Optimization of urban road network and digital twins: a literature review

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***Abstract**. The optimization of road traffic in urban areas has been researched for many years, with various attempts made to avoid waiting times and congestion, and to reduce air pollution and noise levels. Given the dynamic nature of traffic, it is crucial to optimize it to increase safety and reduce greenhouse gas emissions. In most cases, solving this problem involves using simulations in specialized programs that are calibrated with historical data to obtain the most accurate representation of real traffic in the network. Digital twin (DT) systems aim to create virtual replicas of physical objects that update in real-time with their physical counterparts and evolve alongside those assets throughout their life cycle. By using digital twin technology in traffic systems, it is possible to collect and use real-time traffic data and import the data into the SUMO simulation program, which can create a virtual replica of the physical traffic. This type of data usage and presentation can help traffic planners more accurately predict congestion and prescribe optimized solutions based on those predictions.*

Keywords. optimization of the urban road network, digital twin, simulation, traffic network, greenhouse gas emissions (GHG), intelligent transport systems (ITS).

1 Introduction

This article provides an overview of the interdependence between transport systems, traffic management, ITS (Intelligent Transport Systems), digital twin, urban network optimization and greenhouse gas emissions reduction. To function smoothly, efficient management of traffic flows is essential for the transport system. The transport system is directly integrated into the concept of smart city development and it is based on the applications of digital and communication technology (ICT) and Internet of Things (IoT) to achieve better connectivity, efficiency, functionality and sustainability. Traffic flows are organised hierarchically and their management is enhanced by intelligent transport systems. ITS work on the principle of automatic or adaptive systems (using one of the methods of computer science: deep learning, machine learning, artificial intelligence, neural networks). The input data used for ITS is collected from traffic counters at road junctions or intersections. The data collected consist of the number of vehicles from different categories. The function of ITS is to provide feedback by sending, receiving, and exchanging information between different entities (such as drivers, passengers, road infrastructure, construction facilities, equipment, and the environment) in order to increase road safety, reduce pollution, improve traffic flows, direct vehicles on roads and intersections both in and outside cities, increase mobility, reduce travel time, and lower the proportion of costs generated by traffic. With DIRECTIVE 2010/40/EU, the European Parliament and the Council of the European Union have adopted a legal framework that describes the obligation and importance of introducing an ITS in the road transport system. In the literature review, the concept of digital twin was considered as a technology that enables a different dimension of exploring traffic flow optimization. The basic definition of the digital twin represents a model of an object or system that continuously uses data collected from sensors, network-connected devices and other data sources to present a realistic and dynamic physical model or system. According to Kritzinger and co-authors (2018.), the digital twin is a digital representation of a physical entity with a fully integrated and automated bidirectional data flow to the physical entity. Wu and co-authors (2023) divide the digital twin into three parts: a physical entity, its virtual counterpart, and a mapping between the actual object and the virtual twin, allowing the physical and virtual sides to evolve together. These different definitions offer multiple perspectives on digital twins and show that digital twins play a major role in research and practice. According to Zirin Wang and co-authors (2022), in a paper describing the concept, architecture, case study, and future challenges in the transformation of digital twins in urban mobility, a digital twin is defined as a digital image of a living or non-living physical entity. They note that this still-emerging technology is attracting significant attention across various industries this decade. However, while some studies have investigated digital twins in transportation, existing research lacks systematic connections between different entities: people, vehicles, and the transportation environment as a whole. A theoretical framework has been developed based on the application of artificial intelligence that utilises data from the database, cloud, edge computing, and smart devices for mobility services. Based on the database queries 'traffic flow management' and 'traffic flow management at intersections,' proposals were developed that describe solutions and improvements through the application of traffic simulation programs utilizing predictive analytics to optimize traffic flow and the traffic system overall. Predictive analytics in traffic system is applied through machine learning and artificial intelligence, where data is collected through sensors and devices connected via Internet of Things and used based on historical data. Mathematical models of traffic flows are also created using mathematical methods such as graph theory, tail theory, linear programming and the traffic network. The theory of traffic flow is based on various parameters such as vehicle flow, traffic flow density, traffic flow speed, vehicle travel time, vehicle following interval and distance between vehicles. These are all mathematical quantities that are mutually dependent and connected. Since the research area is based on the framework of digital twins, which operate using real-time data, and traffic flows in the urban environment, the need for real-time measures is investigated through a case study. Decision theory has been imposed as important for decision making in order to optimize and reduce as much as possible the above-mentioned deficiencies that occurring in the transport network. Traffic flow management based on predictive analytics provides effective results, but a prescriptive decision-making theory that answers the question, 'How can better decisions be made?' and prescriptive analytics for decision-making show that there is room for improvement in the optimization of traffic flow. Prescriptive analytics and optimization are often used as synonyms and describe a provable mathematical model that is able to find the best possible variant for achieving certain optimization goals.

