The Process of Smartening Road Traffic Management Systems Using Open-Source Solutions: Simulating Traffic Flow, Volume, Speed and Its Impact on Road Safety in a Digital Twin Platform

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Abstract

The escalating complexity of modern transportation systems, fueled by rapid urbanization and the increasing integration of autonomous vehicles, requires a fundamental shift in traffic management strategies. Traditional traffic models struggle to adapt to the new challenges posed by higher vehicle densities and the diverse operational behaviors of both automated and non-automated vehicles. As a result, existing models often fail to accurately predict traffic flow and road safety in these dynamic environments, particularly due to the unpredictable interactions between different vehicle types.

To address these challenges, digital twin technology offers a promising solution. By creating virtual representations of real-world traffic systems, digital twins enable the integration of real-time data from a network of smart sensors. This integration allows for the simulation of traffic flow under various conditions, incorporating factors such as vehicle volume, speed, and driver behavior. The ability to simulate a wide range of traffic scenarios in a controlled virtual environment facilitates the testing and validation of new traffic management strategies, which can lead to improved road safety outcomes and a more responsive approach to traffic control.

In parallel, the adoption of open-source standards is crucial for the successful implementation of digital twin-based traffic management systems. Open-source software and data formats ensure interoperability, scalability, and collaboration across different platforms and stakeholders, accelerating innovation within the field. These standards help create a collaborative environment where researchers and developers can work together, fostering the continuous improvement and sustainability of traffic management systems. Moreover, the availability of open-source tools reduces entry barriers for researchers and practitioners, making it easier to implement and adopt these advanced technologies, ultimately enhancing the effectiveness of traffic management solutions. This paper explores how integrating smart sensors, open-source standards, and digital twin Platform can significantly enhance road safety.

1. Introduction:

Rapid urbanization and the exponential growth of vehicular traffic have placed unprecedented strain on transportation infrastructure, leading to chronic congestion, safety risks, and environmental degradation. In response, smart traffic management systems have emerged as transformative solutions, leveraging advancements in Internet of Things (IoT), artificial intelligence (AI), and big data analytics to optimize traffic flow, enhance safety, and reduce emissions. These systems promise to revolutionize urban mobility by enabling real-time data collection, dynamic traffic modeling, and adaptive control strategies. However, despite their potential, significant challenges hinder their widespread adoption and effectiveness. Issues such as data inaccuracies, interoperability gaps, computational limitations, and evolving demands posed by connected and autonomous vehicles (CAVs) underscore the need for continued innovation and interdisciplinary collaboration.

This paper examines the current limitations of smart traffic management systems and explores future research directions to address these barriers. By synthesizing insights from existing literature, we highlight critical areas such as the development of robust data governance frameworks, advanced machine learning-driven predictive models, and human-centric design principles that integrate user feedback. Furthermore, we emphasize the importance of scalable simulation tools and adaptive algorithms capable of accommodating the integration of CAVs into mixed traffic environments. Through this analysis, the paper aims to provide a roadmap for researchers, policymakers, and urban planners to advance the capabilities of smart traffic management systems, ensuring their resilience and relevance in an era of rapidly evolving transportation technologies.

2. Smartening Road Traffic Sensors:

Building upon the challenges and opportunities outlined in the introduction, a crucial step towards the realization of smart traffic management lies in the enhancement of road traffic sensor networks. The foundation of any effective smart traffic management system lies in the quality and quantity of data collected. To achieve this, it is essential to upgrade existing road traffic sensor networks by incorporating advanced technologies capable of capturing comprehensive, real-time data on a wide range of traffic parameters. The integration of Internet of Things (IoT) devices (Xu, 2023), (Fuller, 2020), (Lilhore, 2022) plays a pivotal role in this transformation. These devices, strategically deployed across the road network, provide high-resolution data on critical metrics such as traffic volume, speed, density, vehicle type, and classification (Yu, 2019). Additionally, the inclusion of environmental sensors that measure weather conditions—such as rainfall, temperature, and visibility (Fernndez, 2016)—adds another layer of contextual information, which is essential for accurate traffic modeling and prediction.

