

DIGITAL TWIN BASED SMART TRAFFIC MANAGEMENT SYSTEM USING AI

Integrating Artificial Intelligence, Internet of Vehicles and SUMO-Based Simulation for Adaptive, Predictive and Emergency-Aware Urban Traffic Control

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Abstract : The rapid growth in the number of vehicles in urban areas has led to traffic congestion, longer travel times, higher fuel consumption and delays in the movement of emergency vehicles. This paper presents a Digital Twin Based Smart Traffic Management System that integrates Artificial Intelligence (AI), the Internet of Vehicles (IoV) and Digital Twin (DT) technology to monitor, predict, simulate and manage urban traffic. Traffic-related data are collected and pre-processed, and an AI-based prediction module (LSTM/BiLSTM time-series models) estimates traffic density and likely congestion. A Digital Twin of the road network is built in the SUMO (Simulation of Urban Mobility) simulator and kept synchronised with real-time data through TraCI, so that traffic-management strategies can be evaluated virtually before they are applied on real roads. Based on the predicted and simulated conditions, the system performs adaptive traffic signal control, gives priority to emergency vehicles, and recommends alternative routes through a smart rerouting module. A Streamlit-based real-time dashboard presents traffic conditions, predictions, signal status, alerts and route suggestions to traffic officers, authorities and public users. The paper reviews the related literature, analyses the limitations of fixed-time and manually supervised systems, specifies the hardware and software requirements, and describes the architecture and the seven functional modules of the proposed system. The system aims to improve traffic flow, reduce congestion and waiting time, support faster emergency response and enable better decision-making for efficient and sustainable smart cities.

IndexTerms - Digital Twin, Smart Traffic Management, Artificial Intelligence, Internet of Vehicles (IoV), SUMO, Traffic Prediction, Adaptive Traffic Signal Control, Emergency Vehicle Priority, Smart Rerouting.

I. INTRODUCTION

Urbanisation and the steady rise in the number of vehicles have placed heavy pressure on city road networks. The visible consequences are traffic congestion, longer and less predictable travel times, increased fuel consumption and delays in the movement of emergency vehicles such as ambulances and fire-service vehicles. Conventional traffic management relies mainly on fixed-time signals, manual monitoring and basic surveillance. Such methods operate on predefined timing plans and react only after congestion has already formed, so they cannot respond effectively to peak-hour surges, accidents, road blocks or other unexpected events.

Three technologies offer a way to move from reactive to proactive traffic management. Artificial Intelligence (AI) can learn traffic patterns from historical and real-time data and predict congestion before it becomes severe. The Internet of Vehicles (IoV) connects vehicles, roadside infrastructure and traffic-control systems so that fresh traffic information is available for analysis and decision-making. A Digital Twin (DT) is a virtual representation of a physical system that is continuously updated with data from the real environment; it allows scenarios to be observed, analysed and tested virtually before decisions are applied to the real system [3], [13].

This paper presents the Digital Twin Based Smart Traffic Management System Using AI. The system combines AI-based traffic prediction, an IoV-enabled data pipeline and a SUMO-based Digital Twin to support seven functional modules: Traffic Data Collection, AI Traffic Prediction, Digital Twin & SUMO Simulation, Adaptive Traffic Signal Control, Emergency Vehicle Priority, Smart Rerouting and a Real-Time Traffic Dashboard. Together they provide a connected approach that senses, predicts, simulates, decides and visualises, and a simulation-based environment in which traffic-management strategies can be compared before realworld deployment.

NEED OF THE STUDY. Fixed-time signal plans do not consider the actual traffic density on each approach; manual monitoring detects congestion late; emergency vehicles are not automatically given priority at signals; and drivers continue to use congested routes because no intelligent route recommendation is available. There is therefore a need for an integrated system that can predict congestion, adapt signal timing, protect emergency-vehicle movement, redistribute traffic across the network, and allow operators to observe and test decisions safely.

OBJECTIVES. The objectives of this work are: (i) to collect and pre-process traffic data such as vehicle count, speed, density and route information from IoV and simulation sources; (ii) to predict traffic density and congestion using AI-based time-series models; (iii) to create a Digital Twin of the traffic environment using SUMO for safe evaluation of strategies; (iv) to replace fixedtime operation with adaptive traffic signal control; (v) to provide priority passage for emergency vehicles; (vi) to suggest alternative routes when congestion occurs; and (vii) to present all system outputs through a real-time dashboard.

