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Digital Twin and Metaverse Integration for Predictive Traffic Management in Malaysian Smart Cities: A Fuzzy Multi-Criteria Decision-Making Approach

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Abstract

The rapid urbanization of Malaysian cities like Kuala Lumpur has intensified the demand for intelligent, sustainable traffic management systems. This study proposes an integrated framework that combines digital twin technology, metaverse-based visualization, Internet of Things (IoT)-driven real-time data, and Fuzzy Multi-Criteria Decision-Making (MCDM) methods to address the inherent uncertainty and complexity of predictive traffic routing. Key evaluation criteria—cost, speed, fuel efficiency, CO_2 emissions, user comfort, and infrastructure adaptability—were identified through expert consultations. A Fuzzy Analytical Hierarchy Process (AHP) model was developed to rank alternative traffic management solutions. In the case study of Kuala Lumpur's Central Business District (CBD), simulations using a digital twin environment and live IoT feeds indicated that adaptive traffic signaling emerged as the most preferred strategy with a fuzzy weighted score of 0.362, followed by congestion pricing (0.289) and dedicated bus lanes (0.221). Sensitivity analysis revealed that a 10% change in the weight of CO_2 emissions shifted the optimal strategy towards congestion pricing, highlighting the model's adaptability to varying stakeholder priorities. Incorporating a metaverse-based Virtual Reality (VR) interface enabled decision-makers and citizens to experience the impact of different traffic policies visually, fostering greater transparency and engagement. Integrating fuzzy methodologies effectively addressed the uncertainties associated with expert judgments and real-time data variability. The proposed model offers a dynamic, robust, and user-centered decision-support tool for sustainable urban traffic management in Malaysia. The framework also presents significant potential for application in broader smart city planning initiatives across Southeast Asia.

Keywords: Digital twin, Metaverse, Internet of things, Fuzzy analytical hierarchy process, Traffic management, Predictive routing, Smart cities.

1 | Introduction

Rapid urbanization and increased vehicle usage have led to significant congestion in Malaysian cities, particularly in metropolitan areas like Kuala Lumpur, Johor Bahru, and Penang [1], [2]. The inefficiency of current traffic systems results in economic losses due to extended travel times and contributes to

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environmental pollution and reduced quality of life [3]. With Malaysia's vision of developing smart cities under the Malaysia Smart City Framework, there is an urgent need to adopt innovative and data-driven traffic management solutions [4]. Digital twin technology, which involves creating real-time virtual replicas of physical systems, has emerged as a powerful tool for simulating and analyzing urban traffic dynamics. By leveraging data from Internet of Things (IoT) devices such as sensors, traffic cameras, and GPS systems, Digital Twin can offer predictive insights and optimize traffic flow under various conditions [5]. However, the real potential of digital twins can be amplified by integrating them with the metaverse—a shared, immersive virtual environment—allowing for interactive simulations, stakeholder collaboration, and policy testing in a risk-free virtual space [6]. *Fig. 1* illustrates the interaction between the real-world traffic environment, the digital twin model, the metaverse visualization, and predictive analytics for decision-making. Real-time traffic data is captured and mirrored into a digital twin, where simulations are conducted within a metaverse platform. Predictive analytics then processes the simulations to support proactive traffic management decisions, enhancing smart city mobility strategies.

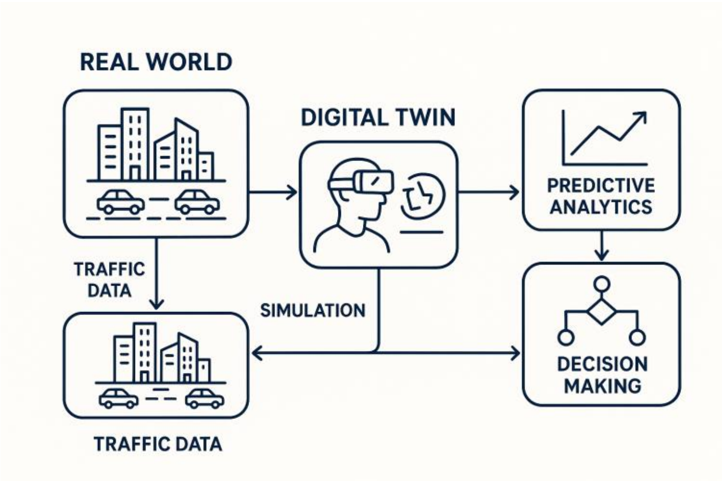

Fig. 1. Conceptual framework of digital twin and metaverse integration in traffic management.