To create a holistic understanding of traffic conditions, it is necessary to integrate data from multiple sources. This includes not only real-time data from various sensors but also information from cameras, which provide visual insights into traffic flow and vehicle behavior (Yu, 2019). Furthermore, combining these data streams with historical traffic data from online repositories (Xu, 2023) can provide a more comprehensive picture. The seamless integration of these heterogeneous data sources depends on the adoption of open-source standards, such as the Message Queuing Telemetry Transport (MQTT) protocol (DOrtona, 2022). MQTT’s lightweight and flexible design ensures reliable communication between diverse devices and systems, regardless of their underlying technologies or manufacturers (Fernndez, 2016).

Once the data is collected, preprocessing becomes crucial for ensuring its reliability and accuracy in traffic simulations. This step involves cleaning, filtering, and transforming the raw data to remove noise, inconsistencies, and errors. Anomaly detection techniques (Bawaneh, 2019) are vital in this process, as they help identify unusual patterns or events that could signal errors in sensor readings or unexpected traffic incidents. By effectively filtering out these anomalies, the accuracy of traffic models and the reliability of subsequent simulations are significantly enhanced, ultimately improving the predictive capabilities of the system

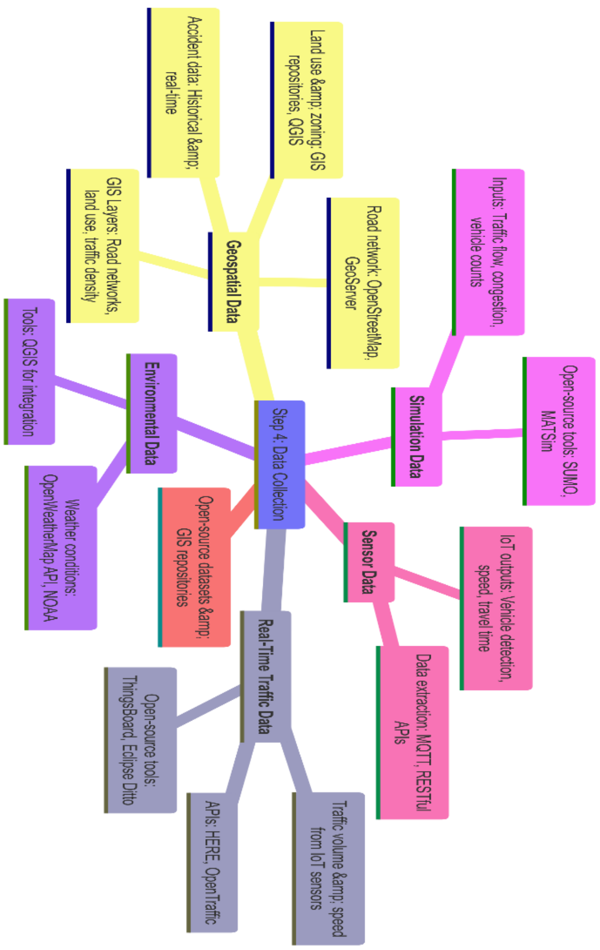

Figure 1. Data Acquisition and Integration

Figure 1. Description
Simulation DataInputs: Traffic flow, congestion, vehicle counts
Open-source tools: SUMO, MATSimSensor Data
IoT outputs: Vehicle detection, speed, travel time
Data extraction: MQTT, RESTful APIs
Real-Time Traffic DataTraffic volume and speed from IoT sensors
APIs: HERE, OpenTrafficOpen-source tools: ThingsBoard, Eclipse DittoGeospatial DataRoad network: OpenStreetMap, GeoServerLand use & zoning: GIS repositories, QGIS
Accident data: Historical & real-time
GIS layers: Road networks, land use, traffic density
Environmental Data
Weather conditions: OpenWeatherMap API, NOAA
Open-source datasets & GIS repositories
Tools: QGIS for integration

3. Open-Source Standards for Traffic Simulation: Software and Methodologies

Building upon the refined sensor data, the next step is selecting and implementing appropriate open-source simulation frameworks to develop accurate and reliable digital twin models of traffic systems. The choice of software depends on several factors, including the specific requirements of the simulation, the available computational resources, and the expertise of the development team (Lint, 2016), (Raju, 2021). Various open-source platforms provide distinct capabilities and functionalities to support different aspects of traffic modeling and analysis.

One such platform, **OpenTrafficSim** (Lint, 2016), is a robust framework designed to extend microscopic traffic models by integrating explanatory mental models. This approach facilitates the incorporation of behavioral theories to better understand driver decision-making (Lint, 2016), which is particularly valuable in traffic environments where both automated and non-automated vehicles coexist. Since driver behavior significantly influences traffic dynamics, accurately modeling these interactions is crucial for predicting and managing traffic flow effectively.