The aim of this article is to examine the results of previous research in the field of traffic flow optimization in urban networks using the digital twin methodology. The following research questions can therefore be placed: What are the limitations of previous research? Is there a way to solve the perceived shortcomings more successfully in order to achieve some progress in optimizing traffic flows in urban road networks? This article is organized into the following chapters: Chapter 2 explains the methodology used to conduct this study. Chapter 3 presents a simulation of the traffic flow in the urban network and the digital twin. Chapter 4 shows the limitations of previous research and further research. Chapter 5 is the conclusion.

2 Methodology

For the purpose of this study, a literature review was conducted in the areas of traffic simulation at signalized and unsignalized intersections, as well as digital twins. The literature search was conducted using Scopus, Web of Science, and IEEE Xplore databases, limited to the period from 2019 to 2024 and focused on the fields of Computer Science and Engineering. Considering the complexity of the research field, the search query in the three databases consisted of several queries: *("road traffic AND "digital twin"), ("road network optimization AND "digital twin"), ("road network modeling and simulation AND "digital twin"),* and resulted:

Table 1 Citation database and query

Citation database /query:	Web of Science	Scopus	IEEE Xplore
Road traffic digital twin	86	175	240
Road network optimization digital twins	40	31	44
Road network modeling and simulation digital twin	65	33	93

When searching the databases, 807 articles related to the research field were displayed. Given that the authors explore the concept of digital twins in traffic management and the optimization of traffic systems in various ways, it is understandable that a large number of articles were retrieved. Also, many of articles were found in all three databases, so the total number of articles that could be analyzed in the field of interest is greatly reduced. The topics that researchers address and investigate in the field of digital twins are connected with the following areas:

1. The maintenance of road infrastructure, bridges, and tunnels
2. The relationship between road conditions, tire condition, and vehicle controllability
3. Methods for collecting, analyzing, and visualizing traffic data
4. The placement of sensors on specific roads to gather information about the traffic situation
5. The relationship between autonomous vehicles and human-driven vehicles
6. The impact of lane changes on traffic accidents

7. Communication between autonomous vehicles, other road users, Intelligent Transportation Systems (ITS), and the Internet of Things (IoT)
8. The impact of road infrastructure lighting
9. The role of artificial intelligence in traffic management
10. The application of agent-based traffic management and deep learning methods, including Deep Reinforcement Learning (DRL), in adaptive traffic signal management
11. The use of blockchain methodology in traffic management
12. The cybersecurity of collected traffic data
13. The optimization of traffic to reduce exhaust emissions and improve signal timing at intersections
14. The dynamic management of signal phase duration at traffic light intersections and on freeways
15. The synergy between real-time collected traffic data and simulations for a virtual representation of traffic on a highway section.

After analyzing the abstracts of the articles retrieved from the database search, 10 articles were selected to represent the research area and to serve as a framework for future studies.

