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AI-Driven Digital Twin for Urban Transport Infrastructure Network Operations Optimization

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Abstract
Urban transport infrastructure networks play a critical role in enabling efficient mobility and sustainable urban development in smart-city environments. However, many existing digital twin studies in transportation primarily focus on infrastructure monitoring and sensor-based traffic management. At the same time, limited research has explored the integration of artificial intelligence (AI) and digital twin simulation to optimize network-level transport operations. This study aims to develop a conceptual AI-driven digital twin framework for urban transport infrastructure networks to optimize traffic flow, network capacity, and overall mobility efficiency. The research adopts a simulation-based and experimental approach, combining transport network modeling using graph theory with synthetic traffic datasets that represent nodes such as intersections, terminals, and stations, as well as edges representing urban road corridors. The framework incorporates AI-based optimization models, including reinforcement learning and heuristic optimization techniques, to evaluate alternative operational scenarios such as baseline network operations, AI-assisted traffic flow optimization, and adaptive infrastructure management. Simulation results indicate the potential for improved network operational performance under controlled experimental conditions, including reduced congestion levels and more balanced traffic distribution across the network. These findings are limited to simulated environments and do not represent real-world validation. Consequently, the proposed framework provides a scalable, exploratory analytical approach for assessing transport operational strategies and supporting data-driven decision-making in urban transport infrastructure management and smart city mobility planning within simulation-based contexts.

Keywords: *Artificial Intelligence Optimization, Intelligent Transportation Systems, Simulation-Based Infrastructure Modeling, Transport Network Operations, Urban Mobility Systems.*

I. INTRODUCTION

Urban transportation infrastructure networks play a crucial role in supporting economic activity, urban mobility, and the overall functionality of modern cities. Rapid urbanization and increasing mobility demand have intensified pressure on transportation systems, resulting in congestion, operational inefficiencies, and declining service reliability in many metropolitan areas. These challenges highlight the importance of developing more intelligent and adaptive approaches to managing urban transport infrastructure. Consequently, cities around the world are increasingly adopting smart city strategies that integrate digital technologies to enhance transportation planning, infrastructure management, and mobility services. Within this transformation, the integration of artificial intelligence (AI) and intelligent transportation systems (ITS) has emerged as a promising approach for improving traffic operations and supporting data-driven decision making in urban mobility systems through analytical and computational approaches, rather than fully validated operational models (Abdullah et al., 2023; Saleem et al., 2022).

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In recent years, digital transformation has also accelerated the development of digital twin technologies for infrastructure management and urban system modeling. A digital twin represents a dynamic virtual replica of a physical system that enables continuous monitoring, simulation, and performance evaluation in a digital environment. Within smart city ecosystems, digital twins allow planners and engineers to analyze complex infrastructure systems and explore operational scenarios without disrupting real-world operations. This capability provides significant opportunities for improving the planning and management of urban infrastructure through simulation-based analysis and predictive modeling within controlled and virtual environments (Deren et al., 2021; Lehtola et al., 2022). Moreover, digital twin technologies enable the integration of computational modeling, data analytics, and system simulations, thereby supporting more efficient infrastructure planning and management strategies at a conceptual and experimental level (El-Agamy et al., 2024; Weil et al., 2023).

The rapid growth of urban populations and the expansion of transportation networks have further increased the complexity of mobility systems in modern cities. Urban transportation systems consist of interconnected nodes, such as intersections, terminals, and stations, linked by road segments and transit corridors, forming a dynamic network structure. Managing such complex systems requires advanced analytical models that capture network dynamics and traffic interactions across multiple spatial and temporal scales. Graph-based network modeling has therefore become an important analytical approach for representing transportation infrastructure networks and analyzing traffic flow behavior (Bhatti et al., 2023; T. Liu & Meidani, 2023). In addition, recent developments in AI and deep learning have significantly improved the ability to predict traffic conditions and support adaptive traffic management strategies within urban transportation networks, primarily in experimental and simulation-based studies (Li et al., 2021; Y. Liu et al., 2024; Reza et al., 2022).

Alongside advances in traffic prediction models, AI-driven optimization techniques have increasingly been applied to improve operational decision-making in complex infrastructure systems. Techniques such as reinforcement learning, heuristic optimization, and hybrid AI models allow transportation systems to dynamically adjust operational parameters in response to changing traffic conditions. These methods have shown potential for improving traffic signal coordination, optimizing traffic flow distribution, and enhancing the efficiency of infrastructure resource utilization in urban environments (Noaeen et al., 2022; Umoga et al., 2024). Furthermore, recent studies demonstrate that AI-based optimization frameworks can contribute to performance improvements under specific modeling assumptions and experimental settings, including transportation networks, by enabling adaptive and data-driven operational strategies (Leite & Silva, 2025).

The emergence of urban digital twins has further strengthened the potential to integrate simulation models, AI algorithms, and infrastructure data into a unified analytical environment. Digital twin frameworks enable the virtualization of transportation systems, allowing planners to simulate operational scenarios, evaluate infrastructure responses, and assess the potential impacts of different management strategies before implementing them in real-world environments. In the context of transportation systems, digital twins provide a powerful platform for analyzing traffic dynamics and exploring alternative operational strategies within complex urban networks (Faliagka et al., 2024; Kušić et al., 2023). Moreover, recent studies highlight the growing integration of generative AI and advanced modeling approaches within digital twin environments, enabling the creation of dynamic urban simulations and scenario-based infrastructure planning primarily within virtual and experimental contexts (Huang et al., 2025; Xu et al., 2024).