Despite these technological advancements, traffic management decisions often involve conflicting criteria—such as minimizing travel time, reducing emissions, lowering costs, and ensuring commuter satisfaction—under uncertain and imprecise conditions. Traditional decision-making methods may fall short of capturing the vagueness and complexity of these criteria [6]. Therefore, there is a growing interest in applying Fuzzy Multi-Criteria Decision-Making (MCDM) approaches, which can effectively model human-like reasoning and deal with imprecise data [7]. This study aims to develop a comprehensive decision-making framework integrating digital twins and the metaverse for predictive traffic management in Malaysian smart cities. By employing a Fuzzy MCDM approach, the model will evaluate multiple conflicting objectives under uncertainty and support city planners in making informed, data-driven, and sustainable traffic policies. *Fig. 2* depicts the continuous lifecycle of a digital twin used in urban mobility management. It begins with data acquisition from real-world sensors, followed by modeling and simulation of traffic environments. Predictive analytics are applied to forecast traffic patterns, leading to real-time optimization and feedback loops that continuously refine and update the system.

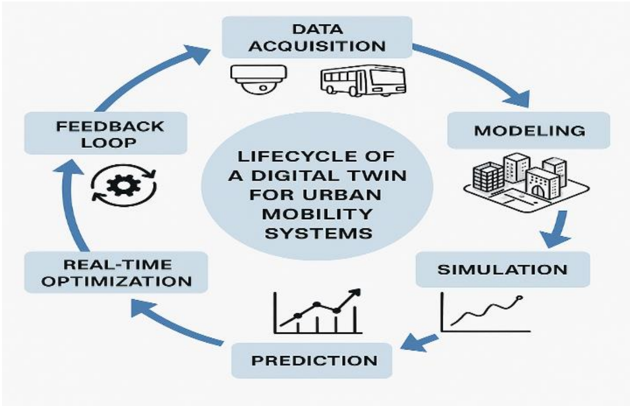

Fig. 2. Lifecycle of a digital twin for urban mobility systems.

Urban transportation in Malaysia is increasingly strained due to rapid urbanization, rising vehicle ownership, and inadequate adaptation of existing traffic systems to real-time demands [8], [9]. Cities like Kuala Lumpur, Johor Bahru, and Penang experience frequent congestion, leading to long travel times, increased fuel consumption, and rising greenhouse gas emissions [10]. As Malaysia embraces its smart city framework (2021–2025), it is critical to explore advanced technologies that can enhance traffic prediction and management capabilities [10]. This study is significant as it leverages the power of digital twins—real-time virtual replicas of physical traffic systems—and the metaverse, an immersive 3D environment, to simulate and manage urban traffic more efficiently.

Recent data from the Department of Statistics Malaysia (2023) indicate that over 75% of the population resides in urban regions, exerting pressure on transport infrastructure. Despite the global trend towards intelligent transportation, Malaysia's adoption of digital twin-based predictive systems remains limited. Moreover, while Fuzzy MCDM techniques are well-documented in other domains, such as supply chain and energy, their integration with immersive simulations for traffic management is still underexplored in Malaysia. Considering that traffic decision-making involves uncertainty and conflicting objectives—such as cost, travel time, emissions, and commuter satisfaction—this gap represents a substantial opportunity for innovation.

The motivation for this research arises from three primary concerns. First, the complexity of urban data collected from IoT-enabled infrastructure—such as sensors, GPS, and surveillance systems—necessitates robust computational models for meaningful interpretation. Second, decision-making in transportation involves multiple stakeholders with often conflicting objectives, making it essential to adopt fuzzy logic to handle imprecise and subjective judgments. Third, with the emergence of metaverse technologies, Malaysia is uniquely positioned to revolutionize transportation planning by offering interactive simulations that allow policymakers, commuters, and engineers to explore various traffic scenarios virtually before implementation. Despite several advancements, the literature reveals important research gaps. Most existing studies on intelligent transportation focus on real-time analytics or IoT but do not consider the combined use of digital twins and the metaverse for scenario analysis in Malaysian cities. Fuzzy MCDM models—especially those using newer techniques like Fermatean fuzzy sets—have not been sufficiently applied to traffic-related decisions under uncertainty. There is also a lack of frameworks that allow for immersive, stakeholder-engaged simulations where urban planners and citizens can interactively assess the impact of traffic policies within a virtual setting. Addressing these gaps can significantly enhance transport policy design and implementation effectiveness.