CONTRIBUTIONS. The main contributions of the paper are: (a) an integrated, seven-module architecture that links prediction, simulation, control, emergency priority, rerouting and monitoring in one pipeline; (b) a closed-loop design in which the Digital Twin is updated with real-time data and dashboard feedback is used to improve prediction; (c) a structured review of related work on Digital Twins, IoV, traffic prediction and traffic-signal control, with its relevance to each module; and (d) a specification of the hardware and software requirements.

ALIGNMENT WITH SUSTAINABLE DEVELOPMENT GOALS. The work supports SDG 9 (Industry, Innovation and Infrastructure) by using AI, IoV and Digital Twin technology to build smart traffic infrastructure with prediction, simulation, adaptive signal control and efficient traffic management. It supports SDG 11 (Sustainable Cities and Communities) by helping to reduce congestion, improve vehicle movement, optimise traffic signals and support efficient transportation for smarter and more sustainable cities.

The rest of the paper is organised as follows. Section II presents the review of related work. Section III analyses the existing and proposed systems. Section IV lists the system requirements. Section V describes the architecture and the functional modules, and Section VI concludes the paper with directions for future work.

II. REVIEW OF RELATED WORK

The literature relevant to the proposed system spans Digital Twins in smart cities and vehicular networks, Digital Twins for energy and infrastructure systems, traffic prediction and control, and information freshness. Each group is summarised below together with its relevance to this work.

2.1 Digital Twins and 6G connectivity in smart cities and vehicular networks

Wang et al. [13] explain how Digital Twin technology can create a virtual representation of real-world urban environments, and how 6G communication provides the high-speed, low-latency and reliable connectivity needed between physical entities and their digital models. They show that continuously updated twins support real-time monitoring, analysis, simulation, prediction and intelligent decision-making, and allow scenarios to be simulated before decisions are applied to the real system. This supports the use of a continuously updated virtual traffic environment in the proposed system.

Tao et al. [6] propose a Deep Reinforcement Learning (DRL)-driven Digital Twin function virtualisation approach for adaptive service response in 6G networks. The twin represents network functions and physical resources so that different service conditions can be evaluated in a virtual space, while DRL selects suitable actions as conditions change. Because traffic conditions also change dynamically, the combination of a twin environment with AI-based decision-making is directly relevant to traffic prediction and adaptive signal control.

Javed et al. [2] study reliable communication for cyber-twin-driven 6G Internet of Vehicles using intelligent reflecting surfaces. The cyber twin maintains information about the physical vehicular system and communication network, supporting analysis and optimisation in a highly dynamic environment. Luo et al. [14] investigate symbiotic communications, in which entities cooperate and share resources, together with blockchain for secure and trustworthy data management in sustainable 6G networks. Kohli et al. [3] present secured authentication schemes for 6G-driven vehicular communication in Industry 5.0 IoT applications, stressing that mobile vehicles communicating continuously with roadside infrastructure need mechanisms that identify legitimate devices and prevent unauthorised access. These three studies provide the communication, trust and security background for IoV-based data collection in the proposed system.

2.2 Digital Twins for energy and infrastructure systems

Several works apply Digital Twins to energy and other infrastructure systems, and their concepts transfer naturally to traffic. Sivanesan et al. [15] present cognitive Digital Twins for microgrid energy management, extending a twin with intelligent decisionmaking so that conditions can be monitored, predicted and optimised, and decisions evaluated virtually before implementation. Liao et al. [5] propose Digital Twin-assisted resource allocation for multi-mode Power IoT with ultra-low Age of Information (AoI), highlighting that outdated information reduces the accuracy of control. Ren et al. [12] combine Digital Twins with explainable, secured and quantised federated learning for voltage stability in smart grids, showing how learning can proceed without sharing all local data and why explainability matters in critical infrastructure.

