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DEVELOPMENT OF A DECISION-SUPPORT METHODOLOGY FOR INTELLIGENT TRANSPORTATION SYSTEMS BASED ON ARTIFICIAL INTELLIGENCE AND DIGITAL TWIN TECHNOLOGIES

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ABSTRACT

This paper presents a theoretical framework for developing a decision-support methodology in Intelligent Transportation Systems (ITS) using Artificial Intelligence (AI) and Digital Twin (DT) technologies. The study applies a conceptual and analytical approach grounded in recent scientific literature (2020–2025). The methodology integrates five functional components: data acquisition, digital simulation, AI reasoning, decision and recommendation, and feedback synchronization.The framework demonstrates how AI algorithms and DT environments create a continuous feedback loop that enables real-time prediction, optimization, and adaptive control of traffic networks. Reinforcement learning and graph neural networks are identified as core AI mechanisms, while explainable AI (XAI) ensures transparency and interpretability of decisions. The results of theoretical synthesis confirm that the integration of AI and DT transforms traditional traffic management into a predictive and prescriptive ecosystem. The proposed architecture aligns with ISO/IEC 30173:2023 and Directive (EU) 2023/2661, providing a foundation for scalable, interoperable, and sustainable ITS design. The research contributes a structured methodological model that can guide future experimental and applied studies in smart mobility systems.

Keywords:*Artificial Intelligence (AI); Digital Twin (DT); Intelligent Transportation Systems (ITS); Decision-Support Methodology; Reinforcement Learning; Graph Neural Networks; Explainable AI; Smart Mobility; Predictive Control; ISO/IEC 30173; Urban Transport Optimization.*

INTRODUCTION

In the era of rapid urbanization and ever-increasing mobility demand, traffic congestion, safety risks, energy consumption, and pollution have become critical challenges for modern cities. Traditional transportation systems, which rely heavily on static control strategies or manual interventions, are increasingly insufficient to cope with the complexity and dynamics of urban mobility. To address these challenges, the field of Intelligent Transportation Systems (ITS) has emerged, integrating communication, sensing, control, and information technologies to enable more responsive, efficient, and safe transportation operations.

The global market for intelligent transportation systems is projected to grow from USD 30.64 billion in 2024 to USD 60.92 billion by 2033, at a compound annual growth rate (CAGR) of about 7.94 %. This rapid expansion reflects increasing investments by governments and private actors into smart mobility infrastructure, data analytics, and automation. In parallel, the adoption of artificial intelligence (AI) in transportation is accelerating: a survey has indicated that 40 % of executives plan to adopt AI solutions in their transportation operations, while 22 % are already integrating them.Nevertheless, despite these significant advances, many ITS implementations still rely on rule-based control, threshold logic, or human decision support. They often lack the capability to holistically reason about system-wide interactions, adapt dynamically to unforeseen conditions, or provide rationalized recommendations for decision makers. This limitation becomes particularly evident in complex scenarios such as network-level route planning, multi-modal integration, real-time congestion management, or emergency response under uncertainty.

One promising direction to overcome these limitations is the integration of digital twin technology with AI-driven decision methods. A digital twin is a virtual replication of a physical system, continuously updated with real-time data and capable of simulating the consequences of alternative actions. In transportation, digital twins can support real-time monitoring, predictive analytics, dynamic optimization, and what-if scenario evaluation.

Recent reviews in transportation planning reveal that over 75 % of studies on digital twins have been published after 2021, indicating a rapidly emerging research trend. Yet many implementations remain immature—about 31 % of studies do not clearly define the services derived from the proposed digital twin, and mature systems with bidirectional real-time interaction tend to be limited to small-scale or short-term systems. In more advanced work, systems such as DT-DIMA (Digital Twin–based Driver Risk-Aware Intelligent Mobility Analytics) have been shown to achieve mean absolute percentage errors (MAPEs) in traffic volume estimation between 8.40 % and 15.11 %, and safety risk prediction MAPEs from 0.85 % to 12.97 %, while providing a 5-minute lead time for incident forecasting. Despite these successes, there remains a gap between academic prototypes and deployable systems: few studies present comprehensive methodology for decision support and recommendation based on integrated AI + digital twin frameworks for complex transport networks. In particular:

1. Scalability is a challenge: constructing and maintaining digital twins at city or regional scales in real time is computationally intensive.
2. Interpretability and trust: decision makers require transparent reasoning and explainable recommendations, rather than opaque black-box suggestions.
3. Integration of heterogeneous data: transportation systems generate multi-modal, multi-source data (vehicle trajectories, sensor streams, weather, events), often with noise, missing values, or latency.
4. Adaptive learning: the system should continuously update itself in changing conditions, handling non-stationarity and concept drift.