This research's core contribution lies in developing an integrated, intelligent traffic management framework that combines digital twin simulation, metaverse-based interaction, and Fuzzy MCDM modeling [11]. This study introduces a novel decision-making system enabling policymakers to evaluate real-time traffic solutions using predictive models and immersive simulations. A Fermatean Fuzzy MCDM approach will be applied to assess and rank alternative traffic management strategies based on key criteria such as efficiency, sustainability, cost, and commuter comfort [12]. Furthermore, the study will conduct a case analysis using real-world data from a major Malaysian city—such as Kuala Lumpur or Cyberjaya—to validate the proposed model. Ultimately, this research offers a powerful decision-support tool that enhances traffic planning in smart cities and contributes to Malaysia's broader goals of sustainable urban development. The remainder of this study is organized as follows: Section 2 presents a comprehensive review of the relevant literature. Section 3 outlines the research problem in detail. Section 4 describes the proposed methodology and the data collection process. Section 5 illustrates the case study application of the proposed framework. Finally, Section 6 provides the conclusions and key findings of the study.

2 | Literature Review

Digital twin technology has emerged as a transformative tool in urban traffic management, enabling real-time simulation and optimization of traffic systems. Dasgupta et al. [13] developed a digital twin-based adaptive traffic signal control framework, demonstrating significant reductions in control delays at signalized intersections by leveraging real-time vehicle trajectory data and predictive algorithms. Integrating digital twins with Intelligent Traffic Light Systems (ITLS) in Malaysia has shown promising results. Waqar et al. [14] assessed the effectiveness of an advanced ITLS incorporating IoT and digital twin technologies in Malaysian cities, reporting substantial improvements in travel time, congestion indices, fuel consumption, and CO_2 emissions. Singapore's "Virtual Singapore" project exemplifies the application of digital twins at a national scale. This 3D digital replica of the city-state utilizes real-time data for traffic simulation, energy planning, and disaster mitigation, serving as a model for other nations aiming to implement a digital twin in urban planning. Integrating digital twin machine learning techniques has further enhanced traffic optimization capabilities. Homaei et al. [15] proposed a hybrid ML-digital twin approach for urban traffic optimization, highlighting the potential of combining predictive analytics with real-time simulations to improve traffic flow and reduce congestion. These studies collectively underscore the efficacy of digital twins in enhancing traffic management through real-time data integration, predictive modeling, and adaptive control mechanisms. However, the application of digital twins in Malaysian urban contexts remains limited, presenting opportunities for further research and implementation.

The convergence of IoT and Artificial Intelligence (AI) has revolutionized predictive traffic systems, enabling real-time data collection and intelligent decision-making. Malathi et al. [16] reviewed AI applications in traffic management, highlighting AI-powered traffic signal control systems, automatic distance and velocity recognition, smart parking systems, and intelligent traffic management systems that utilize real-time data to monitor and optimize traffic conditions. In Malaysia, the integration of AI and IoT in traffic systems is gaining momentum. Nampally [17] proposed an AI-based smart traffic management system that analyzes live Closed-Circuit Television (CCTV) footage to count vehicles and assess traffic density, allowing for adaptive signal control. Their simulation results demonstrated a 34% improvement in traffic flow efficiency compared to traditional static traffic light systems. Alibaba's City Brain project, initially implemented in Hangzhou, China, has been extended to Kuala Lumpur, Malaysia. This AI-controlled city system monitors traffic, detects accidents, and tracks illegal parking by processing vast amounts of data from various city systems and infrastructure, significantly improving traffic flow and response times. These advancements illustrate the transformative impact of AI and IoT on predictive traffic systems, offering scalable and cost-effective solutions for modern urban challenges. Nevertheless, integrating these technologies into existing infrastructure requires careful planning and consideration of data privacy and security concerns.