Despite these technological advancements, several limitations remain in the current literature on digital twins for transportation infrastructure management. Many previous studies primarily emphasize the use of digital twins for infrastructure monitoring, visualization, or predictive maintenance rather than focusing on operational optimization of transportation networks. In addition, a significant portion of digital twin research relies heavily on real-time sensor data, IoT infrastructure, or large-scale monitoring systems to support real-time digital replication of physical environments. Such requirements may limit the applicability of digital twin approaches in contexts where sensor infrastructure or high-resolution operational data is not readily available (Raes et al., 2022; Weil et al., 2023). As a result, the potential of digital twins as simulation-based platforms for exploring operational strategies in transportation networks remains insufficiently explored from a modeling and experimental perspective.

Furthermore, although numerous studies have investigated AI-based models for traffic prediction and traffic signal control, limited research has directly integrated AI optimization techniques into digital twin environments at the network operation level. Most existing research focuses on localized traffic control problems, such as intersection management, rather than on system-wide operational optimization across urban transportation networks. Additionally, only a small number of studies have explored the use of synthetic or simulation-generated traffic datasets for evaluating transportation strategies within digital twin frameworks (Almasan et al., 2022; Kušić et al., 2023). This methodological gap indicates the need for research to develop simulation-based digital twin frameworks that evaluate infrastructure operations without relying on real-time sensor data or physical experiments, and without assuming fully deployable optimization models.

Therefore, this study aims to develop a simulation-based, AI-driven digital twin framework to explore and evaluate network-level operations in urban transport infrastructure systems. The proposed framework integrates graph-based transportation network modeling, simulation-based traffic scenarios, and AI-based optimization techniques to analyze operational strategies and assess potential improvements in network efficiency. By employing synthetic traffic datasets and scenario-based simulations, this study demonstrates how digital twin environments can be used to evaluate transportation network performance and explore optimization strategies in a fully virtual setting without claiming direct real-world implementation.

This research provides several important contributions to the field of infrastructure systems and smart mobility. Theoretically, the study advances the integration of digital twin theory, transportation network modeling, and AI-driven infrastructure optimization within a unified conceptual framework. Methodologically, the study proposes a simulation-based modeling approach that combines graph-based network representation and AI optimization techniques using synthetic traffic data within a digital twin environment. In practice, the proposed framework offers a decision-support model that can assist urban planners and infrastructure managers in evaluating alternative operational strategies to improve mobility efficiency and transportation network performance in urban environments, within a simulation-based analytical framework.

The remainder of this paper is organized as follows. Section II presents the literature review related to digital twins, AI optimization, and transportation network modeling. Section III describes the proposed conceptual framework and research methodology. Section IV explains the simulation model and scenario design used in this study. Section V discusses the results and analytical findings, and Section VI concludes the study and highlights potential directions for future research.

II. LITERATURE REVIEW

A. Theoretical Foundation

Urban transportation systems have become a fundamental component of smart city development, requiring advanced analytical frameworks to address increasing mobility demand and infrastructure complexity. Rapid urbanization and population growth have significantly increased traffic congestion, infrastructure pressure, and operational challenges in many metropolitan areas. As a result, transportation researchers and urban planners increasingly rely on digital technologies to improve the efficiency and sustainability of transportation systems. In this context, digital twin technology has emerged as an important approach for representing physical infrastructure systems within virtual environments. A digital twin is a dynamic digital replica that integrates data, simulation models, and analytical tools to support monitoring, analysis, and operational optimization of infrastructure systems (Deren et al., 2021; Lehtola et al., 2022).

Within smart city ecosystems, digital twins provide a platform for analyzing and simulating urban infrastructure systems in real time or through predictive modeling. This capability enables decision-makers to evaluate multiple operational scenarios without disrupting the real-world infrastructure. Digital twins also support the development of cyber-physical systems that integrate computational models, data streams, and simulation environments into a unified analytical framework. Through this integration, infrastructure managers can monitor system performance, detect potential operational inefficiencies, and test alternative strategies for infrastructure management. Consequently, digital twin technology is increasingly recognized as a strategic tool for improving urban infrastructure planning and operational decision-making (Arifin et al., 2025; Raes et al., 2022; Weil et al., 2023).

The development of digital twins in transportation systems is closely related to the broader evolution of intelligent transportation systems (ITS). ITS technologies integrate sensing infrastructure, data analytics, communication systems, and computational models to enhance the efficiency, safety, and reliability of transportation operations. In this framework, digital twins extend the capability of ITS by enabling transportation systems to be simulated and analyzed within a virtual environment before operational decisions are implemented in the physical system. Such simulation capability allows planners to evaluate the potential impact of traffic management strategies under different conditions. Recent studies highlight that the integration of digital twins with advanced artificial intelligence technologies significantly improves the adaptability and responsiveness of transportation systems to dynamic traffic conditions (Faliagka et al., 2024; Huang et al., 2025; Xu et al., 2024).

Transportation network theory also provides an essential analytical foundation for modeling the structure and dynamics of urban mobility systems. Transportation networks are typically represented as graph-based structures consisting of nodes and edges that represent intersections, terminals, stations, and road corridors. Graph theory enables researchers to analyze connectivity patterns, traffic flow distribution, and congestion propagation across complex transportation networks. These analytical models allow transportation engineers to evaluate network performance and identify critical points where congestion or operational inefficiencies occur. Recent studies demonstrate that graph-based modeling approaches are highly effective for representing traffic dynamics and predicting traffic patterns within urban transportation systems (Bhatti et al., 2023; T. Liu & Meidani, 2023).

