underserved communities; these design orientations depend on societal values and stakeholder input. Recognising the Social Shaping of Digital Twins is therefore crucial: the technology’s evolution will co-depend on legal frameworks, ethical norms, and public engagement. Rather than viewing Digital Twin maturity as a linear technical progression, a CTS-aligned view conceives it as a co-evolution of technology and society – encompassing regulatory standards, user competencies, and cultural acceptance that develop in tandem with the digital tools (Bijker, 2008; Turbay and Firmino, 2023). In summary, grounding the discussion in Science, Technology and Society theory allows us to critically examine how Digital Twins are embedded in social contexts, how they redistribute agency and knowledge, and how we might steer their development toward socially beneficial outcomes instead of unintended inequities (Lenzi, 2019; Feenberg, 2002; Borbach et al., 2025).

DIGITAL TWIN DEFINITIONS AND LEVEL OF MATURITY

Definition

Digital twins, as conceptualised in the reviewed literature, represent advanced virtual models that mirror physical entities and systems, enabling real-time monitoring, simulation, and optimisation of processes across various industries. Initially introduced by Grieves (2005) within the context of Product Lifecycle Management (PLM), digital twins facilitate a comprehensive integration of information throughout a product's lifecycle, from design to disposal. Extending beyond their foundational application, subsequent studies have applied digital twin technologies in diverse settings. For example, Saroj et al., (2021) developed a digital twin for traffic management, which leverages real-time data to dynamically simulate and manage urban traffic flows, demonstrating the potential of digital twins to enhance operational efficiencies and environmental monitoring.

Further research by Feng et al., (2023) also highlighted the robust capabilities of digital twins in enhancing transportation system resilience by integrating the Internet of Vehicles (IoV) and blockchain technologies, which enable real-time decision-making and system adaptations. Similarly, Qu et al., (2024) applied a digital twin framework for real-time traffic crash detection on expressways, emphasising its critical role in improving traffic safety and response strategies.

Level of Maturity

In their 2022 publication, Botín-Sanabria et al. (2022) introduced three fundamental concepts that enhance the comprehensive understanding of Digital Twins. Specifically, the authors proposed the digital model, digital twin, and digital shadow as key concepts to elucidate the main characteristics of this emerging technology. The digital model lacks automatic information flow, requiring manual changes. The digital shadow involves unidirectional flow from the physical to the virtual world. In contrast, the digital twin enables bidirectional interaction, automatically representing the physical counterpart's state and evolution in the virtual world, facilitating seamless integration.

To understand the contrast between Digital Twin models to other models and comprehend their level of implementation within the current industry, Evans et al., (2019) proposed a Digital Twin maturity model, presented in Table 1.

Table 1. Maturity Model for Digital Twins (Evans et al., 2019).

Maturity Element	Definition	Usage
0	Reality capture (e.g. point cloud, drones, photogrammetry, or drawings/sketches).	Brownfield (existing) as-built survey.
1	2D map/system or 3D model (e.g. object-based, with no metadata or BIM).	Design/asset optimization and coordination.
2	Connect model to persistent (static) data, metadata, and BIM Stage 2 (e.g. documents, drawings, asset management systems).	4D/5D simulation, design/asset management, BIM Stage 2.
3	Enrich with real-time data (IoT, sensors).	Operational efficiency.
4	Two-way data integration and interaction.	Remote and immersive operations; control the physical from the digital.
5	Autonomous operations and maintenance.	Complete self-governance with total oversight and transparency.

Fonte:

Element 0 involves reality capture through methods such as surveying point clouds, drones, photogrammetry, and others, to gather and retain data on existing physical assets. Element 1 is limited to object-based models, such as surfaces and shapes, that do not include BIM data or metadata, namely GIS maps and CAD 2D and 3D drawings, to maximise performance, reliability, and lifecycle of physical assets. In element 2, the work produced in element 1 is connected to data sets that remain available over time, namely design and material specifications, creating a reference model where all data can be viewed and analysed, using BIM, for example. Element 3 is defined by the integration of real-time data through a single communication flow from physical to digital assets, using connected devices and the Internet of Things (IoT), to achieve operational efficiency. Element 4 is where the bi-directional communication takes place, either between digital to physical twin or digital to other digital twins, it also allows the physical asset to be modified through the operation of the digital twin. Lastly, element 5 considers the complete autonomy in the operations and maintenance of the Digital Twin.

Nevertheless, most of the studies produced on Digital Twins are at elements 2 or 3 (Botín-Sanabria et al., 2022; Masoumi et al., 2023). Hence, the scope of Digital Twin technology should extend beyond mere 3D models, encompassing dynamic bi-directional communication between physical and digital counterparts, integrating automation into maintenance and operation processes, and accounting for various dimensions within the broader context of Digital Twins (Masoumi et al., 2023).

