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A Socio-Technical Governance Framework for Trustworthy AI-Enabled Transport Digital Twins

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Abstract

The integration of Artificial Intelligence (AI) with transport Digital Twins (DTs) is transforming intelligent transportation systems by enabling real-time monitoring, predictive analytics, traffic optimization, infrastructure management, and autonomous decision support. However, the increasing autonomy and complexity of AI-enabled transport Digital Twins introduce significant challenges related to transparency, accountability, cybersecurity, privacy, data quality, algorithmic bias, human oversight, and operational safety. Existing Digital Twin architectures primarily emphasize technical interoperability and real-time synchronization, while conventional AI governance frameworks often provide limited guidance for the continuous and context-dependent operation of transport Digital Twins. This paper proposes a Socio-Technical Governance Framework for Trustworthy AI-Enabled Transport Digital Twins (STG-TDT). The framework integrates technical controls, organizational governance, human oversight, risk management, ethical assurance, cybersecurity, privacy protection, and continuous performance monitoring across the complete Digital Twin lifecycle. The proposed framework consists of six interconnected layers: data and sensing governance, Digital Twin integrity, AI governance, cybersecurity and privacy, human and organizational oversight, and continuous assurance. A multidimensional Trustworthiness Assurance Score is further proposed to evaluate reliability, safety, security, transparency, explainability, privacy, fairness, accountability, and resilience. The framework is aligned conceptually with established AI risk-management and AI-management approaches, including the NIST AI Risk Management Framework and ISO/IEC 42001. The paper demonstrates how socio-technical governance can provide a systematic foundation for deploying trustworthy AI-enabled transport Digital Twins while maintaining operational safety, regulatory accountability, and public confidence.

Keywords: Artificial Intelligence, Digital Twin, Intelligent Transportation Systems, AI Governance, Socio-Technical Systems, Trustworthy AI, Cybersecurity, Explainable AI, Privacy, Continuous Assurance

1. Introduction

The rapid development of Artificial Intelligence (AI), Internet of Things (IoT), edge computing, cloud computing, and cyber-physical systems has created new opportunities for transforming transportation infrastructure and mobility services. Intelligent Transportation Systems (ITS) increasingly rely on large-scale sensing networks, connected vehicles, roadside infrastructure, traffic-management platforms, and AI-based decision-support mechanisms. Within this environment, Digital Twin technology has emerged as an important paradigm for creating a continuously updated virtual representation of physical

transportation assets, processes, and environments. A transport Digital Twin can represent roads, intersections, vehicles, public transportation networks, traffic signals, bridges, tunnels, and other transportation infrastructure while integrating real-time information from physical systems.

The integration of AI into Digital Twins substantially extends their capabilities. AI models can analyze historical and real-time data to predict traffic congestion, detect anomalies, estimate infrastructure degradation, optimize signal timing, forecast transportation demand, and support emergency-response decisions. Consequently, AI-enabled

Digital Twins have the potential to evolve from passive visualization platforms into intelligent decision-making environments capable of recommending or autonomously executing operational actions.

However, this evolution also creates a fundamental governance challenge. A transportation Digital Twin is not simply a software artifact. It is a socio-technical system in which algorithms interact with physical infrastructure, transportation operators, government agencies, passengers, drivers, maintenance personnel, emergency services, and other stakeholders. Errors in AI predictions or inappropriate automated decisions can therefore have physical, economic, social, and safety consequences. A technically accurate model may still be considered untrustworthy if its decisions cannot be explained, its data are collected without adequate privacy controls, its models exhibit systematic bias, or responsibility for decisions remains unclear.

The NIST Artificial Intelligence Risk Management Framework (AI RMF) emphasizes that trustworthy AI involves characteristics including validity and reliability, safety, security and resilience, accountability and transparency, explain ability and interpretability, privacy enhancement, and fairness with harmful bias managed. Importantly, NIST characterizes AI systems as socio-technical because their risks arise through interactions among technical systems, people, organizational processes, and societal contexts.

Similarly, ISO/IEC 42001:2023 provides requirements for establishing, implementing, maintaining, and continually improving an Artificial Intelligence Management System. It emphasizes structured organizational management of AI-related risks and opportunities, including responsible AI use, transparency, traceability, and continuous improvement.

Despite these developments, a significant gap remains between general AI governance principles and the operational requirements of AI-enabled transport Digital Twins. Transportation systems require continuous synchronization between physical and virtual environments, dynamic decision-making, real-time data processing, safety-critical operations, multiple stakeholder interactions, and continuous model adaptation. Therefore, governance cannot be limited to pre-deployment model assessment. It must operate throughout the Digital Twin lifecycle.