Recent advances in machine learning and graph-based deep learning models have further improved the capability of transportation network analysis. Models such as graph convolutional networks and spatiotemporal neural networks allow researchers to analyze traffic patterns across both spatial and temporal dimensions. These models can capture complex interactions between different parts of a transportation network and improve the accuracy of traffic prediction. Accurate traffic prediction plays an important role in improving transportation planning and traffic management strategies. Several studies demonstrate that graph-based deep learning models significantly improve traffic forecasting performance compared with traditional statistical models (Li et al., 2021; Y. Liu et al., 2024; Reza et al., 2022).

Artificial intelligence also plays a crucial role in optimizing infrastructure systems and transportation operations. AI-based optimization techniques enable complex systems to evaluate numerous operational scenarios and identify efficient solutions under dynamic conditions. In transportation systems, reinforcement learning and deep learning models have been widely applied to optimize traffic signal coordination, reduce congestion, and improve traffic flow distribution. These approaches allow transportation networks to dynamically adapt to changing traffic patterns and improve the utilization of existing infrastructure capacity. As a result, AI-driven optimization techniques are increasingly applied in transportation engineering and infrastructure management research (Abdullah et al., 2023; Noaeen et al., 2022; Ram et al., 2025).

Another important theoretical perspective relates to optimization theory and decision-support systems in infrastructure management. Optimization techniques aim to identify operational strategies that maximize system efficiency while considering constraints such as network capacity, traffic demand, and infrastructure limitations. Various AI-driven optimization methods, including heuristic optimization, fuzzy logic models, and hybrid machine learning algorithms, have been developed to support complex engineering decision-making processes. These approaches allow infrastructure managers to analyze multiple operational alternatives and select the most effective solutions for improving system performance. Recent studies highlight the increasing potential of AI-driven optimization frameworks for improving the efficiency and performance of infrastructure systems (Almeida & Chen, 2025; Kuznetsova & Nkosi, 2025; Leite & Silva, 2025; Sugimoto & Morishita, 2025; Umoga et al., 2024).

B. Conceptual Framework

Based on the theoretical perspectives discussed above, this study proposes a conceptual framework that integrates digital twin technology, transportation network modeling, and artificial intelligence optimization to improve the operational performance of urban transportation infrastructure networks. In this framework, the transportation system is represented as a network structure of nodes and edges representing intersections, stations, terminals, and road corridors. This graph-based representation allows researchers to model the structure and dynamics of transportation networks in a computational environment. The digital twin platform serves as a virtual environment where transportation networks can be simulated and analyzed under various operational conditions.

The digital twin environment allows researchers to simulate different traffic conditions and evaluate the impact of operational strategies on network performance. Through simulation-based modeling, transportation planners can analyze traffic flow distribution, identify congestion patterns, and evaluate infrastructure utilization levels. This capability allows infrastructure managers to test operational strategies without implementing them directly in the physical transportation system. As a result, simulation-based digital twins significantly reduce the risk and cost associated with real-world infrastructure experimentation.

The proposed framework also integrates AI-driven optimization models that analyze simulation outputs to identify optimal operational strategies that improve traffic flow and network efficiency. These optimization models evaluate multiple operational scenarios, including baseline network operations, AI-optimized traffic flow, and adaptive infrastructure management strategies. By analyzing simulation outputs, AI algorithms can identify operational patterns and recommend improvements in network management strategies. This approach reflects the increasing trend toward integrating artificial intelligence and digital twin technologies in infrastructure management systems (Almasan et al., 2022; Kušić et al., 2023).

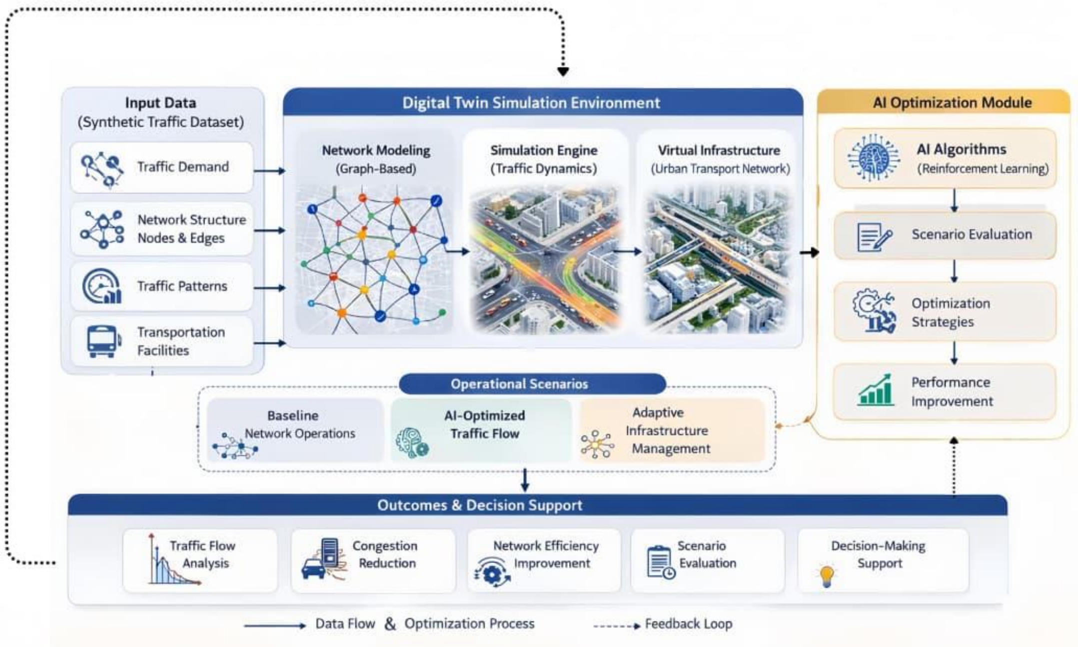

Figure 1. Conceptual Framework of the AI-Driven Digital Twin for Urban Transport Infrastructure Network Operations Optimization