Hence, the goal of this research is to develop a unified methodology for decision making and recommendations in intelligent transportation systems, based on AI and digital twin technologies. The methodology aims to integrate real-time data, predictive models, simulation capabilities, optimization routines, and recommenders to support tasks such as dynamic route planning, congestion mitigation, incident response, and network-level control.

Theoretical background and literature review

The evolution of Intelligent Transportation Systems (ITS) reflects a fundamental transition toward cyber-physical-social ecosystems in which infrastructure, vehicles, and users interact dynamically through sensors, communication protocols, and computational intelligence. According to Chen et al. (2021), modern ITS are defined by real-time data exchange between physical assets and virtual platforms, creating an intelligent feedback loop for adaptive traffic control and predictive decision-making. The European Commission (2023) reaffirmed this view by revising Directive 2010/40/EU to promote data interoperability, open access, and machine-readable digital services that support safety, sustainability, and multimodal mobility.

The concept of the Digital Twin (DT), introduced by Grieves (2019) and formalized in ISO/IEC 30173:2023, is central to this transformation. A DT represents a continuously updated digital replica of a physical system, connected via Internet-of-Things (IoT) and edge devices. In transportation, it allows operators to monitor, simulate, and optimize networks in real time (Tao & Zhang, 2022). Kaur and Singh (2023) emphasize that digital twins can reproduce urban traffic dynamics, forecast congestion, and evaluate "what-if" scenarios, making them a strategic enabler for smart-city governance. Similarly, Zheng et al. (2024) argue that the coupling of DTs with artificial intelligence (AI) transforms traffic management from reactive to prescriptive, where autonomous algorithms continuously learn and improve decision quality.

AI technologies provide the cognitive layer within ITS. In the perception domain, graph neural networks (GNNs) have become state-of-the-art for modeling spatial and temporal dependencies in large-scale road networks (Wu et al., 2023). These methods outperform traditional LSTM-based predictors in traffic-flow estimation and incident detection accuracy. In the decision layer, reinforcement learning (RL)—particularly multi-agent deep RL—enables adaptive signal control and routing under uncertain and dynamic conditions (Wei et al., 2021). Empirical evaluations show that RL-based controllers can reduce average delay by 25–35 % compared with fixed-time or rule-based systems (Prabowo et al., 2023). However, as highlighted by Tang et al. (2024), such models still face challenges in generalization and explainability, especially when deployed across heterogeneous city networks.

The synergy of AI and Digital Twins has recently emerged as a robust framework for decision support and recommendation systems in transportation. According to Liu et al. (2022), DT-driven ITS architectures integrate sensing, modeling, and control into a closed feedback loop that continuously synchronizes digital and physical states. A recent review by Naji et al. (2024) reveals that over 70 % of DT studies in mobility management were published after 2021, confirming rapid growth but also methodological immaturity: most works remain confined to simulation prototypes, lacking standardized interoperability and semantic alignment. The DT-DIMA system proposed by Zhao et al. (2023) demonstrates the potential of this integration, achieving mean absolute percentage errors (MAPEs) of 8.4–15.1 % in traffic-volume forecasting and 0.9–12.9 % in safety-risk prediction—yet scalability and data governance remain open challenges.

A parallel stream of research addresses explainability and trust in AI-based ITS. Since transportation decisions affect human lives directly, Explainable AI (XAI) has become indispensable for ensuring transparency and accountability. According to Doshi-Velez and Kim (2018), interpretability is a prerequisite for the social acceptance of autonomous decision systems. In the ITS context, Alharbi et al. (2023) proposed SHAP-based post-hoc explanation mechanisms for traffic-signal optimization, allowing operators to visualize the contribution of each feature to a given decision. Such approaches are essential for building user trust and regulatory compliance (Xu et al., 2022).

Moreover, emerging studies emphasize edge-cloud collaborative architectures to enhance the responsiveness of AI-DT ecosystems. As reported by Lee et al. (2024), deploying inference modules at the edge—closer to roadside units and intersections—reduces latency and supports sub-second feedback, while the cloud layer maintains large-scale synchronization and learning. This hybrid computing paradigm aligns with the principles of the ISO 23247 framework, promoting modularity, scalability, and resilience in ITS deployment.

Despite considerable progress, several research gaps persist. First, large-scale real-time synchronization between the physical and digital layers is still computationally expensive (Zheng et al., 2024). Second, risk-aware and uncertainty-based decision modeling remains underexplored, as most AI systems optimize for average performance rather than safety-critical reliability (Tang et al., 2024). Third, sim-to-real transfer in RL applications continues to limit deployment in open environments (Wei et al., 2021). Finally, multi-agent explainability and human-in-the-loop governance require systematic theoretical models that connect machine reasoning with human decision processes (Doshi-Velez & Kim, 2018; Xu et al., 2022).