Another widely used open-source platform is SUMO (Simulation of Urban MObility) (Bawaneh, 2019), (Sommer, 2010), (Wei, 2020), (Singh, 2021), which excels in simulating large-scale urban traffic networks with high fidelity. Its microscopic simulation capabilities allow for detailed modeling of individual vehicle behaviors, providing in-depth insights into traffic patterns. Researchers have extensively employed SUMO to evaluate different traffic management strategies and analyze the impact of various factors on traffic flow (Sommer, 2010), (Wei, 2020), (Singh, 2021).

Beyond the selection of simulation platforms, the choice of simulation methodology is equally critical in ensuring the accuracy and realism of traffic models. Agent-based models (Lenfers, 2021) offer a flexible framework for simulating interactions between individual vehicles and their surrounding environment. These models incorporate complex behavioral rules and decision-making processes, making them well-suited for analyzing heterogeneous traffic conditions (Lenfers, 2021). In contrast, continuum dynamics models (Zhang, 2018) adopt a macroscopic perspective, focusing on overall traffic flow rather than individual vehicle movements (Zhang, 2018). The selection of the most appropriate methodology depends on the specific

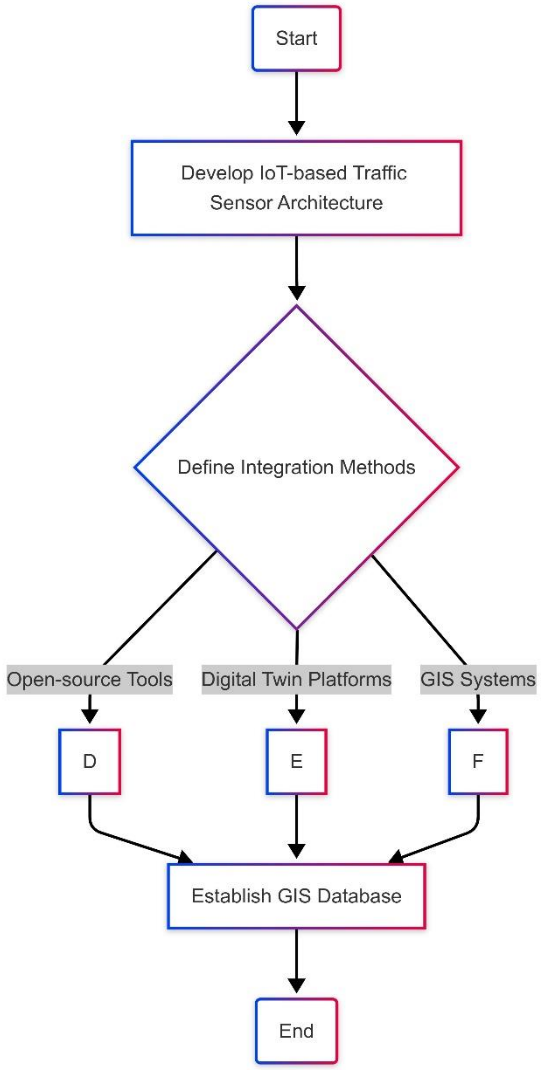

Figure 2. IoT-based Traffic Sensor Architecture and integrating various technologies to establish a GIS database

Figure 2. Description
This flowchart effectively illustrates the stepwise process of integrating IoT, Digital Twins, and GIS tools to create a GIS database for traffic sensor systems: Diagram
Breakdown:
Start (Rounded Rectangle). The process begins with a "Start" node.
Develop IoT-based Traffic Sensor Architecture (Rectangle)
The first step involves developing an IoT-based traffic sensor architecture. Define Integration Methods (Diamond - Decision Node) A decision node determines the integration methods.
Integration Methods (Three Paths - Gray Labels with Black Outlines) The integration is divided into three main categories:
Open-source Tools (D)Digital Twin Platforms (E)
GIS Systems (F)Merge into Establishing a GIS Database (Rectangle)All three integration paths converge into the "Establish GIS Database" step. End (Rounded Rectangle)
The process concludes with an "End" node.
Visual Styling: The flowchart uses gradient-colored borders (blue and pink). Decision points are shown using diamonds, while processes are in rectangles. The integration methods are highlighted with gray labels. Arrows indicate the flow of actions.

objectives of the simulation and the required level of detail. Additionally, integrating **real-time sensor data** into these models—whether agent-based or continuum-based—significantly enhances predictive accuracy (Lenfers, 2021), (Saroj, 2018) by providing continuous feedback on actual traffic conditions.