The metaverse, characterized by immersive virtual environments, presents novel opportunities for urban planning and stakeholder engagement [18]. In Nusantara Capital City, Indonesia, integrating metaverse and digital twin technologies has been proposed to enhance urban planning, foster development, and promote sustainability [18]. The metaverse enables virtual simulations of urban environments, facilitating collaborative planning and decision-making processes [11]. In India and Ghana, urban planners have utilized virtual platforms like Upland Virtual World to enhance land planning and optimize land use-based climate mitigation strategies. These applications demonstrate the potential of the metaverse to support smart sustainable urban development by enabling data transparency, accessibility, and collaboration between public and private sectors.

Singapore's "Virtual Singapore" project is a pioneering example of integrating digital twins with immersive virtual environments for urban planning. This initiative allows real-time data visualization and simulation, aiding traffic management, energy planning, and disaster mitigation efforts [19]. Despite these advancements, the application of metaverse technologies in Malaysian urban planning remains nascent. Challenges such as digital literacy, infrastructural limitations, and data governance must be addressed to fully harness the potential of the metaverse in enhancing urban planning and traffic management. Fuzzy MCDM techniques have been widely employed to address complex decision-making problems involving uncertainty and imprecise information. Ali et al. [8], [9], [12] developed a fuzzy expert system to prioritize traffic calming projects, utilizing fuzzy rules and membership functions to handle the vagueness inherent in traffic-related data. In the Malaysian context, Fuzzy Analytical Hierarchy Process (AHP) and the Taguchi method have been applied to evaluate users' willingness to pay for public transportation. This approach effectively captured users' subjective preferences and provided insights into enhancing public transportation systems [8], [9], [12]. Trivedi et al. [20] applied Fuzzy AHP to assess road safety management, identifying accident-prone areas. This study contributes to the growing literature on smart urban transportation by combining digital twin technologies, Metaverse frameworks, and Fuzzy MCDM techniques in a unified model tailored to the Malaysian urban landscape.

While previous studies have individually explored digital twins or AI-enabled traffic systems, this work is among the first to examine the synergistic integration of digital twins and metaverse platforms to simulate, analyze, and predict traffic behavior in real time. Additionally, it adopts advanced fuzzy decision-making models, such as Fermatean Fuzzy AHP and Fuzzy TOPSIS, which allow for a more nuanced handling of uncertainties and expert judgments in evaluating traffic management criteria. Moreover, this research enriches the theoretical framework by introducing a multi-dimensional simulation architecture that mirrors actual traffic behavior through a virtual environment, enabling urban planners and traffic authorities to experiment with real-time solutions before physical implementation. It also bridges a conceptual gap by applying metaverse-enabled collaboration and data visualization tools to stakeholder communication in urban mobility planning—a facet previously underexplored in traffic management research. The case focuses on Malaysian cities and provides localized insights and practical guidelines for adapting global smart city innovations to the Southeast Asian urban context. Despite the advancements in digital twin technology and AI-based traffic control systems, there remains a notable gap in their combined application with metaverse platforms for traffic optimization, particularly in the context of developing countries like Malaysia.

Most existing research has either focused on smart traffic lights or isolated AI models without integrating immersive, collaborative environments such as the metaverse for predictive planning. Moreover, the application of Fuzzy MCDM methods, especially those using Fermatean fuzzy sets, has not been widely explored in conjunction with digital twin-based traffic modeling. Another significant gap lies in the absence of real-time, participatory, and visually immersive simulation tools that can be used by urban planners, policymakers, and citizens alike to design and evaluate traffic management strategies collaboratively. While digital twins are gaining popularity, their linkage with metaverse technologies to enhance interactive decision-making and stakeholder engagement remains underutilized. There is also a lack of localized studies that reflect the unique urban structure, congestion patterns, and technological readiness of Malaysian cities, creating a critical need for context-specific modeling approaches and solutions.

3 | Research Problem

In recent years, smart city technologies have opened up new possibilities for managing urban transportation systems more efficiently. However, despite technological advancements, several critical challenges hinder the realization of intelligent, adaptive, and sustainable traffic management in countries like Malaysia. This study addresses three significant issues: uncertainty in real-time traffic prediction, integration complexity between digital twin and metaverse platforms, and multi-criteria conflict in stakeholder preferences.