Cheng et al. [8] describe a real-time cyber-physical Digital Twin for a wide-area power grid, showing that a twin must reflect physical changes in real time to remain useful and that Digital Twins extend beyond manufacturing to large-scale infrastructure. Ioannou et al. [11] present a distributed AI framework for nano-grid power management, in which intelligence is distributed across components to improve scalability and flexibility. Gitzel et al. [10] discuss cognitive assistance and prognosis systems for power distribution grids, where future-oriented analysis helps operators act before problems occur. Together these works motivate realtime twin synchronisation, distributed processing of data from many sources, and prognosis-based (predictive) decision support in the traffic setting.

2.3 Traffic prediction and traffic-flow control

Wang et al. [7] propose a Synchronous Spatiotemporal Graph Transformer for traffic data prediction. Graph-based learning represents the relationships between traffic locations, while a Transformer mechanism captures temporal patterns, so that both spatial and temporal dependence are exploited. The study shows that learned models can capture traffic patterns better than fixed rules and is highly relevant to the AI Traffic Prediction module. Ding et al. [9] present an intelligent traffic-flow control system based on 6G communication and an optimised Genetic Algorithm. They note that traditional signal systems use fixed timing plans that respond poorly to changing conditions, and use optimisation to search for better signal timings while 6G enables fast exchange of information between vehicles and infrastructure. This work is directly relevant to adaptive signal control and IoV communication.

2.4 Information freshness and Digital Twin-based network topology

Talak et al. [1] study the improvement of Age of Information in wireless networks. AoI measures how fresh the information at a receiver is, and decisions based on stale information may not represent the current state of the system. In vehicular networks, frequent updates on traffic and road conditions are needed, which is why fresh IoV data are essential for the Digital Twin. Jia and Wang [4] propose a virtual network topology-based Digital Twin for spatial-temporal load-balanced user association in 6G heterogeneous networks. The twin allows association decisions to be evaluated virtually, and the spatial-temporal viewpoint parallels traffic, where conditions vary with location, vehicle density and time of day.

Table 1. Relevance of the reviewed literature to the modules of the proposed system

Literature group	Key contribution	Relevant module(s)
6G Digital Twins in smart cities and DRL-driven twins [6], [13]	Virtual representation of the physical environment; adaptive, learning-based decisions evaluated in a twin	Digital Twin & SUMO Simulation; Adaptive Traffic Signal Control
Cyber-twin IoV, blockchain and authentication [2], [3], [14]	Reliable, trusted and secure vehicle-infrastructure communication	Traffic Data Collection (IoV data); future security work
Cognitive and cyber-physical twins, prognosis [8], [10], [15]	Twin-based monitoring, prediction and optimisation; realtime twin updates	AI Traffic Prediction; Digital Twin & SUMO Simulation
AoI and resource allocation [1], [5]	Importance of fresh data for accurate control	Traffic Data Collection; Real-Time Dashboard
Federated learning and distributed AI [11], [12]	Privacy-aware learning; distributed intelligence for scalability	AI Traffic Prediction; future scalability
Spatiotemporal traffic prediction [7]	Graph-Transformer prediction using spatial and temporal dependence	AI Traffic Prediction
Intelligent flow control and optimisation [9]	Moving beyond fixed-time signals with optimisation	Adaptive Traffic Signal Control; Smart Rerouting

2.5 Research gap

The reviewed studies demonstrate the value of Digital Twins, AI-based prediction and adaptive control individually. However, many concentrate on one or two functions, such as communication reliability, resource allocation, data prediction or signal optimisation, rather than on a complete traffic-management pipeline. The system proposed here brings traffic data collection, AI prediction, Digital Twin simulation, adaptive signal control, emergency vehicle priority, smart rerouting and a real-time dashboard into a single, connected architecture built with widely available tools (Python, SUMO, TraCI and Streamlit), so that every decision can be predicted, simulated and observed in one place.

III. SYSTEM ANALYSIS

System analysis studies the existing traffic-management methods, identifies their limitations and defines the requirements for an improved system. The increase in congestion, inefficient signal management, delayed emergency-vehicle movement and lack of real-time coordination are the main problems considered.