The adoption of **open-source standards** is essential for ensuring interoperability, scalability, and collaborative development. These standards enable researchers and developers to share data, models, and simulation tools, fostering a cooperative environment that accelerates innovation. By promoting transparency and accessibility, open-source methodologies contribute to the continuous enhancement of digital twin-based traffic management solutions, ultimately leading to more effective and efficient traffic control systems. Figure3 is flowchart illustrates a structured approach to diagnosing and resolving sensor failures in an IoT-based traffic management system. The systematic troubleshooting method ensures minimal downtime and maintains the accuracy of traffic data collection for digital twin platforms, GIS systems, and smart city applications.

4. Digital Twin Framework for Traffic Management: Architecture and Implementation

A robust digital twin framework is essential for effectively managing and monitoring road traffic by integrating data from smart sensors with the simulation capabilities of open-source software. This framework is typically structured into three interconnected layers (Bao, 2021): the data access layer, the calculation and simulation layer, and the management and application layer. Each layer plays a crucial role in ensuring the accuracy, efficiency, and usability of the digital twin for traffic management.

The data access layer is responsible for collecting and integrating traffic data from multiple sources. This includes real-time data from smart sensor networks, surveillance cameras (Xu, 2023),

and external repositories containing historical traffic records (Xu, 2023). The ability to efficiently handle vast amounts of real-time and archived data while ensuring high data quality and consistency is fundamental to the reliability of the digital twin. Additionally, the selection of appropriate data storage and retrieval technologies significantly influences the performance and responsiveness of the system.

At the core of the digital twin framework lies the calculation and simulation layer, where advanced traffic modeling and predictive analysis take place. This layer employs open-source simulation tools such as OpenTrafficSim (Lint, 2016) and SUMO (Bawaneh, 2019), alongside methodologies like agent-based modeling (Lenfers, 2021) and continuum dynamics modeling (Zhang, 2018). These tools enable the detailed representation of traffic flow, driver behavior, and congestion patterns, making it possible to assess real-time traffic conditions and predict future scenarios. Given the computational intensity of large-scale urban traffic simulations, leveraging high-performance computing resources is crucial to maintaining efficiency and accuracy.

traffic management strategies (Bao, 2021). Furthermore, the use of open-source standards across all layers ensures seamless interoperability, encourages collaborative research and development, and fosters continuous advancements in smart traffic management solutions. Figure 4. Entity-Relationship Diagram for Digital Twin (ERD) for a digital twin represents the structural relationships between different entities within a digital twin system.

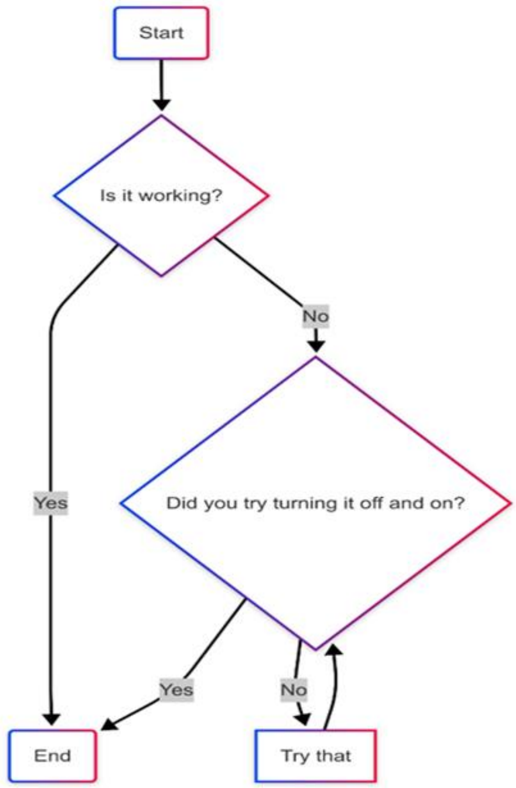

Figure3.This flowchart represents a decision-making process for troubleshooting an IoT-based traffic sensor system, which is a key component of system architecture design in smart transportation networks

Figure3.Description
Start: The troubleshooting process begins.
Check System Functionality: Determine whether the IoT-based traffic sensor is operating correctly.
If yes, the process ends.
If no, proceed to the next step.
Restart Procedure: Assess whether a system reboot (turning the sensor off and on) has been attempted.
If yes, the process ends.
If no, the user is advised to restart the system and re-evaluate functionality.
Loop Until Resolved: The process continues until the sensor is confirmed to be working correctly.