COMPREHENSION OF DIGITAL TWINS WITHIN THE TRANSPORTATION SECTOR

Transportation is a fundamental procedure, that the population depends on, which can be defined as the movement of people or assets from one geographical location to another, granting access to key destinations such as workplaces, educational institutions, health care services, retail establishments, and various essential services (Abdel Wahed Ahmed and Abd El Monem, 2020).

As a result of the growing population number in cities, the urban transportation network has caused economic issues due to high fuel consumption and pollution generation owing to long traffic congestions, with the addition of housing developments that increase demand on the network. To maintain efficient transportation, supply must meet travel demand, such as providing adequate transportation infrastructure and efficient traffic management systems (Shi, 2009).

The lifecycle of a transportation infrastructure is generally broken down into planning, design, operation, and monitoring. The planning phase involves conceptual planning, feasibility studies, and the definition of project goals, needs, risks, funding requirements, and design alternatives. Upon confirming feasibility and securing funding, the project advances to the design phase. In this stage, a design team creates documents that incorporate the owner's requirements, standards, and criteria, as well as relevant codes (Belcher and Abraham, 2023).

With advancements in technologies like IoT, big data, AI, and machine learning, Digital Twin has become integral to various facets of transportation. It optimizes urban traffic, monitors highways, facilitates collaboration within intelligent vehicle infrastructure, and supports the development of autonomous driving. The oscillation of urban traffic and its effects present an adequate scenario for the applications of a Digital Twin solution since the technology is mostly used on objects that change over time (Wright and Davidson, 2020).

A study on the definition, framework, operation, and enabling technologies of Digital Twin smart freeways was conducted, in 2023, by Fu et al. asserted that, within the topic discussed, the DT approach strives to identify real-time system states and forecast traffic parameters in advance, subsequently deploying dynamic traffic control strategies, namely mitigating traffic congestion and maintaining common freeway infrastructure capacity.

Current State of Brazilian Transportation Infrastructure

According to a national road survey carried out by Confederação Nacional do Transporte – CNT (2023), the Brazilian road network spans around 1.7 million kilometers, with only 12.4% paved (213.5 thousand kilometers). Based on the 2035 National Logistics Plan – PNL – (MINFRA, 2021), the railway network comprises 20,821 kilometers with 195 terminals, exhibiting uneven distribution. The Brazilian railway system is marked by diverse operators reflecting historical investments in mining and agriculture. The waterway network, centered mostly on the Amazon River, integrates navigation routes, lakes, coastal areas, and long-distance routes, encompassing 79 port cities and 103 locations.

The road survey carried out by CNT (2023), encompassed 111,502 kilometers on its assessment, it reveals that only 32.5% (36,312 km) of assessed Brazilian roads are in Excellent or Good condition. Predominant issues, particularly in pavement conditions (56.8%), necessitate proactive interventions to maintain quality. Signage problems affect 63.4%, and road geometry receives the poorest evaluation at 66.0%. Continuous maintenance is crucial to prevent deeper degradation and higher restoration costs.

To prepare Brazilian transportation for global integration, it's crucial to anticipate trends shaping logistics. Neglecting these trends may harm international competitiveness and exacerbate domestic logistical challenges. Disruptive technologies, driven by national and international e-commerce, are reshaping delivery expectations. The Internet of Things (IoT), Big Data, Artificial Intelligence (AI), and 5G networks play pivotal roles, forming Industry 4.0 components in the 2035 National Logistics Plan (PNL). Technological impacts on transport were studied and integrated into the PNL 2035 scenarios, encompassing autonomous vehicles, digital logistics transformation, and electrification trends. These factors offer efficiency gains, cost reductions, and environmental benefits, shaping the future landscape of Brazil's transport system (MINFRA, 2021).

CASE STUDIES FROM GLOBAL IMPLEMENTATION OF DIGITAL TWIN TECHNOLOGIES

The exploration of global implementations of digital twin technologies in various sectors is pivotal for understanding their impact and potential. The case studies, presented in Table 2, were selected to showcase how digital twins effectively address complex challenges, enhance operational efficiencies, and facilitate strategic decision-making across diverse organizational and geographical contexts. Each case study elucidates the levels of maturity these implementations have achieved, as defined by Evans et al., (2019), highlighting the broad applications and significant outcomes of these advanced systems. From enhancing traffic management in urban environments to optimizing supply chain resilience during global disruptions, these examples offer a comprehensive look at the potential and adaptability of digital twin technologies. The summarized details in Table 2 provide insights into the scope, technological depth, and tangible benefits of these digital twin deployments, illustrating the state-of-the-art in their implementation.