3.1 Existing system

The existing traffic-management system mainly depends on conventional traffic signals, fixed-time signal control, manual monitoring and basic traffic surveillance. In many locations signals operate on predefined timing intervals without considering the actual traffic density on each road. Traffic conditions may change continuously during peak hours, accidents, road blocks or other unexpected situations, but conventional systems cannot always respond immediately to these changes. Monitoring is generally carried out using cameras, sensors, manual observation or existing control infrastructure, and the collected information is often used for monitoring rather than for continuous prediction and intelligent decision-making. When congestion occurs, traffic authorities may need to identify the problem manually and take action. Emergency vehicles may be delayed because signals cannot automatically give priority based on their current movement, and vehicles continue to use congested routes because no intelligent route recommendation exists. The existing approach therefore provides basic control and monitoring but has limited adaptability, prediction capability, real-time coordination and intelligent decision-making.

3.2 Limitations of the existing system

The principal limitations are as follows. (i) Conventional signals use predefined timing intervals and do not dynamically change the signal duration according to current traffic density. (ii) Sudden changes such as congestion, accidents, road blocks or unusual traffic flow are not handled immediately. (iii) Manual monitoring and intervention are common, and action is generally taken after congestion has occurred instead of predicting and preventing it. (iv) Ambulances, fire engines and other emergency vehicles may be delayed at signals because automatic priority management is limited. (v) Intelligent alternative routes are not provided when a road becomes highly congested.

3.3 Proposed system

The proposed Digital Twin Based Smart Traffic Management System Using AI provides an intelligent and adaptive approach to traffic management. It collects traffic-related information and analyses it to understand current conditions; AI techniques predict traffic so that possible congestion is identified early, and adaptive signal control replaces dependence on fixed-time plans. A Digital Twin of the traffic environment, built with SUMO, represents and simulates the traffic scenario so that traffic behaviour and management strategies can be evaluated in a controlled environment. An Emergency Vehicle Priority mechanism supports the faster movement of emergency vehicles by providing suitable signal-control decisions, and Smart Rerouting identifies alternative routes when the current route is heavily congested. A Real-Time Traffic Dashboard provides a centralised view of traffic information, prediction results, simulation information and management decisions through a single interface. Overall, the system moves from conventional, reactive management towards an intelligent, predictive, adaptive and simulation-supported approach.

3.4 Advantages of the proposed system

The proposed system offers the following advantages. **Adaptive traffic signal control** reduces the limitations of fixed-time systems and manages intersections more efficiently. **AI-based traffic prediction** identifies possible congestion and supports decisions before severe congestion occurs. **Real-time monitoring** provides updated information about congested areas and changes in traffic flow. **Digital Twin-based simulation** allows traffic conditions and strategies to be analysed with SUMO without experimenting on real roads. **Improved traffic flow** results from combining prediction, adaptive control and intelligent

management. **Emergency vehicle priority** reduces delays for ambulances and fire-service vehicles. **Smart rerouting** helps vehicles avoid congested roads and distributes traffic across available routes. Together, these features support **reduction in congestion** and **reduction in travel delay**.

Table 2. Comparison of the existing and proposed traffic management systems

Parameter	Existing system	Proposed system
Signal control	Fixed-time, predefined intervals	Adaptive, based on traffic density and predicted conditions
Congestion handling	Reactive; manual identification after it occurs	Predictive; AI-based early identification
Monitoring	Cameras, sensors and manual observation	Real-time dashboard with live map, density view and alerts
Testing of strategies	Directly on real roads	Digital Twin and SUMO simulation before deployment
Emergency vehicles	Limited automatic priority at signals	Signal priority with continuous route monitoring
Route guidance	No intelligent alternative routes	Smart rerouting to less congested routes
Data usage	Mainly for monitoring	Prediction, simulation, control and visualisation

IV. SYSTEM REQUIREMENTS

The system is developed and executed on a standard personal computer. The hardware requirements are summarised in Table 3 and the software requirements in Table 4.