The management and application layer serves as the interface between the digital twin and decision-makers, providing tools for visualizing real-time traffic conditions, analyzing simulation outcomes, and implementing traffic control strategies. This layer features interactive dashboards, data-driven decision support systems, and automated traffic management solutions, such as dynamic traffic light adjustments and predictive congestion mitigation measures (Xu, 2023). Ensuring an intuitive user experience is vital, as clear and actionable insights empower urban planners and traffic authorities to make informed decisions.

The choice of technologies at each layer significantly impacts the overall performance, scalability, and adaptability of the digital twin framework. Cloud computing (Serrano, 2016), offers a flexible and cost-effective approach to managing large datasets and executing complex simulations, while machine learning algorithms enhance predictive accuracy and facilitate proactive

This diagram typically consists of entities, attributes, and relationships, illustrating how real-world systems, processes, and data are linked in a virtual environment.

5. Discussion and Conclusion: The Promise of Smart Traffic Management for Enhanced Road Safety

The integration of smart traffic sensors, open-source simulation frameworks, and digital twin technology offers a powerful approach to improving road safety and traffic efficiency. By creating virtual representations of real-world traffic systems, digital twins enable the simulation of various scenarios, allowing for the evaluation of different traffic management strategies.

The use of open-source standards fosters collaboration, interoperability, and scalability, ensuring the long-term sustainability of these systems.

Although challenges such as data accuracy, interoperability, and computational resources remain, ongoing research and development efforts are actively addressing these limitations. The incorporation of advanced technologies like machine learning and AI further enhances the capabilities of smart traffic management systems. The ultimate goal is to create safer and more efficient transportation systems, reducing congestion, improving travel times, and minimizing the risk of accidents. To achieve this, future research should focus on refining simulation models, integrating user feedback, and adapting to the evolving landscape of connected and autonomous vehicles. The continued development and adoption of open-source standards will be essential for ensuring the widespread implementation of these advanced traffic management systems.

A key aspect of smart traffic management is its ability to enhance road safety, which remains the ultimate objective of these systems. The digital twin framework plays a crucial role in evaluating the effectiveness of various safety measures and optimizing traffic management strategies. By simulating different scenarios, including accidents, it enables the assessment of various interventions in a controlled environment.

Surrogate safety measures, derived from simulation models, provide quantitative metrics for evaluating the safety performance of different traffic management strategies. Measures such as time-to-collision, post-encroachment time, and speed differential offer more objective assessments of safety improvements than relying solely on accident statistics. The ability to simulate a wide range of scenarios—including varying traffic volumes, speeds, and weather conditions—ensures a comprehensive evaluation of the effectiveness of different safety interventions. Furthermore, the integration of real-time sensor data into the digital twin framework significantly enhances the accuracy of safety assessments.

By incorporating real-world traffic conditions into simulations, the results align more closely with actual traffic behavior, offering a realistic estimate of the safety improvements achieved.

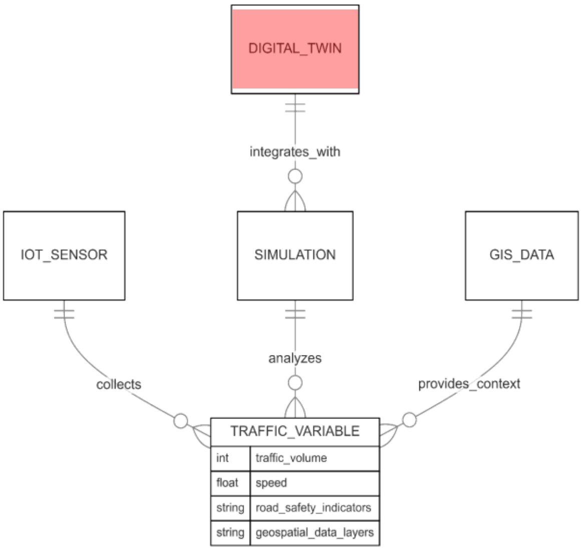

Figure4.Entity-Relationship Diagram

Figure4. Description

Key Relationships:

1.Monitors: The sensors monitor the physical entity and send real-time data to the digital model. The relationship connects the sensor and physical entity through the data collection process.