Table 2. Global case studies and their Digital Twin Maturity Model based on Evans et al., 2019

Author, year [Maturity Element]	DT Model details	Location	Reason for Maturity Element adoption	Outcomes
Burgos and Ivanov, (2021) [2]	Development of a supply chain digital twin to determine the impact of COVID-19 on German food retail and supply chain performance.	29 supermarket locations in Germany, Austria, the Czech Republic, Italy, and Hungary.	Data was obtained through secondary sources such as demand patterns and supplier networks, instead of utilizing real-time integration.	Impact analysis of pandemic scenarios, understanding of supply chain vulnerability and resilience, strategies to enhance supply chain resilience and financial and operational performance metrics.

Author, year [Maturity Element]	DT Model details	Location	Reason for Maturity Element adoption	Outcomes
Chen et al., (2024) [4]	Creation of a 3D digital twin model with a shared visualization for collaborative air traffic management operations.	A model aligned with Singapore's Changi Airport.	The system allows for two-way data interaction where air traffic controllers (ATCOs) manipulate aircraft movement through the MR interface.	Enhanced situational awareness and decision-making, increased collaboration efficiency, positive user feedback on usability and interaction, and potential for real-world application.
Feng et al., (2023) [4]	Proposition of a digital twin model to enhance the resilience and adaptability of transportation systems to uncertain events.	Traffic data from Xi'an Rail Station.	The digital twin supports real-time decision-making and operational adjustments with two-way data integration from IoV and blockchain technologies.	Improved data sharing, enhanced system resilience, operational efficiency, real-world validation, and adaptability to traffic conditions.
Fu et al., (2023) [4]	The use of SUMO, applying Digital Twin Freeway control.	A simulated urban intersection.	The system demonstrates two-way data integration and interaction, as it allows for adjustments and controls based on the data received and analyzed within the simulation environment.	Enhanced traffic management, improved safety and efficiency, dynamic response capability, integrated control strategies, the feasibility of smart freeway concepts, and validation through simulation.
Jiang et al., (2022) [2]	Provision of sustainable urban road approach based on digital twins, multi-criteria decision making, and geographical information systems.	Mortlake, southwest of London.	The study does not incorporate dynamic data, the authors focused on integrating static and historical data such as topographic, traffic, and noise data.	Enhanced urban planning, improved decision making, and sustainability focus.
Saroj et al., (2021)	Development of a Digital Twin for a	North Avenue Smart	The digital twin model leverages real-time data from	Enhanced traffic management and operational

Author, year [Maturity Element]	DT Model details	Location	Reason for Maturity Element adoption	Outcomes
[4]	Connected Corridor Real-Time Traffic Management.	Corridor, Atlanta, GA, USA	multiple sources (like traffic volume and signal timing data), allowing for dynamic simulation of traffic conditions and effectively providing real-time feedback for managing traffic and environmental conditions.	efficiency, improved real-time responsiveness to changing traffic conditions, better decision-making capabilities for traffic control, and enhanced environmental performance tracking.
Qu et al., (2024) [4]	Application of a digital twin framework for the detection of traffic crashes on non-intelligent expressways.	Nanjing Ring expressway.	The author predicts interactive functions for the model that utilizes real-time traffic data, therefore it employs two-way data integration and interaction.	Improved traffic crash detection and response strategies, comprehensive understanding of crash key factors, and employment of cost-effective and efficient multi-source traffic crash detectors.
Saroj et al., (2023) [3]	Investigating the effects of data imputation methods on digital twin performance measures for traffic management in a connected corridor.	North Avenue Smart Corridor, Atlanta, Georgia, USA.	The focus of the study is on exploring data imputation methods for addressing data gaps in traffic volume and signal data streams used by a digital twin. The research aims to optimize data quality and reliability rather than advancing real-time data integration capabilities or interactive system functionalities.	The study evaluates how different data imputation strategies affect the accuracy of the digital twin in simulating real-time traffic conditions, ultimately aiding in better decision-making, and improving traffic management strategies.

Fonte:

The review of current digital twin implementations highlights several research initiatives that stand out due to their innovative approaches and significant impacts on their respective fields. For instance, the study by Burgos and Ivanov, (2021) provided crucial insights into the resilience of supply chains during the COVID-19 pandemic, employing a digital twin to simulate various disruption scenarios in the European food retail sector. Similarly, the research conducted by Chen et al., (2024) focused on enhancing air traffic management at Singapore's Changi Airport, demonstrating the potential of 3D digital twins in improving situational awareness and operational efficiency through real-time, interactive visualizations.