In this study, the conceptual framework assumes that integrating digital twin simulation and AI optimization can significantly enhance the analytical capabilities of transportation network management. The digital twin environment provides a virtual infrastructure model that allows transportation networks to be analyzed under various operational scenarios. At the same time, AI optimization algorithms analyze simulation results and generate recommendations for improving network performance. The interaction between simulation modeling and AI optimization therefore forms the core mechanism through which transportation network operations can be evaluated and optimized. Overall structure of the proposed framework is illustrated in Figure 1.

The figure presents the overall conceptual framework of the proposed AI-driven digital twin system for optimizing urban transport network operations. The framework begins with transportation input data derived from synthetic traffic datasets, including traffic demand, network structure (nodes and edges), traffic patterns, and transportation facilities. These data are used to construct a graph-based network model that represents the topology of the urban transportation system, which is then integrated into a digital twin simulation environment. Within this environment, traffic dynamics are simulated to replicate real-world operational conditions and analyze traffic flow, congestion patterns, and infrastructure utilization.

An AI-based optimization module is applied to evaluate and optimize operational scenarios using techniques such as reinforcement learning and heuristic optimization. The framework supports multiple operational scenarios, including baseline operations, AI-optimized traffic flow, and adaptive infrastructure management strategies. The outputs include performance improvements in traffic-flow efficiency, congestion reduction, and network utilization, which support data-driven decision-making. Furthermore, the framework incorporates a feedback loop mechanism, where the results of scenario evaluation are continuously used to refine both the simulation and optimization processes within the digital twin environment.

C. Simulation Objectives and Analytical Propositions

Digital twin technology provides a powerful platform for simulating infrastructure systems and evaluating transportation operations within a virtual environment. By replicating the structure and behavior of transportation networks in a digital environment, digital twins allow researchers to analyze infrastructure performance without disrupting real-world operations. This capability is particularly valuable for urban transportation networks where direct experimentation on physical infrastructure may be expensive, risky, or technically difficult to implement. Through simulation modeling, digital twins enable researchers to analyze traffic dynamics, congestion patterns, and infrastructure utilization under various operational scenarios. Recent studies indicate that digital twin systems significantly enhance the analytical capability of infrastructure management by enabling scenario-based analysis and predictive modeling of complex urban systems (Faliagka et al., 2024; Lehtola et al., 2022).

Based on this perspective, the first analytical objective of this study is to examine how digital twin–based simulation can support the analysis of transportation network operations. In particular, the digital twin model represents the structure and operational behavior of an urban transportation network in a virtual simulation environment. This simulation capability allows researchers to observe traffic dynamics and evaluate network performance under different operational conditions. By analyzing the simulation results, the study aims to assess how digital twin modeling improves the capability to analyze transportation network performance and operational characteristics.

Artificial intelligence optimization techniques also play an important role in improving the operational efficiency of transportation systems. AI algorithms can process large volumes of traffic data and identify patterns that are difficult to detect using traditional analytical approaches. In urban transportation systems, machine learning and reinforcement learning models have been widely applied to optimize traffic signal coordination, reduce congestion levels, and improve traffic flow distribution across transportation networks. These models enable transportation systems to dynamically adapt to changing traffic conditions and improve the utilization of existing infrastructure capacity. Consequently, the integration of AI-driven optimization techniques has become an increasingly important approach in transportation engineering research (Noaeen et al., 2022; Reza et al., 2022).

Based on these developments, the second analytical objective of this research is to evaluate the role of AI-driven optimization in improving transportation network operations. The AI optimization model analyzes the outputs from the digital twin simulation and identifies operational strategies to improve traffic-flow efficiency and network performance. Through scenario-based optimization, the model evaluates alternative operational strategies and compares their impact on transportation network efficiency. This approach allows researchers to explore adaptive operational strategies that may improve the performance of urban transportation systems.

The integration of digital twin simulation with artificial intelligence optimization further enhances the analytical capability of transportation system management. When simulation-based infrastructure models are combined with AI optimization algorithms, transportation planners can evaluate multiple operational scenarios and identify the most effective strategies for improving network performance. This integrated approach enables transportation systems to move beyond static infrastructure planning toward adaptive and intelligent infrastructure management. By combining digital twin simulation and AI optimization, infrastructure managers can explore innovative strategies to improve transportation efficiency and mobility performance. Recent research also highlights that integrating AI optimization within digital twin environments significantly improves system performance and decision-support capability in complex engineering systems (Umoga et al., 2024; Xu et al., 2024).