2.Updates: The digital model is periodically updated based on the data from sensors and IoT devices. This relationship reflects how the virtual model evolves over time with input from real-world conditions.

3.Analyzes: The analytics system analyzes the data provided by sensors to inform decision-making processes. The relationship here is between the data storage and the machine learning models or analytics tools.

4.Simulates: The digital model may simulate future states of the physical entity based on historical data and predictive models, creating a loop of continuous refinement.

5.Interacts: The system can interact with the physical entity in real-time or based on predictive insights (e.g., sending alerts for maintenance needs).

Key Entities:

1.Physical Entity: Represents the real-world object or system being modeled (e.g., a bridge, building, or vehicle).

Attributes: Physical characteristics such as dimensions, location, material type, and other relevant specifications.

2.Digital Model: The virtual representation of the physical entity.

Attributes: Geospatial data, 3D models, simulation data, and monitoring data from sensors.

3.Sensors/IoT Devices: Devices that gather data from the physical entity in real time (e.g., temperature, stress, humidity sensors).

Attributes: Sensor ID, type, data collected (e.g., pressure readings), location.

4.Data Storage: The system where all real-time and historical data is stored for analysis.

Attributes: Data storage type (cloud, on-premises), size, update frequency, and access permissions.

5.Analytics and Machine Learning Models: Algorithms used to process and analyze the data gathered from the sensors.

Attributes: Algorithm type (e.g., predictive maintenance model), data inputs, output results

This continuous feedback loop between the physical and virtual worlds supports ongoing refinements in traffic management strategies. By analyzing the simulated impact on key safety metrics, such as accident rates and severity, decision-makers can make evidence-based improvements to road safety interventions.

6. Challenges and Future Directions: Addressing Limitations and Expanding Capabilities

Despite the considerable potential of smart traffic management systems, several challenges must be addressed to fully realize their benefits. A critical concern is data accuracy, as inaccurate sensor readings can lead to flawed simulations and poor decision-making. Ensuring interoperability among different sensor systems and software platforms is another significant challenge, as seamless integration is essential for effective system performance. Additionally, robust data governance mechanisms are crucial to ensuring data privacy, security, and responsible use. The computational demands of large-scale traffic simulations also require substantial computing resources and efficient algorithms to handle system complexity.

To overcome these challenges and expand the capabilities of smart traffic management systems, future research should focus on several key areas. A primary goal is the development of more sophisticated simulation models that accurately capture the complex interactions between vehicles, infrastructure, and the environment. The integration of advanced machine learning techniques offers great potential for improving traffic prediction and control, enabling more proactive management strategies. Additionally, improving sensor data accuracy and reliability through advanced calibration techniques and error correction methods is critical for ensuring the effectiveness of these systems.

Another essential area for future development is the integration of user feedback to enhance the usability and effectiveness of smart traffic management systems. By incorporating the perspectives of drivers and other road users, these systems can be designed to better meet public needs and encourage greater acceptance and adoption.

Finally, the increasing prevalence of connected and autonomous vehicles necessitates new models and algorithms to address their unique characteristics and interactions with human-driven vehicles. Developing future-proof traffic management systems that can adapt to the evolving transportation landscape will be crucial for ensuring traffic flow efficiency and safety in the era of autonomous mobility. (Zhang, 2018)

References

Lint, Hans Van, Schakel, W., Tamminga, G., Knoppers, P., and Verbraeck, A. 2016."Getting the Human Factor into Traffic Flow Models: New Open-Source Design to Simulate Next Generation of Traffic Operations" https://doi.org/10.3141/2561-04

Fuller, Aidan, Fan, Zhong, Day, Charles, and Barlow, Chris. 2020. "Digital Twin: Enabling Technologies, Challenges and Open Research". Institute of Electrical and Electronics Engineers. https://doi.org/10.1109/access.2020.2998358