3.1 | Uncertainty in Real-Time Traffic Predictions

One of the most pressing issues in traffic management is the uncertainty in real-time predicting traffic conditions. Numerous dynamic factors influence traffic flow, including weather, accidents, road construction, and fluctuating demand patterns, all of which introduce variability and randomness into traffic models. Traditional traffic prediction systems often lack the flexibility to account for these uncertainties robustly. While machine learning and IoT-enabled devices have improved the availability and accuracy of traffic data, their effectiveness is still limited by data quality, sensor coverage, and contextual variability in Malaysian cities, especially in semi-urban and rural regions. Without accounting for uncertainty in data interpretation, prediction errors can result in flawed or suboptimal decision-making.

3.2 | Complexity in Integrating Digital Twin Data and Metaverse Simulations for Policy Evaluation

Another significant challenge lies in digital twins' technical and methodological integration with metaverse-based simulation platforms. Digital twin creates real-time replicas of urban infrastructure and traffic systems using sensor data, while the metaverse offers immersive and interactive 3D environments for visualizing and simulating urban policies. However, fusing these two technologies in a seamless and scalable manner is not straightforward. It requires synchronizing high-volume real-time data, consistent modeling standards, and advanced computational frameworks capable of interoperability between physical and virtual systems. In Malaysia, the infrastructure and policy frameworks for such integration remain underdeveloped, creating bottlenecks for deploying full-scale smart transportation systems that utilize digital twins and metaverse environments for strategic planning, testing, and decision-making.

3.3 | Multi-Criteria Conflict in Stakeholder Preferences

Urban transportation decisions are inherently multi-objective, involving conflicting interests among various stakeholders [21], [22]. For instance, commuters often prioritize shorter travel time, whereas environmental agencies emphasize emissions reduction, and city planners may focus on cost efficiency or long-term infrastructure sustainability. These preferences frequently conflict, creating a MCDM problem that must balance trade-offs systematically and justifiably. This complexity is further exacerbated in Malaysian cities where diverse socio-economic conditions and localized mobility needs necessitate context-specific prioritization of objectives. Current planning tools often fail to capture this diversity in stakeholder perspectives, leading to decisions that may be technically sound but socially or environmentally suboptimal. Thus, advanced decision support tools like Fuzzy MCDM models can incorporate imprecise, uncertain, and conflicting preferences into a unified and rational decision framework.

4 | Methodology

To address the multifaceted challenges in predictive traffic management within Malaysian smart cities, this study employs an integrated methodology that combines Fuzzy MCDM, digital twin simulation, metaverse visualization, and IoT-driven real-time data integration. The framework analyzes, evaluates, and visualizes optimal traffic management solutions under uncertainty and conflicting stakeholder priorities. The key methodological components are outlined below.

4.1 | Criteria Selection

The first step in the methodology involves identifying and selecting evaluation criteria that reflect the priorities of various stakeholders, such as commuters, city planners, environmental agencies, and transportation authorities. Through a literature review and expert consultations, the following six criteria were selected:

I. Cost: Economic feasibility of implementing and maintaining the traffic solution

II. Speed: Improvement in average travel time across selected routes or zones

III. Fuel efficiency: Reducing vehicle fuel consumption contributes to cost savings and environmental sustainability

IV. CO_2 emissions: Environmental impact measured through carbon output, aligning with climate goals

V. User comfort: Perception of ease, safety, and convenience for end users during travel

VI. Infrastructure adaptability: The flexibility of the traffic system to integrate with existing or future smart city infrastructure

Each criterion captures a different dimension of traffic management performance and is subject to imprecise judgment, necessitating fuzzy decision-making tools.

4.2 | Use of Fuzzy Analytical Hierarchy Process for Criteria Weighting and Solution Ranking

The Fuzzy AHP is employed to determine the relative importance of each criterion and rank alternative traffic management solutions. Fuzzy AHP enhances traditional AHP by incorporating fuzzy logic to better manage vagueness and subjectivity in human judgment, especially in pairwise comparisons among criteria.