This research addresses this gap by proposing a Socio-Technical Governance Framework for Trustworthy AI-Enabled Transport Digital Twins (STG-TDT). The framework combines technical assurance with organizational, human, ethical, regulatory, and societal controls. The primary objective is to establish a continuous governance mechanism through which the trustworthiness of AI-enabled transport Digital Twins can be designed, monitored, assessed, and improved.

1.1 The major contributions of this paper are as follows

1. A socio-technical governance architecture specifically designed for AI-enabled transport Digital Twins is proposed.
2. A lifecycle-oriented governance mechanism is developed covering data acquisition, Digital Twin construction, AI development, deployment, operation, monitoring, and retirement.
3. Technical and socio-organizational trustworthiness

dimensions are integrated into a unified assurance model.

4. A Trustworthiness Assurance Score is proposed for continuously evaluating the operational trustworthiness of transport Digital Twins.
5. Governance responsibilities are distributed among AI developers, transportation operators, infrastructure owners, regulators, cybersecurity teams, and human decision-makers.

2. Literature Review

Digital Twin (DT) technology has emerged as an important approach for developing intelligent transportation systems by connecting physical transportation assets with virtual models, real-time data, simulation, and analytics^[1, 3]. Recent studies have investigated DT applications in traffic management, intelligent highways, connected vehicles, infrastructure monitoring, and mobility services. Ge and Qin^[1] provide a systematic review of Digital Twin-based ITS and highlight architectures, services, data fusion, edge computing, federated learning, blockchain, and secure communication as important research directions. Other studies have emphasized the role of DTs in transportation infrastructure management, real-time traffic simulation, and mobility optimization^[2, 3].

The integration of Artificial Intelligence (AI) with Digital Twins has further enhanced their predictive and decision-making capabilities. Machine learning, deep learning, computer vision, and reinforcement learning have been applied for traffic prediction, congestion management, anomaly detection, predictive maintenance, and intelligent transportation control^[4, 6]. AI-enabled DTs can therefore move beyond simple monitoring toward predictive and prescriptive transportation management. However, the increasing autonomy of AI also introduces concerns regarding model reliability, explain ability, bias, model drift, and accountability^[7, 8].

Trustworthiness has consequently become an important research issue in Digital Twin research. Lu *et al.*^[9] specifically examined trustworthy road Digital Twins and reported that inaccurate or unreliable Digital Twins can result in incorrect decisions, financial losses, inefficient infrastructure management, and safety risks. Trustworthy AI research similarly identifies reliability, safety, security, transparency, explain ability, privacy, fairness, and accountability as important dimensions of trustworthy intelligent systems^[7, 10]. These dimensions are particularly important in transportation because AI-generated recommendations may directly influence physical infrastructure and public mobility.

Cybersecurity and privacy represent another major challenge. Transport Digital Twins depend on interconnected sensors, IoT devices, communication networks, cloud/edge platforms, and AI models, making them vulnerable to data manipulation, unauthorized access, adversarial attacks, and model poisoning^[11, 12]. Research on AI-based Digital Twin cybersecurity indicates that AI can be used both to strengthen DT security and to create new attack surfaces that require additional protection^[11]. Privacy is also important because transportation DTs may process vehicle locations, travel patterns, video information, and other sensitive data.

AI governance research has increasingly focused on establishing mechanisms for accountability, transparency, risk management, and responsible AI deployment. Batool *et al.* [13] found that existing AI governance research covers organizational, industry, national, and international levels but remains fragmented regarding who governs AI, what should be governed, and when governance should occur. NIST's AI Risk Management Framework further emphasizes the functions Govern, Map, Measure, and Manage for managing AI risks throughout the system lifecycle [14]. Similarly, ISO/IEC 42001 provides a management-system approach for responsible and continually improving AI governance [15]. Despite these developments, existing studies largely address transport Digital Twins, AI governance, cybersecurity, and trustworthy AI as separate research areas. There remains a limited number of integrated frameworks specifically designed for the continuous governance of AI-enabled transport Digital Twins. In particular, the combined consideration of Digital Twin integrity, AI reliability, cybersecurity, privacy, explain ability, human oversight, accountability, and continuous assurance remains insufficiently explored. Therefore, this research proposes a Socio-Technical Governance Framework for Trustworthy AI-Enabled Transport Digital Twins (STG-TDT) to bridge this gap.