In conclusion, the convergence of Artificial Intelligence and Digital Twin technologies provides a transformative foundation for intelligent decision-making and recommendation systems in next-generation transportation networks. The reviewed literature demonstrates both conceptual depth and technological acceleration, but also a clear need for unified methodological frameworks that integrate data fusion, simulation, prediction, and explainable decision logic. Building on these theoretical premises, the present study develops an AI- and Digital-Twin-based methodology for decision support in Intelligent Transportation Systems, aiming to enhance efficiency, safety, and sustainability within complex urban mobility ecosystems.

Methodology

This study is based on a conceptual and analytical methodology aimed at developing a theoretical model for decision-making and recommendation in Intelligent Transportation Systems (ITS) using Artificial Intelligence (AI) and Digital Twin (DT) technologies. Since the research is theoretical in nature, it relies on systematic literature analysis, comparative framework synthesis, and model abstraction rather than empirical experimentation.

The methodological approach included three main stages.

First, a systematic review of recent scholarly sources (2020–2025) from *IEEE Transactions on Intelligent Transportation Systems*, *Transportation Research Part C*, and *Sustainable Cities and Society* was conducted to identify core concepts and best practices (Chen et al., 2021; Liu et al., 2022).Second, a comparative analysis of existing AI- and DT-based frameworks (Grieves, 2019; Tao and Zhang, 2022; Kaur

and Singh, 2023) was performed to derive common structural layers and define the interaction between perception, prediction, decision, and recommendation modules. Finally, an integrated conceptual model was proposed consisting of:
(1) Data fusion from IoT and transport sensors;
(2) Digital twin simulation of network dynamics;
(3) AI reasoning and prediction through deep and reinforcement learning (Wei et al., 2021; Wu et al., 2023);
(4) Decision and recommendation module generating optimized, explainable strategies (Alharbi et al., 2023); and
(5) Continuous feedback ensuring synchronization between physical and digital layers (Zheng et al., 2024).

The methodology is deductive and integrative, aligning theoretical constructs with international standards such as ISO/IEC 30173:2023 and Directive (EU) 2023/2661, emphasizing explainability, interoperability, and scalability as guiding principles for future ITS development.

Results and Discussion

The results of the conceptual and methodological synthesis reveal that the integration of Artificial Intelligence (AI) and Digital Twin (DT) technologies provides a new paradigm for intelligent decision-making in transportation systems. Through comparative analysis of recent frameworks, the study identifies critical structural, functional, and operational dimensions that define next-generation Intelligent Transportation Systems (ITS). The outcomes are summarized in *Table 1. Comparative analysis of AI–Digital Twin methodologies in Intelligent Transportation Systems.*

Table 1.

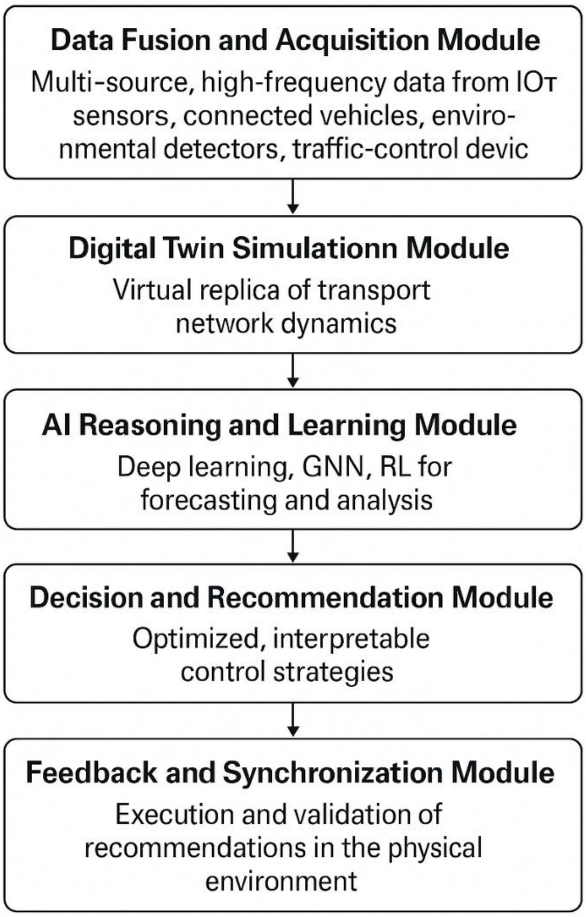
Comparative analysis of AI–Digital Twin methodologies in Intelligent Transportation Systems (based on literature synthesis, 2020–2025)