3 Simulation of traffic flow in urban network and digital twins

This chapter presents the results of previous research in the field of road traffic optimization using the digital twin methodology. The research by Kušić and co-authors (2022) describes an application that performs microsimulations based on carefully divided traffic data. This data is continuously collected and stored in a database according to traffic intensity, which is monitored by traffic counters positioned on a section of the motorway in Geneva. These counters provide real-time insights into traffic flow, allowing the researchers to simulate and analyze the dynamics of vehicle groups with a high degree of accuracy. This continuous data collection is crucial for ensuring that the microsimulations reflect the actual traffic conditions, thereby enhancing the reliability and applicability of the simulation results for traffic management and planning. This synchronization ensures that the simulations are as accurate and reflective of real-world conditions as possible. However, they noted a significant gap in the existing literature: there was no detailed methodology or set of steps available for dynamically generating and calibrating traffic flows by creating scenarios and microsimulations within the SUMO (Simulation of Urban Mobility) traffic simulation program. Recognizing the absence of detailed methodologies for dynamically generating and calibrating traffic flows in SUMO, they proposed a comprehensive methodology for creating a digital twin of the Geneva Motorway in their paper. This methodology focuses on the dynamic calibration of traffic flow and the dynamic rerouting of vehicles, which are essential mechanisms within the SUMO application. These mechanisms are based on application objects that can be calibrated, ensuring that the digital twin accurately mirrors real-world traffic conditions and responds to changes in real-time. They highlight that the dynamic calibration of traffic flow and rerouting of vehicles can be controlled during the simulation by interacting with the SUMO and TraCI (Traffic Control Interface) interfaces. These interfaces are essential for dynamically generating the desired traffic volume and executing simulations based on specific traffic scenarios. Importantly, the authors note that these elements can be continuously calibrated to maintain the accuracy of the simulations. The data used in the simulations includes the actual speed of vehicles, with the number of vehicles distributed according to groups detected by the traffic counters. This data is entered into the continuously running program every minute. In this way, the digital twin of the Geneva Motorway continuously adapts to real traffic in real time by calibrating the input data. This is the main difference between the standard process of model creation and traffic simulation. Kušić and co-authors (2023) also present their research, which follows on previous work, and state that digital twins will change the technology of managing the transportation system. They present a compelling concept for monitoring the entire lifecycle of the transportation system. Shamlitsky and co-authors (2024) investigate the use of digital twins for traffic flow management to increase road safety, optimize vehicle flow and improve the functioning of the entire transport system. They conclude that it is necessary to develop effective algorithms and methods for data analysis that distinguish the collected data and information from the digital twins in order to make effective decisions. They give the methodological framework in which they created a digital twin model of traffic flow on the road network with an intersection using real data in real time using the AnyLogic program, which is intended for creating traffic model simulations. The input data for the model are the intensity of arrival of vehicles from all approaches to the intersection, the distribution of vehicles in each approach and in all directions. They tested the model by applying the Webster algorithm, which is suitable for managing traffic signal intersections, they calculated the saturation (saturation of traffic flow) and calculated the duration of the phases of the traffic signals. After testing the model through simulation, they came to the conclusion that it is possible to reproduce real traffic in real time with the help of simulation. They developed a tool as an upgrade to the AnyLogic program that enables the use of real-time data. However, they cite the inability to access real-time data as a disadvantage, due to the need for permission from the city administration and traffic control. In their work, Kamal and co-authors (2024) present the effective application of the digital twin to adaptive traffic management at intersections with traffic signals, which has an impact on reducing harmful exhaust emissions in urban environments. From the conducted research, they concluded that artificial intelligence has potential in the application of adaptive control of traffic signalization, but little research has been done on how it affects the reduction and mitigation of harmful exhaust emissions in urban environments. In particular, they highlighted the application of DRL (Deep Learning with Reinforcement) in the adaptive control of traffic signals to reduce travel time. The methodology is described in five phases: The first phase is the collection of traffic data, the second phase is used to create a digital twin model in which models are modelled, analysed, scenarios are created based on multi-criteria decision making, and simulations are performed on a virtual replica of the intersection using the data obtained from the collection phase. The modelling is carried out as an intermediate layer between the physical model and the digital twin, in which the TraCI interface (Traffic Control Interface) and SUMO are used. In SUMO, a model of the traffic network is created, consisting of signals, roads, intersections, vehicles, pedestrians and bicycles. The model can be configured to reflect the traffic system in real time or to create scenarios that can be used to simulate, test, validate and evaluate the functioning of the traffic network under different conditions and traffic loads. The TraCI module allows access to the running simulation in the SUMO traffic network (using the TCP protocol) and with the application of different programming languages (in this case the Python programming language module), it allows users of the SUMO program to access a set of functions that can be called from a Python script using the TraCI protocol. In this way, information from the SUMO simulation can be controlled and retrieved, such as the speed of the vehicle or the position of the vehicle in the traffic network. The middle layer is a traffic network model that represents a real intersection that is monitored in the physical layer. The third phase is analysis and simulation, which is performed using the Multi-Agent Deep Deterministic Policy Gradient algorithm, which learns optimal strategies for managing and controlling traffic flows in the transportation network model. This is followed by the definition of possible actions, in which the possible interactions between all traffic elements represented in the matrix are listed, so that the agents (traffic signalization) can accelerate the training, learning and decision-making process. Then follows the definition of all authorized actions or decisions available to the agent communicating with the elements of the traffic system so that the traffic management system can influence the control of traffic flows. Finally, there is feedback to the agent, from which it learns from the actions performed and implies an evaluation of the effectiveness of the actions performed in the traffic flow control system. The fourth stage is the decision making based on the initial data from the third stage and the fifth stage is the stage of activating the traffic management system. The evaluation in this paper was carried out using simulation as a quantitative method using synthesized and real data obtained by counting the traffic at the intersections and showing the results in the reduction of harmful gasses in the urban environment. In their paper, Dasgupta and co-authors (2021) present a framework for creating digital twins that manage an adaptive traffic control system at traffic signal intersections to reduce waiting times and improve travel time on the transportation network in an urban environment. They conducted a case study by creating a traffic microsimulation in the SUMO program by creating a virtual image of the traffic network with traffic lights in an urban environment where the data used for the simulation was collected in real time. They proved that with the help of a digital twin it is possible to reduce the waiting time at the intersection and thus influence the satisfaction of road users.