3. Problem Statement

The integration of Artificial Intelligence (AI) with Transport Digital Twins (TDTs) enables real-time monitoring, prediction, simulation, and intelligent decision-making in transportation systems. However, the increasing dependence on AI introduces challenges related to data integrity, model reliability, cybersecurity, privacy, explain ability, bias, accountability, and human oversight [1, 5]. Existing Transport Digital Twin research mainly focuses on technical capabilities such as real-time synchronization, traffic prediction, infrastructure monitoring, and optimization, while AI governance studies generally address AI systems at a broader organizational level [6, 10]. As a result, there is a lack of an integrated governance mechanism specifically designed for the continuous and dynamic operation of AI-enabled Transport Digital Twins.

Furthermore, the trustworthiness of a Transport Digital Twin can change during operation because of sensor failures, data drift, model degradation, cyberattacks, changing traffic conditions, and inappropriate human interaction. Existing approaches often evaluate these aspects independently and provide limited mechanisms for continuous assurance, stakeholder accountability, and human-in-the-loop decision-making [11, 15]. Therefore, a comprehensive socio-technical governance framework is required to integrate technical, organizational, human, ethical, and security considerations throughout the Digital Twin lifecycle.

This research addresses this gap by proposing a Socio-Technical Governance Framework for Trustworthy AI-Enabled Transport Digital Twins (STG-TDT) that integrates data governance, Digital Twin integrity, AI governance, cybersecurity, privacy, explain ability, human oversight, accountability, and continuous assurance. The framework aims to provide a systematic mechanism for ensuring that

AI-enabled Transport Digital Twins remain reliable, secure, transparent, accountable, and trustworthy throughout their operational lifecycle.

4. Methodology

The proposed research adopts a design science research approach to develop and evaluate the Socio-Technical Governance Framework for Trustworthy AI-Enabled Transport Digital Twins (STG-TDT). The methodology integrates technical, organizational, human, cybersecurity, privacy, and trustworthiness aspects into a unified lifecycle. The overall research process is presented in Fig. 1, which progresses from requirement analysis to framework design, governance development, trustworthiness assessment, prototype implementation, and performance evaluation.

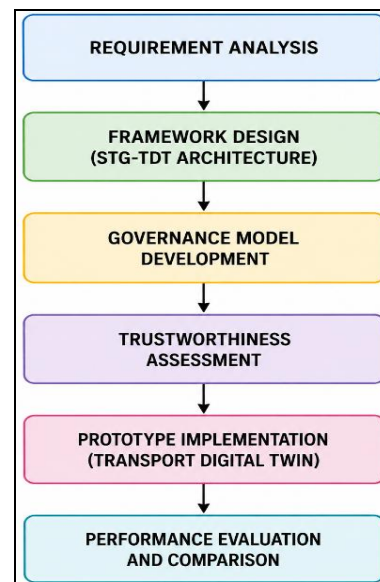


Fig 1: Methodology Framework for the Proposed STG-TDT Approach

Figure 1 presents the overall methodology adopted for developing the proposed Socio-Technical Governance Framework for Trustworthy AI-Enabled Transport Digital Twins (STG-TDT). The methodology progresses from requirement analysis and framework design to governance development, trustworthiness assessment, prototype implementation, and final performance evaluation. This sequential process ensures systematic development and validation of the proposed framework.

4.1 Requirement Analysis

The first stage identifies the major requirements and risks associated with AI-enabled Transport Digital Twins. Existing research on Digital Twins, Intelligent Transportation Systems, trustworthy AI, cybersecurity, privacy, explainable AI, and AI governance is examined to identify requirements related to data quality, Digital Twin integrity, AI reliability, security, privacy, explain ability, accountability, human oversight, safety, and resilience.

4.2 Framework Design

Based on the identified requirements, the proposed STG-TDT architecture is designed. The framework integrates six major components: data and sensing governance, Digital

Twin integrity, AI governance, cybersecurity and privacy, human and organizational governance, and continuous assurance. These components work together to ensure that both the technical and socio-organizational aspects of the Transport Digital Twin are governed throughout its lifecycle.

4.3 Governance Model Development

The governance model establishes controls for data collection, AI model development, validation, deployment, monitoring, and retirement. Data governance focuses on data quality, provenance, integrity, and privacy. AI governance addresses model reliability, explain ability, bias, model drift, and version management. Cybersecurity mechanisms protect the Digital Twin infrastructure and communication channels, while organizational governance defines responsibilities among transportation authorities, system operators, AI developers, cybersecurity teams, infrastructure owners, and regulators.