The process involves the following steps:

I. Hierarchy structuring: The decision problem is structured into three levels: The goal (Optimal traffic solution), the criteria (e.g., cost, speed, etc.), and the alternatives (e.g., smart traffic signals, congestion pricing, adaptive lane usage).

II. Pairwise comparisons using fuzzy numbers: Experts provide linguistic preferences (e.g., equally important, moderately more critical), which are converted into triangular or trapezoidal fuzzy numbers.

III. Calculation of fuzzy weights: A fuzzy comparison matrix is formed, and the synthetic extent analysis method is used to derive normalized weights for each criterion.

IV. Solution ranking: The fuzzy weights are then used to evaluate and rank traffic solutions based on their performance scores under each criterion.

This step ensures that decision-making accounts for human uncertainty, conflicting preferences, and expert knowledge.

4.3 | Simulation via Digital Twin + Metaverse Interface

Once solutions are ranked, the next phase involves simulating their real-world impacts using a digital twin environment integrated with a metaverse-based Virtual Reality (VR) interface. The digital twin replicates a segment of an urban traffic system (e.g., Kuala Lumpur's city center) using real-time and historical data. It dynamically reflects current traffic conditions, vehicle movement, congestion hotspots, and control measures.

I. The digital twin environment is developed using simulation platforms such as Unity or AnyLogic and integrated with transportation models (e.g., microscopic traffic flow models).

II. The metaverse interface enables stakeholders to engage with the simulation through immersive 3D environments accessible via VR headsets or desktop applications.

III. This platform allows for real-time "what-if" scenario testing, such as evaluating the effect of lane changes, signal timing, or toll policies.

This immersive interface enhances collaborative decision-making and policy evaluation by enabling stakeholders to visualize the consequences of their choices in a virtual yet realistic setting.

4.4 | Real-Time Data Integration via Internet of Things

To make the simulation environment responsive and dynamic, the system is powered by real-time data collected through IoT devices, including:

I. GPS trackers are embedded in public and private vehicles to track movement and speed.

II. CCTV and traffic camera feeds visually confirm traffic flow and congestion.

III. Smart traffic lights and roadside sensors that record vehicle counts, queue lengths, and pedestrian movement.

IV. Weather and event data that can impact traffic patterns (e.g., rainfall, public gatherings).

This data is collected, filtered, and integrated into the digital twin model via data pipelines and edge computing systems to ensure low-latency updates. It also feeds into the machine learning models that help predict congestion patterns and update the digital twin accordingly.

5 | Case Study: Kuala Lumpur

In this section, we apply the proposed methodology to a real-world case study in Kuala Lumpur, Malaysia's capital city. Kuala Lumpur is known for its heavy traffic congestion, making it an ideal location to study the application of digital twins, the metaverse, and fuzzy MCDM for traffic management. The case study demonstrates the use of the Fuzzy AHP model, the digital twin simulation platform, and the integration of real-time IoT data to predict and optimize traffic routing. Additionally, we explore how traffic management decisions change when fuzzy parameters vary, reflecting the inherent uncertainties in urban traffic systems.

5.1 | Case Study Setup: Kuala Lumpur Traffic Model

Kuala Lumpur faces complex traffic congestion issues due to rapid urbanization, high vehicle density, and insufficient public transport alternatives in certain areas. For the case study, we focus on a representative urban area of Kuala Lumpur, specifically the Central Business District (CBD), which experiences the highest traffic volume, especially during peak hours.

Data collection: The required real-time data is collected using IoT-enabled traffic sensors, vehicle GPS trackers, CCTV cameras, and smart traffic lights at key intersections. Historical traffic data also captures daily patterns, average speeds, congestion levels, and accident hotspots.

Model Inputs:

I. Criteria selection: The criteria for evaluating traffic management solutions include cost, speed, fuel efficiency, CO_2 emissions, user comfort, and infrastructure adaptability.

II. Alternatives: Several traffic management alternatives are considered, including:

Adaptive traffic signal systems: Using real-time traffic data to adjust signal timings dynamically.

Congestion pricing: Charging vehicles for entering high-congestion zones during peak hours.

Dedicated bus lanes: Creating exclusive lanes for public transportation to reduce traffic congestion.