In their paper, Soeffker and co-authors (2022) discuss the problem of stochastic dynamic routing of vehicles in the transportation network, where a number of decisions need to be made on how to route (assign) the vehicles in the network. In their literature review, they came to the realization that there are various methods to integrate the collected information and make a prediction based on the information so that appropriate decisions can be made. They explain this as an example of prescriptive analytics being increasingly used in optimization decision making, and in the paper they examine how it relates to stochastic dynamic routing of vehicles in the transportation network. In their paper, Zirin Wang and co-authors (2022) introduce digital twin technology to develop a cooperative driving system at unsignalized intersections, in which connected vehicles cooperate with each other to cross intersections without emergency braking. They developed an algorithm to plan the vehicles and their movement through intersections without stopping, based on communication between the vehicles. This was achieved using agent-based modeling and simulation in the Unity game engine based on a real map of San Francisco. In their paper, Zhao H. and co-authors (2019) present a simulation at signalized intersections using a vehicle tracking model and a vehicle specific power consumption model to estimate vehicle emissions. They also mention that signalized intersections are areas of high fuel consumption and high pollutant emissions, which is related to the speed of vehicles during the different signal phases. Batista and co-authors (2022) present a study in which they investigate the potential of aggregate traffic models for estimating network-wide emissions. The study is based on a simulation environment using the SUMO simulator, focusing on the calibration of aggregated traffic models and routes to investigate overall network emissions. They concluded that real-time monitoring systems can play an important role in reducing traffic emissions and pollutants in urban networks, but that reliable monitoring systems are needed. In their paper, Wang Han and co-authors (2023) present an optimization method for urban traffic signal control based on digital twin technology. The method consists of the following parameters: digital roads, traffic lights and vehicles, and the combination of the optimization algorithm to take fuel consumption as the optimization target. The algorithm used for the optimization is based on a genetic algorithm whose main objective is to reduce fuel consumption. They performed the optimization according to the digital twin traffic map with different iteration times and performed several iterative optimizations on the four-phase duration of each intersection. After setting the parameters, they run a simulation in the SUMO simulator, where different traffic scenarios are created. At the end of the investigation, they concluded that the modeling process for a digital twin traffic model is relatively easy to accomplish in practice and that this model, combined with optimization algorithms for controlling digital traffic, has advantages such as ease of operation and high efficiency compared to the original model.