Xu, Haowen, Berres, A., Yoginath, Srikanth B., Sorensen, H., Nugent, P., Severino, Joseph, Tennille, Sarah A., Moore, Alex, Jones, Wesley B., and Sanyal, J.. 2023. "Smart Mobility in the Cloud: Enabling Real-Time Situational Awareness and Cyber-

Physical Control Through a Digital Twin for Traffic". https://doi.org/10.1109/TITS.2022.3226746

Lilhore, U., Imoize, A., Li, Chun-Ta, Simaiya, Sarita, Pani, S., Goyal, Nitin, Rana, A., and Lee, ChengChi. 2022. "Design and Implementation of an ML and IoT Based Adaptive Traffic-Management System for Smart Cities". Italian National Conference on Sensors. https://doi.org/10.3390/s22082908

Yu, Yanwei, Tang, Xianfeng, Yao, Huaxiu, Yi, Xiuwen, and Li, Zhenhui. 2019. "Citywide Traffic Volume Inference with Surveillance Camera Records". IEEE Computer Society. https://doi.org/10.1109/tbdata.2019.2935057

Fernndez, Susel, Hadfi, Rafik, Ito, Takayuki, Marsa-Maestre, Ivn, and Velasco, J. 2016. "Ontology-Based Architecture for Intelligent Transportation Systems Using a Traffic Sensor Network". Italian National Conference on Sensors. https://doi.org/10.3390/s16081287

DOrtona, Cristian, Tarchi, D., and Raffaelli, C.. 2022. "Open-Source MQTT-Based End-to-End IoT System for Smart City Scenarios". Future Internet. https://doi.org/10.3390/fi14020057

Bawaneh, Mohammad and Simon, V. 2019. "Anomaly Detection in Smart City Traffic Based on Time Series Analysis". International Conference on Software, Telecommunications and Computer. https://doi.org/10.23919/SOFTCOM.2019.8903822

Raju, Narayana and Farah, Haneen. 2021. "Evolution of Traffic Microsimulation and Its Use for Modeling Connected and Automated Vehicles". Hindawi Publishing Corporation. https://doi.org/10.1155/2021/2444363

Sommer, Christoph, German, Reinhard, and Dressler, Falko. 2010. "Bidirectionally Coupled Network and Road Traffic Simulation for Improved IVC Analysis". IEEE Computer Society. https://doi.org/10.1109/tmc.2010.133

Wei, Long, Yu, Zheng, Jin, Zhongming, Xie, Liang, Huang, Jianqiang, Cai, Deng, He, Xiaofei, and Hua, XianSheng. 2020. "Dual Graph for Traffic Forecasting". Institute of Electrical and Electronics Engineers. https://doi.org/10.1109/access.2019.2958380

Singh, Gagan Deep, Kumar, Sunil, Alshazly, Hammam, Idris, Sahar Ahmed, Verma, Madhushi, and Mostafa, Samih M.. 2021. "A Novel Routing Protocol for Realistic Traffic Network Scenarios in VANET". Wiley. https://doi.org/10.1155/2021/7817249

Lenfers, Ulfia A., Ahmady-Moghaddam, Nima, Glake, Daniel, Ocker, Florian, Osterholz, Daniel, Strbele, Jonathan, and Clemen, T.. 2021. "Improving Model PredictionsIntegration of Real-Time Sensor Data into a Running Simulation of an Agent-Based Model". Sustainability. https://doi.org/10.3390/su13137000

Zhang, Yuming, Zhang, Guohui, Fierro, R., and Yang, Yin. 2018. "Force-Driven Traffic Simulation for a Future Connected Autonomous Vehicle-Enabled Smart Transportation System". None. https://doi.org/10.1109/TITS.2017.2787141

Saroj, Abhilasha J., Roy, Somdut, Guin, Angshuman, Hunter, M., and Fujimoto, R. 2018. "Smart City Real-Time Data-Driven Transportation Simulation". Online World Conference on Soft Computing in Industrial Applications. https://doi.org/10.1109/WSC.2018.8632198

Serrano, Diego, Baldassarre, M. T., and Stroulia, Eleni. 2016. "Real-time traffic-based routing, based on open data and open-source software". World Forum on Internet of Things. https://doi.org/10.1109/WF-IoT.2016.7845419

Bao, L., Wang, Qiulan, and Jiang, Yan. 2021. "Review of Digital twin for intelligent transportation system". https://doi.org/10.1109/iceert53919.2021.00064