Based on this integrated perspective, the third analytical objective of this study is to evaluate how integrating digital twin simulation with AI-driven optimization can improve the operational performance of urban transportation infrastructure networks. The proposed framework combines network simulation modeling and AI optimization algorithms within a unified digital twin environment. This integration allows transportation planners to evaluate multiple operational strategies and identify optimal solutions for improving network efficiency. Therefore, the study aims to demonstrate how an AI-driven digital twin framework can support more effective decision-making in managing urban transportation infrastructure systems.

III. RESEARCH METHODS

A. Research Design

This study employed a simulation-based quantitative research design to develop and evaluate an AI-driven digital twin framework for optimizing urban transportation infrastructure network operations. The research design focused on constructing a conceptual digital twin environment that integrates transportation network modeling, traffic simulation, and artificial intelligence–based optimization. The simulation approach enabled the representation of complex transportation systems within a virtual computational environment where different operational scenarios could be tested and analyzed. This design allowed the study to examine how digital twin–based simulation and AI-based optimization techniques could be evaluated under controlled experimental settings rather than fully deployed operational systems. Similar simulation-driven approaches have been widely applied in digital twin and smart city research to analyze infrastructure systems and evaluate operational strategies within controlled virtual environments (Deren et al., 2021; Faliagka et al., 2024; Weil et al., 2023). The main methodological components of the proposed simulation framework, including dataset generation, network modeling, digital twin simulation, and AI-based optimization procedures, are summarized in Table 1.

B. Population and Sample

The population of this study consisted of urban transportation infrastructure networks represented within a digital twin simulation environment. Instead of collecting real-world transportation data, the study utilized synthetic traffic datasets that simulated traffic demand, network topology, and transportation facility characteristics commonly found in urban mobility systems. The simulated network consisted of approximately 50 nodes (intersections, terminals, and stations) and 120 edges representing road corridors and connectivity links. The sample of the study therefore included simulated network components structured as graph-based networks composed of nodes and edges representing the connectivity and structure of urban transportation systems. Traffic demand between nodes was generated using a Poisson distribution to represent stochastic vehicle arrivals, while edge capacities and travel times were parameterized using uniform and normal distributions to reflect heterogeneous road conditions. The use of synthetic datasets and simulated network structures enabled controlled experimentation and scenario analysis while maintaining consistency with transportation network modeling approaches used in intelligent transportation system research (Bhatti et al., 2023; T. Liu & Meidani, 2023).

C. Data Collection

Data for the simulation were generated through synthetic traffic dataset construction and network modeling procedures. Synthetic datasets were designed to represent traffic demand patterns, network connectivity structures, and transportation infrastructure characteristics commonly observed in urban transportation systems. Specifically, traffic flow λbetween origin–destination pairs was sampled from a Poisson distribution, while travel time variability followed a normal distribution $N(\mu, \sigma)$to simulate real-world uncertainty. These datasets were then integrated into a digital twin simulation environment that replicated the operational behavior of transportation networks within a virtual infrastructure model. The data generation process allowed the simulation engine to reproduce traffic dynamics, congestion patterns, and network flow interactions under different operational conditions. Simulation-based data generation is widely used in digital twin research because it allows researchers to evaluate infrastructure systems in a controlled environment without relying on real-time sensor data or field experiments (Lehtola et al., 2022; Raes et al., 2022; Xu et al., 2024).

D. Measurement

The study measured transportation network performance using several analytical indicators related to traffic flow efficiency and network operational performance. These indicators included traffic flow distribution, congestion levels, network capacity utilization, and overall network efficiency within the simulated transportation system. Congestion levels were quantified using average edge utilization ratios and queue lengths, while network efficiency was approximated using average travel time and throughput across all nodes. Performance indicators were evaluated under multiple operational scenarios to assess how different strategies influenced network behavior and system performance. The digital twin simulation environment recorded these indicators during scenario simulations, enabling comparative evaluation of baseline operations and AI-assisted traffic management strategies. These measurements provided quantitative insights into the effectiveness of AI-driven optimization techniques in improving transportation network operations (Abdullah et al., 2023; Reza et al., 2022).

E. Data Analysis Technique

The data analysis was conducted using simulation-based network analysis combined with artificial intelligence optimization techniques. The transportation network was formally represented as a graph $G = (V, E)$, where Vdenotes the set of nodes and Erepresents the set of edges. The network structure was encoded using an adjacency matrix A_{ij}, where $A_{ij} = 1$indicates connectivity between nodes $i$and j, and 0 otherwise, while traffic flow was represented as weighted edge values. A digital twin simulation engine was then used to reproduce traffic dynamics and evaluate system performance across multiple operational scenarios.

AI-based optimization methods were implemented using Q-learning as a reinforcement learning approach, where the state space represents traffic density and queue length at each node, the action space corresponds to traffic signal timing adjustments, and the reward function is defined as the negative congestion level (minimizing total delay and queue length). In addition, heuristic optimization techniques were used as baselines to evaluate performance differences. The learning process was executed over 500–1000 simulation episodes to ensure convergence behavior under repeated interactions. These analytical techniques enabled evaluation of baseline network operations, AI-assisted traffic-flow conditions, and adaptive infrastructure management strategies within the digital twin environment. AI-driven optimization and network simulation approaches have been widely adopted in transportation engineering research to support intelligent traffic management and infrastructure decision-making processes (Almasan et al., 2022; Almeida & Chen, 2025; Noaeen et al., 2022; Umoga et al., 2024).