4.1 Hardware requirements

Table 3. Hardware requirements

Component	Recommended specification	Purpose
Processor	Intel Core i5 or equivalent multi-core processor	Executes the Python application, processes traffic data, runs AI operations and handles the SUMO simulation
RAM	Minimum 8 GB	Runs Visual Studio Code, Python, SUMO, Streamlit and the required libraries, and handles traffic data and simulation smoothly
Storage	Minimum 256 GB	Stores source code, Python environment, dependencies, SUMO files, traffic data, output files, screenshots and other resources
Display	Standard HD display	Used for development, debugging, observing the SUMO simulation and accessing the Streamlit dashboard

4.2 Software requirements

Table 4. Software requirements

Software / library	Role in the system
Operating system (Windows)	Provides the environment to install Python, SUMO, Visual Studio Code, libraries and supporting software
Python 3.11	Primary programming language for data processing, AI-based analysis, simulation control and application development
Visual Studio Code	Main development environment for writing, executing and debugging Python programs
SUMO	Traffic simulation platform that represents roads, vehicles, traffic signals and traffic movements
SUMO-GUI	Graphical interface to visualise vehicle movement, road networks and signal operation during simulation
TraCI and TraCI Python library	Interface between the Python application and SUMO for retrieving traffic information and controlling vehicles and signals
Software / library	Role in the system
Streamlit	Interactive web-based dashboard for traffic information, prediction results and simulation outputs
Pandas	Loading, organising, cleaning, filtering and analysing structured traffic data
NumPy	Numerical and mathematical operations during data processing and AI-based analysis
Scikit-learn	Machine-learning algorithms and utilities for the traffic prediction component
Git	Source-code management and version control during development

V. SYSTEM ARCHITECTURE AND METHODOLOGY

5.1 Architecture

The architecture represents the complete flow of the smart traffic management process (Fig. 1). The flow starts with Traffic Data / IoV, where vehicle and traffic-related information is collected. This information is given to the AI Traffic Prediction module, which analyses it and predicts current or possible traffic conditions. The predicted information is connected with the Digital Twin and SUMO environment, where the traffic scenario is represented and simulated virtually. Based on the analysed and simulated conditions, the Adaptive Traffic Signal Control module performs dynamic signal adjustment. From this point the system supports Emergency Vehicle Priority, which provides faster passage for emergency vehicles at intersections, and Smart Rerouting, which suggests better routes when congestion is present. Finally, the Real-Time Traffic Dashboard displays the relevant traffic information and system decisions, providing a centralised view for monitoring traffic and understanding the actions performed by the system. The architecture thus gives an integrated flow from data collection and AI prediction to simulation, adaptive control, emergency priority, smart rerouting and real-time monitoring.

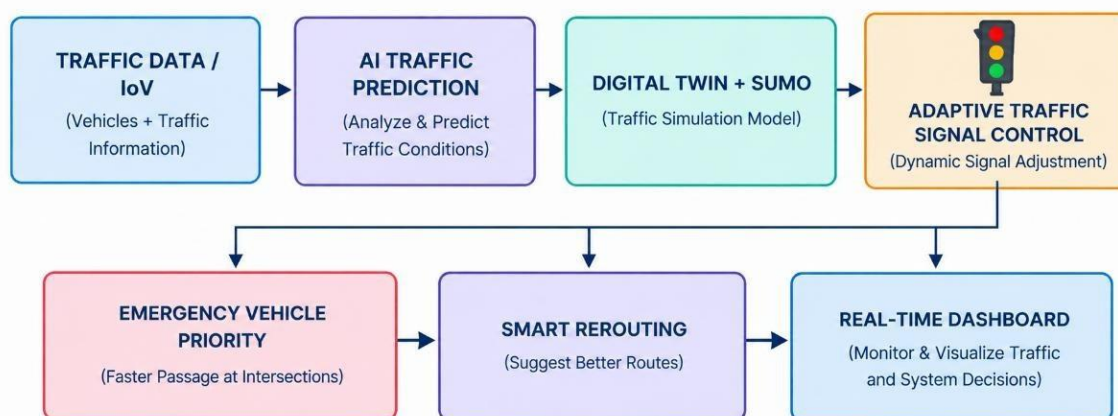


Fig. 1. Architecture of the proposed Digital Twin based smart traffic management system

5.2 Working procedure

The overall operation of the system can be described as a continuous control loop, summarised in Algorithm 1. **Algorithm 1.** Working procedure of the proposed system

1. Collect traffic data (vehicle count, speed, density, route information) from IoV, real-time inputs and simulation.
2. Pre-process the data (cleaning, noise removal, normalisation) and store processed and historical data.
3. Predict short-term traffic flow and classify traffic density (Low / Medium / High) using the trained LSTM/BiLSTM model.
4. Update the SUMO-based Digital Twin with the real-time and predicted data and obtain the synchronised simulation output.
5. Determine optimal signal timing using a reinforcement-learning or heuristic algorithm; update signal phases and send commands to SUMO.
6. If an emergency vehicle is detected (GPS / vehicle signal), analyse its route and give it a priority path through the signals.
7. If a route is congested or an incident is detected, compute and suggest better alternative routes.
8. Display predictions, signal status, alerts and route suggestions on the dashboard; use feedback to update data and improve prediction.
9. Repeat from Step 1 for the next time interval.