Digital twin platform: A detailed digital twin of the Kuala Lumpur CBD area is created using Unity or AnyLogic, simulating key roads, intersections, and the traffic flow. This simulation mirrors the actual traffic system in real time, updating traffic data continuously from IoT sensors.

5.2 | Application of the Fuzzy Analytical Hierarchy Process Model

The Fuzzy AHP methodology evaluates and ranks the traffic management alternatives. Experts in urban planning, traffic engineering, and environmental sustainability provide pairwise comparisons to assign fuzzy weights to the criteria. These fuzzy weights are expressed using triangular fuzzy numbers (e.g., 1/3, 1, 3 for slightly more important, equally important, and much more important, respectively). The pairwise comparison matrix (Fuzzy weights) of the proposed problem is represented in *Table 1*.

Table 1. Pairwise comparison matrix (Fuzzy weights).

Criteria	Cost	Speed	Fuel Efficiency	CO_2 Emissions	User Comfort	Infrastructure Adaptability
Cost	(1, 1, 1)	(1, 3, 5)	(1, 3, 5)	(1, 3, 5)	(1, 3, 5)	(1, 3, 5)
Speed	(1/5, 1/3, 1)	(1, 1, 3)	(1, 3, 5)	(1, 3, 5)	(1, 3, 5)	(1, 3, 5)
Fuel efficiency	(1/5, 1/3, 1)	(1/5, 1/3, 1)	(1, 1, 3)	(1, 3, 5)	(1, 3, 5)	(1, 3, 5)
CO_2 emissions	(1/5, 1/3, 1)	(1/5, 1/3, 1)	(1/3, 1/5, 1)	(1, 1, 3)	(1, 3, 5)	(1, 3, 5)
User comfort	(1/5, 1/3, 1)	(1/5, 1/3, 1)	(1/3, 1/5, 1)	(1/3, 1/5, 1)	(1, 1, 3)	(1, 3, 5)
Infrastructure adaptability	(1/5, 1/3, 1)	(1/5, 1/3, 1)	(1/3, 1/5, 1)	(1/3, 1/5, 1)	(1/3, 1/5, 1)	(1, 1, 3)

The fuzzy comparison matrix is then processed using the synthetic extent analysis method to derive the fuzzy weights for each criterion. After normalization, the final rankings of the alternatives are obtained.

5.3 | Simulation and Impact Visualization with Digital Twin + metaverse

The digital twin of the Kuala Lumpur CBD area is simulated using the aforementioned traffic management alternatives. The real-time traffic data from IoT devices is continuously fed into the digital twin, updating the model to reflect the current traffic situation. The metaverse interface allows stakeholders to immerse themselves in the virtual environment, experiencing the traffic flow, congestion, and impact of different management strategies. For instance:

Congestion pricing: Stakeholders can visualize the reduction in traffic volume as vehicles are charged for entering high-traffic zones.

Adaptive traffic signals: The dynamic adjustment of traffic lights based on real-time data shows travel time and fuel efficiency improvements.

Dedicated bus lanes: The effect of introducing exclusive lanes for public transport is simulated, showing how bus frequencies improve and overall congestion decreases. Simulation results are captured and visualized in the metaverse environment, highlighting the effectiveness of each alternative.

5.4 | Real-Time Data Integration via Internet of Things

As traffic data is collected from IoT-enabled sensors (e.g., GPS, bright traffic lights, and CCTV), the digital twin updates in real-time. For instance, a sudden traffic jam due to an accident or a weather-related disruption is immediately fed into the model. The system dynamically adjusts predictions, re-routing vehicles as necessary. The integration ensures that the traffic model reflects the current situation, enabling responsive decision-making. *Table 2* presents a comparative evaluation of traffic management alternatives across six key performance criteria. It highlights how each option—adaptive traffic signals, congestion pricing, and dedicated bus lanes—performs in terms of cost, speed, fuel efficiency, CO_2 emissions, user comfort, and infrastructure adaptability.

Table 2. Evaluation of traffic management alternatives based on key performance criteria.