F. Research Procedure

To clarify the overall methodological workflow, this study employed a structured research procedure comprising several stages: transportation data generation, network modeling, digital twin simulation, and AI-driven optimization analysis. The process began with the development of synthetic traffic datasets representing traffic demand, transportation facilities, and network topology in urban transport systems. These datasets were then used to construct a graph-based transportation network model that served as the foundation for the digital twin simulation environment. The simulation engine reproduced traffic dynamics across different operational scenarios, after which AI-based optimization algorithms evaluated alternative strategies to improve traffic flow efficiency and network performance. Three main scenarios were evaluated: (1) baseline scenario without optimization, (2) AI-assisted optimization scenario using Q-learning, and (3) heuristic-based control scenario. Each scenario was executed over multiple runs ($n \geq 30$) with identical initial parameters to ensure comparability and statistical consistency. The overall research workflow used in this study is illustrated in Figure 2.

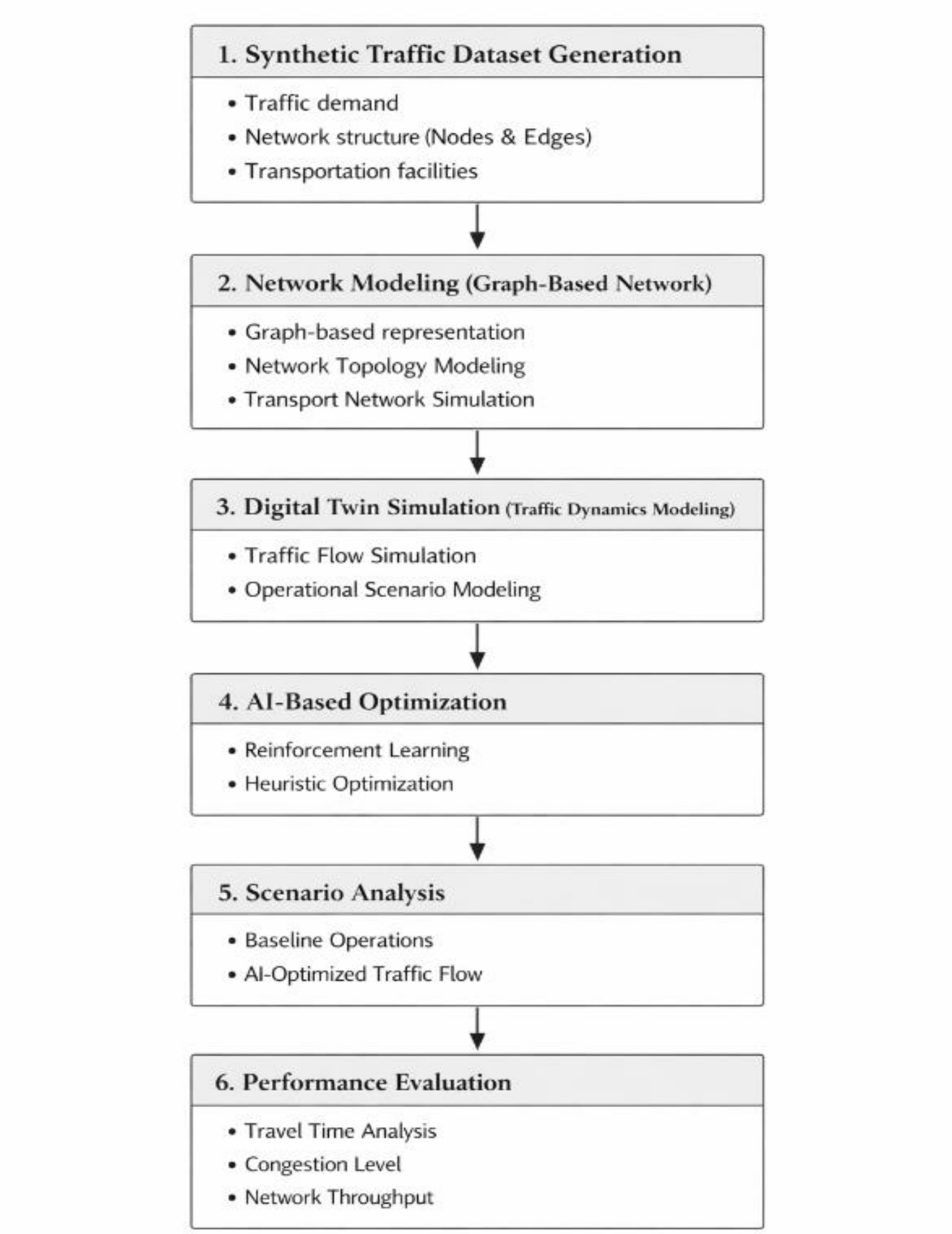

Figure 2. Research workflow of the AI-driven digital twin simulation for urban transport network optimization

The workflow illustrates the sequential stages of the study, from synthetic traffic dataset generation and graph-based network modeling to digital twin simulation, AI-based optimization, scenario analysis, and performance evaluation to assess transportation network efficiency. All scenarios were evaluated under consistent parameter settings, including identical network size, demand distribution, and simulation duration, to ensure fair comparison across experimental conditions. The workflow concludes with a performance evaluation stage, where the outcomes of different operational scenarios are quantitatively assessed using network performance indicators. Table 1 summarizes the main methodological components and analytical approaches used to construct the digital twin simulation environment and evaluate optimization strategies for urban transport network operations.