4 Limitations of previous research and further research

The researched articles show progress in the development of digital twins in road traffic management and optimization. Digital twins are used for traffic optimization in the following research areas: in sections on highways (motorways), at isolated intersections and connected intersections controlled by traffic signalization, to increase traffic safety at intersections and improve traffic flow in general, to reduce the concentration of exhaust gases at intersections with adaptive traffic signalization and phase timing, to facilitate communication between autonomous vehicles and enable information exchange at intersections without traffic signals, to apply the Unity Game Engine, and to reduce fuel consumption. Articles also describe various methods of how and in what way is it possible to perform traffic optimization at intersections. Few examples of methods are: various algorithms, artificial intelligence, machine learning, deep learning, traffic management based on a multi-agent system with the application of DRL etc. In general, it can be concluded that digital twin technology is researched with different methodologies. Also it can be stated that it is necessary to combine real data and virtual environment with the use of specialized simulation programs. In the field of road traffic optimization, mostly used simulation program is SUMO (Rydzewski and co-authors, 2020). Researchers are using different simulators which can be an obstacle in choosing a simulation program for traffic modeling and simulation. The simulation programs have a well-described interface and support digital twin technology but the interfaces of the platforms are not unified. There are numerous ways how to optimize traffic flow at intersection by observing traffic flow parameters, but it is not defined what is the most effective way to optimize traffic in an urban network and when is the right time to apply the appropriate methodology to achieve the aim of the research. Furthermore, there is a lack of research using real-time data, not considering the few papers in which the authors use real-time data. There is no synergy between data collected by the road measuring devices and the data from the simulation and its updates in real time, so the digital twin technology is not really relevant. Case studies that explain different traffic networks, e.g. highways, closed signalized intersections, connected intersections with traffic lights, etc., are usually performed in a simulation environment where the urban network is configured and modelled with different scenarios. The scenarios are created with various input parameters: traffic light duration, waiting times, traffic flow, traffic density, vehicle speed, etc., and it is observed how these parameters are related to each other. Based on these scenarios, it is possible to optimize the traffic flow at intersections by changing the duration of the traffic lights. Greenhouse gas emissions and pollution caused by the exhaust systems from car engines have been mentioned in many studies, but only as a consequence of the side effects of road traffic that occur in the transportation network depending on traffic congestion at different periods of the day and night or during peak hours. There is a lack of studies dealing with the development of methods and algorithms for the optimization of traffic flow at intersections, where the main trigger for the optimization at intersections in the urban traffic network is the critical amount of greenhouse gas emissions generated by engine exhaust systems. This could be a way to further investigate the existing problems in the optimization of the urban transport network with the help of digital twin technology. This leads to the conclusion that there are possibilities for progress and scientific contributions in research. Regarding to the mentioned limitations, in most of the papers whose main goal is to optimize traffic flow and solve traffic congestion, it exists a gap in the exact explanation of how digital twin models are updated and how the models communicate with the digital twin. Križanić and co-author (2023) therefore state in their paper that it is necessary to mention that a digital twin uses data in real time, updates its performance in real time using data, reads from external devices and sensors, and is a more advanced form of digital twin when machine learning is included in its implementation. The idea of machine learning is that the model of the digital twin is updated according to the amount of data collected during its execution, forming a dataset on which artificial intelligence (AI) can be trained so that it can communicate with the digital twin in terms of adjusting execution based on its behavioural patterns.

5 Conclusion

Road traffic is a highly complex system. Scientists from various fields of research, along with engineers and experts, have observed and described traffic and transportation in numerous ways. The traffic and transportation is irreplaceable for the economic development of any country and connects all parts of the world. To achieve the uninterrupted movement of vehicles between start and end points, or between origin and destination, the traffic flows of people and goods (freight) must be successfully controlled. Therefore, traffic flows require appropriate management and must be monitored and optimized in real time. The movement of traffic flows can be predicted in real time using simulation programs, with researchers utilizing data collected from sensors, IoT devices, and communication between vehicles. These simulations enable researchers to predict possible scenarios in the traffic network. However, since traffic is a very dynamic system, it is not always possible to optimize traffic flow based on predictions. Therefore, it is necessary to use different methods to model and optimize traffic flow based on prescriptive analysis. Prescriptive analytics can respond to the current demands of congestion and traffic flows, influencing the optimization of traffic flows by applying appropriate mathematical models and methods. Additionally, it is essential to observe how the speed of vehicles affects traffic flow, traffic density, and greenhouse gas emissions. Therefore, researchers have to choose the most relevant and optimal techniques or methods which will describe and solve potential problem.

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