Alternative	Cost	Speed	Fuel Efficiency	CO_2 Emissions	User Comfort	Infrastructure Adaptability
Adaptive traffic signals	High	High	Medium	Medium	High	High
Congestion pricing	Medium	Medium	High	High	Medium	Medium
Dedicated bus lanes	Low	Medium	High	Medium	High	High

Adaptive traffic signals: This solution scores the highest in speed, user comfort, and adaptability. It significantly reduces travel time by optimizing signal timings based on real-time traffic conditions.

Congestion pricing: While it incurs a medium cost, it leads to significant reductions in CO_2 emissions and fuel consumption, making it a highly sustainable solution for peak-hour congestion.

Dedicated bus lanes: This alternative scores low on cost but provides excellent user comfort and infrastructure adaptability benefits, particularly for public transportation users. The final ranking is determined by aggregating the fuzzy weightings with the performance evaluations, offering a holistic view of which traffic management solution is most beneficial across different stakeholder objectives.

5.5 | Demonstrating Decision Changes with Fuzzy Parameter Variations

Finally, the sensitivity of decision outcomes to variations in fuzzy parameters is tested. The decision rankings are adjusted by modifying the fuzzy membership values (e.g., from optimistic to pessimistic) for specific criteria, demonstrating the impact of uncertainty on the optimal solution. For example, if experts are more confident about the cost of adaptive traffic signals, the ranking might shift, making it appear more attractive. Conversely, a pessimistic view of cost might elevate the appeal of congestion pricing due to its advantages for environmental and fuel efficiency. This case study demonstrates how integrating Fuzzy AHP, digital twin simulation, and metaverse visualization can lead to effective, adaptive, real-time traffic management solutions for Kuala Lumpur. The proposed methodology provides a robust and flexible framework for urban traffic management in smart cities by considering stakeholder preferences, uncertainty in traffic predictions, and real-time data integration. The study highlights how decision-making in transportation can evolve with the increasing complexity of urban mobility systems and the role of interactive, immersive decision tools for stakeholders.

6 | Conclusion

This study proposed an integrated framework that leverages digital twin technology, the Metaverse environment, IoT-based real-time data, and Fuzzy MCDM methods to address the complex and uncertain challenges of traffic management in Malaysian smart cities, with a focused case study on Kuala Lumpur. Through developing and applying a Fuzzy AHP model, we systematically ranked various traffic management solutions considering key evaluation criteria such as cost, speed, fuel efficiency, CO_2 emissions, user comfort, and infrastructure adaptability. The fuzzy methodology allowed us to manage the uncertainty and subjectivity inherent in expert judgments, making the decision-making process more robust and realistic. By incorporating digital twin simulations, we could model the dynamic behavior of urban traffic systems with high precision, creating a near-real-time virtual replica of Kuala Lumpur's CBD.

Integrating Metaverse interfaces further enhanced stakeholder engagement, offering immersive visualization of policy impacts and enabling decision-makers, urban planners, and citizens to experience the implications of different traffic management strategies before real-world implementation. The real-time integration of IoT data (From GPS, smart traffic lights, and CCTV) ensured the simulation environment stayed dynamic and reflective of ground realities. This feature allowed the model to adapt to changing traffic conditions and emergencies, providing predictive routing recommendations that are both efficient and environmentally sustainable. The case study results revealed that different traffic management alternatives, such as adaptive traffic signals, congestion pricing, and dedicated bus lanes, perform variably depending on the prioritized criteria and the uncertainty parameters.

Significant contributions of the study include:

I. The development of a hybrid methodology combining Fuzzy AHP, Digital Twins, IoT, and Metaverse technologies for predictive traffic management.

II. A demonstration of how uncertainty and real-time data streams can be effectively managed to produce adaptive traffic solutions.

III. Providing a decision-support framework that is not only technically sound but also user-centered through immersive visualization tools.

The research fills key gaps in the existing literature by merging digital twin predictive capabilities with immersive metaverse experiences and applying fuzzy decision-making techniques in a real-world Malaysian urban setting. This area has been largely underexplored. The proposed approach paves the way for more innovative, resilient, and citizen-centered traffic management in Malaysia and potentially in other emerging smart cities worldwide. Future work could expand the model to larger urban regions, incorporate machine learning algorithms for predictive analytics, and enhance metaverse-based stakeholder collaboration for broader urban planning initiatives.

Data Availability

The required data is available in this manuscript.

Conflicts of Interest

There are no competing interests to declare.

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