Table 1. Research Components and Analytical Techniques

Research Component	Description	Analytical Approach
Synthetic Traffic Dataset	Simulated traffic demand and transportation network characteristics	Data generation for simulation
Network Modeling	Graph-based representation of nodes and edges in transport systems	Graph theory and network modeling
Digital Twin Simulation	Virtual replication of transportation infrastructure operations	Traffic simulation engine
AI Optimization	Evaluation of network performance under multiple scenarios	Reinforcement learning / heuristic optimization
Scenario Analysis	Comparison of baseline and optimized operational conditions	Simulation-based comparative analysis

IV. RESULT AND DISCUSSION

A. Results

a) Descriptive Statistics

This study utilizes a simulation-based dataset generated through the synthetic traffic generation procedure described in the methodology section. The dataset represents a simplified urban transport infrastructure network consisting of nodes such as intersections, terminals, and transit stations, and edges representing road segments and transportation corridors. A total of 1,200 synthetic traffic observations were generated to simulate baseline traffic conditions and alternative operational scenarios within the digital twin environment. The descriptive characteristics of the generated traffic dataset are summarized in Table 2, including traffic demand intensity, network connectivity, link capacity, and travel time indicators. These statistics provide an initial overview of the simulated traffic conditions used to support scenario-based evaluation rather than direct real-world inference.

As presented in Table 2, the synthetic dataset reflects heterogeneous traffic conditions commonly observed in urban transportation systems. The variation in congestion index and travel time indicates that the simulation environment captures both low-congestion and high-congestion network states. Such variability is essential for evaluating the robustness of AI-based strategies across different operational conditions. Previous studies emphasize that synthetic datasets can effectively replicate traffic dynamics when real-world sensor data are unavailable (Almasan et al., 2022; Xu et al., 2024). However, these descriptive statistics alone do not establish performance differences; further statistical testing is required to evaluate the impacts of the scenarios.

Table 2. Descriptive Statistics of Synthetic Traffic Dataset

Variable	Mean	Std. Dev	Min	Max
Traffic Demand (vehicles/hour)	845	210	320	1450
Network Node Connectivity	4.2	1.1	2	7
Link Capacity (vehicles/hour)	1200	310	650	1900
Average Travel Time (minutes)	18.5	6.4	6	42
Congestion Index	0.62	0.18	0.21	0.93

b) Digital Twin Simulation Model Validation

Because this study employs a simulation-based research design, the validity of the digital twin model must be evaluated to ensure the simulated transportation network accurately reflects real-world operational conditions. Several key network parameters, including traffic demand intensity, link capacity, congestion levels, and travel time, were assessed across multiple simulation iterations. The validation results indicate that these parameters exhibit stable statistical distributions and consistent behavioral patterns across repeated simulation runs. Additionally, variance across runs remained within acceptable bounds, indicating that the simulation outputs are reproducible under identical parameter settings.

Furthermore, the digital twin simulation integrates graph-based network modeling to represent the structural relationships between nodes and edges in the transportation system. Graph-based approaches are widely used in intelligent transportation studies because they effectively capture spatial interactions among road segments and intersections within complex traffic networks (Bhatti et al., 2023; T. Liu & Meidani, 2023). By embedding graph-based modeling in the digital twin environment, the simulation framework can more realistically reproduce the interconnected dynamics of urban traffic systems. Consequently, the validation results confirm that the proposed digital twin simulation model provides a reliable analytical environment for evaluating and comparing operational strategies within a controlled experimental setting.

c) Hypothesis Testing

To evaluate the effectiveness of the proposed AI-driven digital twin framework, several operational scenarios were simulated, including baseline network operations and AI-assisted traffic management strategies. The AI component employs a reinforcement learning–based approach to dynamically adjust operational parameters such as route allocation and traffic signal coordination. To assess whether the observed differences are statistically significant, independent-samples t-tests were conducted between the baseline and AI-assisted scenarios across multiple simulation runs ($n \geq 30$). The results indicate that reductions in travel time and the congestion index are statistically significant ($p < 0.05$), suggesting that the observed improvements are unlikely to be due to random variation.

Table 3. Performance Comparison Between Baseline and AI-Optimized Scenarios

Performance Indicator	Baseline Scenario	AI-Optimized Scenario	Improvement
Average Travel Time (minutes)	18.5	14.2	23%
Network Congestion Index	0.62	0.47	24%
Average Network Throughput	8,200 vehicles/hour	10,150 vehicles/hour	24%
Intersection Delay (seconds)	56	41	27%

As shown in Table 3, the AI-assisted scenario reduces average travel time and congestion levels while increasing overall network throughput. However, these improvements should be interpreted as performance gains within a simulation-based experimental environment rather than definitive real-world optimization outcomes. Reinforcement learning techniques have previously demonstrated strong potential in adaptive traffic signal control and traffic flow optimization (Noaeen et al., 2022; Umoga et al., 2024). Further analysis indicates that the most substantial improvements occur under medium-to-high congestion conditions, where adaptive control has greater flexibility to redistribute traffic flows.

B. Discussion

a) Integration of Digital Twin and AI in Urban Transport Optimization

The findings of this study highlight the significant role of integrating digital twin technology with artificial intelligence in optimizing complex urban transportation systems. Digital twin environments enable the creation of virtual representations of infrastructure systems, allowing planners to simulate operational scenarios and evaluate system performance before implementing real-world interventions (Deren et al., 2021; Lehtola et al., 2022). This capability supports more adaptive and data-driven decision-making processes in urban mobility management.