5.3 Modules and their description

The proposed system consists of seven major modules: Traffic Data Collection, AI Traffic Prediction, Digital Twin & SUMO Simulation, Adaptive Traffic Signal Control, Emergency Vehicle Priority, Smart Rerouting and the Real-Time Traffic Dashboard. Each module is described below.

A. Traffic Data Collection

- Gathers vehicle count, speed, traffic density and route information from IoV, real-time inputs and simulation data.
- Pre-processes the data through cleaning, noise removal and normalisation.
- Stores processed and historical data and passes it to the AI prediction module.

B. AI Traffic Prediction

- Takes historical and real-time traffic data, weather and time information, and event/holiday data as input.
- Uses an LSTM/BiLSTM time-series model to learn traffic patterns and predict short-term traffic flow.
- Classifies traffic density as Low, Medium or High and identifies likely congestion areas for signal control and rerouting.

C. Digital Twin & SUMO Simulation

- SUMO represents roads, vehicles, intersections and traffic-signal behaviour in a virtual environment.
- TraCI links the Python application with SUMO, and real-time data keeps the Digital Twin synchronised.
- Traffic-management strategies are tested safely in simulation before practical implementation.

D. Adaptive Traffic Signal Control

- Uses prediction results, current signal status, queue length, vehicle count and priority flags.
 - A reinforcement-learning or heuristic algorithm sets signal timing, adjusts cycle length and green time, and avoids starvation of minor roads.
 - Updates signal phases in real time and sends commands to SUMO.
- ### E. Emergency Vehicle Priority
- Detects emergency vehicles such as ambulances and fire-service vehicles through GPS or vehicle signals.
 - Analyses the vehicle's route and the traffic conditions along it.
 - Adjusts signals to give a priority path and keeps monitoring until the vehicle has passed.
- ### F. Smart Rerouting
- Detects congestion and incidents from real-time traffic data and alerts.
 - Finds better alternative routes by analysing the condition of different routes.
 - Sends route suggestions to drivers through an app or system and distributes vehicles across available routes.

G. Real-Time Traffic Dashboard

- A Streamlit-based interface that combines sensor, SUMO, AI-prediction and signal data.
- Provides a live traffic map, traffic density view, signal status monitoring, alerts and route suggestions.
- Gives access to traffic officers (desktop/web), public users (mobile app) and authorities (admin).

VI. CONCLUSION AND FUTURE WORK

This paper presented a Digital Twin Based Smart Traffic Management System Using AI that integrates Artificial Intelligence, the Internet of Vehicles, Digital Twin technology and SUMO traffic simulation to manage changing traffic conditions. The system collects traffic information, predicts congestion, simulates the traffic environment, and supports adaptive traffic signal control, emergency vehicle priority and smart rerouting, with a real-time dashboard providing a centralised interface for monitoring traffic and system outputs. Compared with conventional fixed-time and manually supervised methods, the proposed system is more adaptive, predictive and intelligent, and it can help improve traffic flow, reduce unnecessary delays, support emergency-vehicle movement and assist better traffic-management decisions.

Several enhancements are planned as future work. (i) GPS tracking and ETA prediction can be added for emergency vehicles such as ambulances, fire engines and police vehicles to monitor their locations and estimate arrival times accurately. (ii) Audio alerts can notify nearby drivers about approaching emergency vehicles so that they can clear the way and ensure safe movement. (iii) Traffic signals can be prepared in advance to give priority to emergency vehicles and reduce waiting time, and this can be extended to multiple intersections for faster movement. (iv) The AI-based traffic prediction and Digital Twin simulation can be further improved to analyse changing traffic conditions, test different scenarios and enhance overall efficiency.

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