Another notable study by Fu et al., (2023) utilized SUMO for applying digital twin technology to simulate and control traffic at an urban intersection, illustrating the twin's capability to enhance traffic management and safety dynamically. Each of these studies achieved a maturity level of 4, showcasing advanced capabilities in real-time data processing and two-way data integration.

However, it is noteworthy that none of the research included in the analysis reached Level 5 maturity, the highest level described by Evans et al., (2019). Level 5 signifies a fully autonomous system capable of self-learning and self-optimisation without human intervention. The absence of Level 5 maturity in the surveyed studies highlights a significant gap in current digital twin technology applications, indicating potential areas for future research and development. The progression towards Level 5 maturity represents a frontier in digital twin technology, promising revolutionary changes in how industries operate and manage complex systems autonomously.

This technological gap also reveals broader socio-technical challenges. As Feenberg (2002) argues, technological progress is often constrained not only by engineering limitations but also by institutional and cultural readiness. Even in advanced economies, the transition toward autonomous Digital Twins requires organizational trust in data-driven systems, regulatory adaptation, and public acceptance — all factors that extend beyond purely technical maturity.

CASE STUDIES FROM BRAZILIAN IMPLEMENTATION

Exploring the application of digital twin technologies within Brazil, this section showcases how these advanced tools address specific local challenges in the transportation sector. Featured case studies highlight the integration of digital twin technology in two distinct areas: the maintenance of unpaved roads in forestry enterprises and urban walkability enhancement in Florianopolis. These examples demonstrate the strategic use of digital twins in improving operational efficiencies and enhancing quality of life.

Table 3. Brazilian case studies and their Digital Twin Maturity Model based on Evans et al., 2019

Author (year) [Maturity Level]	DT Model details	Location	Reason for Maturity Element adoption	Outcomes
Arrivabeni, (2021) [2]	No specific DT model was developed, rather a technical, economic, and	The study addresses unpaved roads generally in the context	The HDM-4 and Simio software are used to conduct simulations for various	Optimized maintenance strategies, simulated through digital twin concepts,

Author (year) [Maturity Level]	DT Model details	Location	Reason for Maturity Element adoption	Outcomes
	environmental analysis of unpaved road maintenance using Digital Twin technology.	of forestry enterprises, without specifying a singular geographic location.	maintenance strategies on unpaved roads. These simulations aim to aid decision-making through scenario modeling and visualization, but they lack real-time data integration and interactive capabilities that characterize higher maturity levels.	can significantly improve road quality, reduce maintenance costs, and minimize environmental impacts. It emphasizes the potential for enhanced decision-making in road maintenance and management within forestry enterprises.
Schmitt et al., (2023) [2]	Development of a digital twin prototype to analyze urban walkability, focusing on counting pedestrians on sidewalks using ultrasonic sensors and an Arduino Uno board to enhance urban planning and pedestrian safety.	Florianopolis, Brazil.	The prototype utilizes sensor data to monitor pedestrian traffic and does not demonstrate real-time data integration or interactive system feedback capabilities typical of higher maturity levels.	Provides insights into pedestrian traffic patterns and supports urban planning efforts to improve walkability and pedestrian safety in urban areas.

Fonte:

The case studies illustrate diverse applications and maturity levels of digital twin technology in Brazil. The first study, led by Arrivabeni, (2021), focuses on the technical, economic, and environmental aspects of maintaining unpaved roads using digital twin concepts. Although no specific digital twin model was developed, the use of simulation tools like HDM-4 and Simio facilitated scenario-based planning and decision-making, underscoring the potential benefits of digital twin methodologies in enhancing road maintenance strategies and reducing environmental impacts.

Conversely, the second case study from Florianopolis, led by Schmitt et al., (2023), developed a digital twin prototype to improve urban walkability. Utilizing ultrasonic sensors and Arduino technology, this project monitored pedestrian traffic in real-time, providing valuable data to urban planners aimed at enhancing pedestrian safety and walkability. Like the first case, this prototype did not achieve a high maturity level due to the absence of real-time data integration and interactive system feedback capabilities.

These examples from Brazilian implementations showcase the promising yet early-stage integration of digital twin technology within local infrastructure projects. They highlight the potential of digital twins to provide significant improvements in infrastructure management and urban planning, while also revealing the current limitations in achieving higher levels of technological maturity and broader system integration.