4.4 Trustworthiness Assessment

The proposed framework evaluates the trustworthiness of the Transport Digital Twin using multiple dimensions, including reliability, safety, cybersecurity, transparency, explain ability, privacy, fairness, accountability, and resilience. These dimensions are continuously monitored using appropriate technical and governance indicators. The assessment helps identify degradation in system performance and determines whether corrective action or human intervention is required.

4.5 Prototype Implementation

For validation, a prototype Transport Digital Twin environment can be developed using a traffic simulation platform such as SUMO. The environment represents transportation elements such as roads, vehicles, intersections, traffic signals, and traffic flows. AI models can be integrated for traffic prediction, congestion detection, anomaly detection, and intelligent decision support. The Digital Twin continuously receives transportation data and maintains a virtual representation of the physical transportation environment.

4.6 Continuous Monitoring and Human Oversight

The framework continuously monitors data quality, Digital Twin synchronization, AI performance, cybersecurity conditions, and operational risks. Issues such as sensor anomalies, model drift, data manipulation, cyberattacks, and unreliable AI recommendations are identified through continuous monitoring. Human oversight is applied according to the risk level of decisions. Low-risk decisions may be automated, whereas medium- and high-risk decisions require human confirmation or authorization. AI recommendations, system conditions, human interventions, and final decisions are recorded to support accountability and auditability.

4.7 Performance Evaluation

Finally, the proposed STG-TDT framework is evaluated against conventional Transport Digital Twin approaches. The evaluation considers AI performance, Digital Twin synchronization, cybersecurity, privacy, explain ability,

governance compliance, operational reliability, and resilience. The results are used to determine whether the proposed framework provides improved trustworthiness and governance compared with conventional approaches.

Thus, the proposed methodology provides a continuous and lifecycle-oriented governance process that connects technical assurance with human and organizational oversight. This enables AI-enabled Transport Digital Twins to operate in a more reliable, secure, transparent, accountable, and trustworthy manner.

5. Results and Discussion

Since the proposed STG-TDT framework is primarily a framework-based study, the results are presented in terms of the proposed governance architecture, trustworthiness dimensions, risk-management mechanism, and expected comparative evaluation rather than fabricated experimental values.

5.1 Framework-Level Results

The proposed STG-TDT framework integrates six governance components: data and sensing governance, Digital Twin integrity, AI governance, cybersecurity and privacy, human and organizational governance, and continuous assurance. The integration of these components addresses the major limitations identified in the literature, where technical performance, cybersecurity, AI governance, and human oversight are often considered independently.

The framework establishes a continuous relationship between transportation data, the Digital Twin, AI models, human decision-makers, and governance controls. This enables trustworthiness to be assessed throughout the Digital Twin lifecycle rather than only during system development or deployment.

5.2 Trustworthiness Assessment

The framework evaluates the Transport Digital Twin across nine dimensions: reliability, safety, cybersecurity, transparency, explain ability, privacy, fairness, accountability, and resilience. This multidimensional assessment provides a broader evaluation than conventional approaches based only on AI prediction accuracy.

The proposed approach also enables organizations to identify the specific source of trust degradation. For example, reduced reliability may result from model drift, while reduced security may indicate abnormal network activity or data manipulation. Similarly, reduced Digital Twin integrity may indicate synchronization or sensor problems. This allows governance actions to be targeted rather than applying the same response to every system failure.

5.3 Risk-Based Governance Results

The proposed framework establishes a risk-based response mechanism in which system behavior determines the required level of governance intervention. Normal conditions are handled through continuous monitoring, while moderate risks trigger enhanced monitoring and investigation. High-risk conditions require human confirmation, and critical conditions can result in temporary restriction or suspension of AI-driven operations.

This mechanism is particularly important for transportation

applications because incorrect AI decisions may affect physical infrastructure and public safety. Instead of allowing AI to operate with unrestricted autonomy, the proposed approach provides controlled levels of automation based on the potential consequences of a decision.

5.4 Human Oversight and Accountability

A significant outcome of the proposed framework is the explicit integration of human oversight. Conventional AI-enabled Digital Twin systems may focus heavily on automation, whereas STG-TDT assigns human responsibility according to the risk associated with AI decisions. The framework also maintains records of AI recommendations, model versions, supporting data, confidence information, human interventions, and final decisions. This improves accountability and provides an audit trail for investigating incorrect or unexpected decisions. It also reduces the risk of excessive dependence on AI recommendations, particularly in safety-critical transportation scenarios.