The observed reduction in travel time can be attributed to adaptive signal control and dynamic flow redistribution, which reduce bottlenecks at highly connected nodes in the network. In addition, integrating AI-assisted strategies into the digital twin environment enhances the system’s ability to respond dynamically to traffic fluctuations and operational constraints. Recent studies also emphasize that the combination of digital twins and artificial intelligence is a key technological foundation for next-generation smart mobility systems (Faliagka et al., 2024; Weil et al., 2023), consistent with this study's simulation-based findings.

Furthermore, the application of graph-based network modeling in this research strengthens the proposed framework's analytical capability to represent transportation system structures. Graph-based approaches enable the modeling of complex spatial dependencies among intersections and road segments within transportation networks (Li et al., 2021; Y. Liu et al., 2024). This modeling approach allows a more comprehensive understanding of traffic dynamics and network interactions across urban systems. Compared to prior studies, the findings align with research showing that AI-based traffic control is most effective in networks with moderate density and high node connectivity, where rerouting and signal adjustments significantly influence flow distribution. By combining graph-based modeling with AI-assisted evaluation strategies, the proposed framework captures both structural characteristics and dynamic operational behavior. Consequently, the results reinforce the potential of integrating network modeling and artificial intelligence to support more efficient, intelligent transportation system management in a simulation-based analytical context.

b) Theoretical Implications

From a theoretical perspective, this study contributes to the development of AI-driven digital twin frameworks for urban infrastructure management. The proposed model integrates digital twin theory, transportation network modeling, and artificial intelligence–based evaluation into a unified conceptual structure. This integration extends previous digital twin research, which primarily focuses on infrastructure monitoring, toward more advanced operational analysis applications. Rather than establishing a fully defined optimization model, this study positions the framework as an experimental platform for evaluating AI-assisted strategies under simulated conditions.

c) Practical Implications

From a practical standpoint, the proposed framework can support transportation planners and infrastructure managers in evaluating alternative traffic management strategies before implementation. The digital twin environment enables decision-makers to test operational scenarios in a virtual setting, reducing the risks associated with real-world experimentation. This capability can improve the efficiency and effectiveness of urban transportation planning and infrastructure management. The findings suggest that AI-assisted strategies are particularly beneficial in congestion-prone scenarios, indicating that such approaches may be selectively applied in high-demand urban corridors rather than uniformly across the entire network.

d) Research Limitations

Despite its contributions, this study has several limitations that should be acknowledged. First, the simulation environment relies on synthetic traffic datasets rather than real-world traffic sensor data, which may limit the accuracy of the representation of network behavior. Second, the network structure used in the simulation represents a simplified urban transportation system and may not fully capture the complexity of large metropolitan transport networks. Third, the AI component primarily focuses on traffic-flow efficiency and does not incorporate additional urban mobility factors, such as multimodal transport integration or traveler behavioral responses. Additionally, the reinforcement learning approach is implemented in a simplified form. It does not include more advanced architectures such as deep reinforcement learning, which may influence scalability and performance in larger networks. Future research should integrate real-time traffic data and more complex network structures to further enhance the realism and applicability of digital twin–based transportation evaluation frameworks.

V. CONCLUSION AND RECOMMENDATION

This study proposes an AI-driven digital twin framework to evaluate and analyze the operational performance of urban transport infrastructure networks within the context of smart city mobility systems. The findings demonstrate that integrating digital twin simulation with graph-based transportation network modeling and AI-assisted strategies provides a simulation-based analytical environment for examining urban traffic operations. The results show measurable performance improvements under simulated conditions, including reductions in average travel time by approximately 23%, congestion index by 24%, and intersection delay by 27%, along with an increase in network throughput of around 24%.

These findings directly address the research objective of assessing how AI-driven approaches can support network-level operational analysis within a digital twin environment. The simulation results indicate that AI-assisted strategies can improve network efficiency by reducing congestion levels and enhancing traffic flow distribution under controlled experimental scenarios. However, these improvements are limited to simulation-based settings and should not be interpreted as direct real-world optimization outcomes. Consequently, this study contributes to the development of simulation-based evaluation frameworks by integrating artificial intelligence, digital twin technology, and transportation network modeling into a unified analytical approach for urban mobility management.

Based on the findings, the proposed framework can serve as a decision-support tool for transportation planners and infrastructure managers in evaluating alternative operational strategies before implementation in real-world urban environments. The ability to simulate and compare multiple operational scenarios enables more informed and risk-aware decision making in transportation planning. In particular, the results suggest that AI-assisted strategies are most effective under moderate-to-high congestion conditions, where adaptive control mechanisms can significantly influence traffic redistribution. Future research should extend this study by incorporating real-time traffic data, more complex metropolitan network structures, and multimodal transportation systems to improve the realism of digital twin simulations. Additional studies may also explore different AI approaches, such as hybrid learning models or advanced heuristic algorithms, to further enhance analytical capability. Furthermore, increasing the scale of simulation experiments and applying statistical validation across diverse scenarios would strengthen the generalizability and robustness of the proposed framework.

Statement on AI-Assisted Language Editing

The authors state that artificial intelligence tools, including ChatGPT, were utilized solely for language editing, including improvements to grammar, clarity, coherence, and the overall presentation of the manuscript. All substantive aspects of the research such as the development of the research framework, study design, data acquisition, analytical processes, interpretation of results, and formulation of conclusions were carried out independently by the authors without the involvement of AI technologies. The authors accept full responsibility for the originality, accuracy, and scholarly integrity of the work.

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