From a Science, Technology, and Society perspective, these early-stage Brazilian implementations illustrate how technological maturity depends on social and institutional context. The limited integration of Digital Twins is linked to unequal digital infrastructure and to the concentration of technical expertise within a few research centers. As Turbay and Firmino (2023) emphasise, innovation in transport can only be effective when accompanied by inclusive governance and capacity-building policies that address digital inequality.

COMPARATIVE ANALYSIS: THE GLOBAL IMPLEMENTATION OF DIGITAL TWIN TECHNOLOGIES WITH THOSE SPECIFICALLY WITHIN BRAZIL

Globally, digital twin technologies in transportation feature advanced capabilities such as real-time data integration, predictive modelling, and high operational control. These implementations often achieve higher maturity levels (e.g., Level 4) and are used in complex applications like air traffic management and urban traffic optimisation. In contrast, Brazil's use of digital twins is in the early stages, focusing on specific challenges such as unpaved road maintenance and urban walkability. These applications typically reach only Level 2 maturity, relying on static data and basic simulations without real-time integration or automated feedback.

The state of the art in digital twin technology globally includes sophisticated management, planning, and operational functionalities. In management, advanced digital twins integrate IoT sensors and real-time data, enabling proactive maintenance and reducing downtime and costs. For planning, digital twins simulate scenarios for infrastructure development, optimising designs and minimising risks before implementation. In operations, real-time data allows for dynamic traffic management, optimised routing, and immediate incident responses, enhancing efficiency and reducing congestion.

In Brazil, current applications are limited to static data and basic simulations, addressing localised issues without real-time capabilities. To achieve the advanced state of the art seen globally, Brazil needs to invest in IoT infrastructure and real-time data integration. This would enable proactive management, optimised planning, and efficient operations, making transportation systems more efficient, resilient, and sustainable. By focusing on these areas, Brazil can significantly enhance its transportation infrastructure, aligning with global advancements in digital twin technology.

Beyond financial investment, this comparative analysis suggests that the path toward higher Digital Twin maturity in Brazil involves fostering socio-technical alignment. As Bijker (2008) notes, technologies evolve through the interaction of technical artefacts and the social groups that shape their meaning. Thus, strengthening collaboration between public authorities, academia, and citizens is essential to ensure that Digital Twin adoption in Brazil reflects local priorities and contributes to equitable, sustainable development.

CONCLUSION

Brazil's digital twin applications in transportation currently stand at an early stage, generally reaching only Level 2 maturity. This limited advancement is primarily due to a lack of real-time data integration and reliance on static simulations for localized applications. Contributing factors include insufficient infrastructure for IoT deployment, limited access to advanced technological resources, and a nascent understanding of digital twin potentials within the transportation sector.

To bridge this gap, Brazil must invest in IoT infrastructure and data analytics capabilities. Collaboration between government bodies, academia, and the private sector can stimulate the development and implementation of more advanced digital twin applications. With appropriate investment and strategic initiatives, Brazil can elevate its digital twin maturity to align more closely with global standards, achieving higher levels of operational efficiency, resilience, and sustainability in its transportation infrastructure.

Beyond technical readiness, advancing Digital Twin maturity also requires socio-technical alignment. As Feenberg (2002) notes, technological systems are embedded in power relations and reflect institutional priorities. Thus, Brazil's digital transformation in transportation must ensure that innovation is guided by inclusive and ethical governance. The collaboration between public agencies, academia, and private actors should not only focus on infrastructure investment but also on creating participatory frameworks for decision-making and capacity building, ensuring that Digital Twins serve public values rather than narrow interests (Bijker, 2008; Turbay and Firmino, 2023).

Future studies should focus on integrating real-time data streams from IoT sensors into digital twin models, investigating scalable solutions for complex transportation networks, and encouraging interdisciplinary research. Additionally, assessing digital twin technologies' economic and environmental impacts and studying the necessary policy and governance frameworks will support widespread adoption. Addressing these areas will significantly advance the maturity and effectiveness of digital twin technologies in Brazil's transportation sector, ensuring they become a pivotal tool for sustainable and efficient infrastructure management.

Addressing these areas will significantly advance not only the technical but also the social maturity of Digital Twin technologies in Brazil. From a Science, Technology, and Society perspective, digital maturity entails more than technological sophistication: it depends on the ethical, cultural, and institutional contexts in which technologies operate (Lenzi, 2019). Therefore, policies must simultaneously foster technical innovation and safeguard transparency, data ethics, and equitable access to digital infrastructure. Ultimately, Digital Twins should be viewed as co-evolving systems where technology and society mutually shape one another — a dynamic that determines whether digitalisation will promote social inclusion or deepen existing inequalities (Feenberg, 2002; Bijker, 2008).

RESUMO

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