5.5 Cybersecurity and Privacy

The proposed framework treats cybersecurity and privacy as continuous governance requirements rather than separate technical functions. Continuous monitoring can identify

abnormal sensor behavior, unauthorized access, data manipulation, and other threats that could compromise the Digital Twin. Privacy governance additionally controls the collection, processing, storage, and sharing of transportation data. This is important because transport Digital Twins may process vehicle locations, travel patterns, camera information, and other potentially sensitive information. Integrating privacy into the governance architecture strengthens responsible use of transportation data.

5.6 Comparative Discussion

The proposed framework provides several advantages compared with conventional AI-enabled Transport Digital Twins. Conventional approaches generally emphasize prediction, simulation, optimization, or Digital Twin synchronization. AI-governed approaches provide additional controls for model validation and risk management but may not fully address Digital Twin integrity and transportation-specific human oversight. In contrast, STG-TDT integrates technical and socio-technical governance within a single lifecycle. Its main advantage is therefore not only improved AI performance but improved control over how AI is developed, deployed, monitored, interpreted, and governed.

Table 1: Compares governance capabilities across Conventional TDT, AI-Governed TDT, and STG-TDT.

Evaluation Dimension	Conventional TDT	AI-Governed TDT	Proposed STG-TDT
Data Governance	Limited	Moderate	Comprehensive
Digital Twin Integrity	High focus	Moderate	Continuous
AI Governance	Limited	High	Continuous
Cybersecurity	Basic/Separate	Integrated	Continuous and risk-based
Privacy	Limited	Moderate	Integrated
Explainability	Limited	Moderate	Integrated
Human Oversight	Limited	Moderate	Risk-based
Accountability	Limited	Moderate	Explicit
Continuous Assurance	Limited	Moderate	Comprehensive
Socio-Technical Governance	Low	Moderate	High

5.7 Discussion

The findings demonstrate that trustworthy AI-enabled Transport Digital Twins require governance beyond conventional technical performance measures. High prediction accuracy alone cannot guarantee trustworthy operation because the overall system is influenced by data quality, cybersecurity, Digital Twin synchronization, human decisions, organizational responsibilities, and changing operating conditions. The proposed STG-TDT framework addresses this issue by treating trustworthiness as a continuous socio-technical property. This approach is consistent with established AI risk-management principles that emphasize governance, risk identification, measurement, and management throughout the AI lifecycle. It also extends these principles into the specific context of transportation Digital Twins. The framework provides particular value for safety-sensitive transportation applications because it links AI confidence and system risk with human intervention. As system conditions become uncertain or potentially hazardous, the degree of automation can be reduced and human decision-making can be increased.

5.8 Key Findings

The major findings of the proposed research are that integrated governance is more appropriate than isolated technical controls, continuous monitoring is essential because AI and Digital Twin conditions can change during operation, human oversight is necessary for high-impact transportation decisions, and trustworthiness should be evaluated across multiple dimensions rather than through AI accuracy alone. Overall, the results indicate that the proposed STG-TDT framework provides a structured foundation for developing secure, reliable, explainable, accountable, and resilient AI-enabled Transport Digital Twins. Future experimental implementation using a transportation simulation environment and real-world datasets is required to quantitatively validate these findings

6. Conclusion

The integration of Artificial Intelligence with Transport Digital Twins offers significant opportunities for intelligent traffic management, predictive analytics, infrastructure monitoring, and automated decision support. However, the

increasing intelligence and autonomy of these systems introduce challenges related to reliability, cybersecurity, privacy, explain ability, accountability, safety, and human oversight. This study proposed the Socio-Technical Governance Framework for Trustworthy AI-Enabled Transport Digital Twins (STG-TDT) to address these challenges through an integrated lifecycle-oriented approach.

The proposed framework combines data governance, Digital Twin integrity, AI governance, cybersecurity and privacy, human and organizational oversight, and continuous assurance. Unlike conventional approaches that primarily focus on technical performance, STG-TDT considers trustworthiness as a continuous socio-technical property influenced by technology, people, organizations, and operational environments. The proposed risk-based governance mechanism also enables human intervention when AI decisions involve significant operational or safety risks. Overall, the framework provides a structured foundation for developing reliable, secure, transparent, accountable, and resilient AI-enabled Transport Digital Twins. Future research will focus on implementing the framework using a real or simulated transportation environment, validating the proposed trustworthiness assessment mechanism, and conducting quantitative comparisons with existing Digital Twin governance approaches.

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