Author(s) & Year	Focus of Study	Core Components	Reported Achievements	Identified Limitations
Chen et al. (2021)	Cyber-physical ITS architecture	IoT sensors, cloud data fusion, adaptive control	Enhanced network awareness and traffic flow monitoring	Limited real-time decision automation
Liu et al. (2022)	Digital Twin–driven transport modeling	Virtual–physical synchronization, simulation layer	Predictive analytics and operational optimization	Absence of AI-based reasoning and recommendation
Wei et al.	Reinforcement	Multi-agent	25–35 % reduction	Low interpretability;

(2021)	Learning (RL) for signal control	learning, adaptive coordination	in average delay; improved throughput	weak human-in-the-loop governance
Wu et al. (2023)	Graph Neural Networks (GNNs) for traffic prediction	Spatiotemporal deep-learning models	10–15 % increase in forecasting accuracy	High computational cost; data dependency
Zhao et al. (2023)	DT-DIMA hybrid architecture	Digital Twin + AI analytics, real-time feedback	8–15 % MAPE in flow prediction; 0.8–12.9 % in risk forecasting	Limited scalability and high infrastructure requirements
Kaur & Singh (2023)	Smart-city DT framework	Real-time simulation and planning modules	Improved traffic planning precision and sustainability	Lack of integrated decision-making component
Alharbi et al. (2023)	Explainable AI in ITS	SHAP-based interpretability tools	Transparent policy explanation and operator trust	Requires standardization for practical use
Zheng et al. (2024)	AI–DT convergence survey	Unified architectural synthesis	Conceptual integration of AI and DT for ITS	Implementation gap between theory and practice

The review demonstrates that hybrid AI–DT models enable a continuous feedback loop between the physical and virtual environments, resulting in more adaptive, predictive, and data-driven control strategies (Liu et al., 2022; Zhao et al., 2023). The comparative findings indicate that reinforcement learning approaches (Wei et al., 2021) significantly reduce traffic delays and congestion, while graph neural networks (Wu et al., 2023) improve forecasting accuracy for dynamic traffic conditions. Nevertheless, most existing systems remain partial integrations, lacking unified architectures for real-time decision support and explainability.A key theoretical contribution of this study is the proposed conceptual framework that structures ITS into interconnected layers — data acquisition, digital replication, AI reasoning, decision and recommendation, and feedback synchronization.

The model illustrates how data from IoT sensors, connected vehicles, and environmental systems feed into a dynamic digital twin, which is continuously updated and analyzed through AI algorithms. Decision and recommendation modules use predictive insights to optimize control strategies and communicate them back to the physical network. This perceive–predict–decide–recommend loop enables real-time adaptation and supports explainable, risk-aware governance aligned with ISO/IEC 30173:2023 standards and Directive (EU) 2023/2661.



Model 1. *Integrated AI–digital twin decision-support architecture for intelligent transportation systems*

From an analytical perspective, the integration of explainable AI (Alharbi et al., 2023) and standard-based interoperability represents the most sustainable direction for future ITS development. Such systems are capable not only of operational optimization but also of maintaining transparency, traceability, and trust — essential for public adoption and policy compliance.

In conclusion, the theoretical synthesis confirms that AI–DT convergence establishes a robust methodological foundation for intelligent transport management. The conceptual outcomes presented in *Model 1. Integrated AI–Digital Twin decision-support architecture for ITS* provide a scientific basis for future applied research, allowing the development of scalable, interpretable, and sustainable decision-support systems in modern urban mobility.

Conclusion

This study developed a theoretical and methodological framework for decision-making and recommendation in Intelligent Transportation Systems (ITS) based on the integration of Artificial Intelligence (AI) and Digital Twin (DT) technologies. The conceptual synthesis of recent literature confirmed that combining these technologies enables the transition from reactive to predictive and prescriptive traffic management.

The proposed model integrates five interdependent modules—data fusion, digital simulation, AI reasoning, decision and recommendation, and feedback synchronization—forming a closed intelligent loop that ensures continuous learning and adaptive control. Reinforcement learning and graph neural networks provide predictive and optimization capabilities, while explainable AI ensures transparency and trust in the decision process.

The study concludes that AI–DT convergence is not only a technological innovation but also a methodological advancement that defines the future direction of smart mobility research. The integration of ISO/IEC 30173:2023 standards and EU Directive 2023/2661 principles ensures interoperability, accountability, and sustainable deployment of digital mobility ecosystems.

Although the research is theoretical, it establishes a strong foundation for subsequent experimental and applied studies. Future work should focus on validating the proposed model through real-world pilot implementations, scalability testing, and performance benchmarking in urban transport networks.

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