Sustainable Intelligent Transportation Systems via Digital Twins: A Contextualized Survey

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***Abstract*—Intelligent transportation systems (ITS) have been attracting the attention of industry and academia alike for addressing issues raised by the 2030 agenda for sustainable development goals (SDG) approved by the United Nations. However, the diversity and dynamics of present-day transportation scenarios are already very complex, turning the management of ITS into a virtually impossible task for conventional traffic control centers. Recently, the digital twin (DT) paradigm has been presented as a modern architectural concept to tackle complex problems, such as the ones faced by ITS. This survey aims to provide a piece-wise approach to introducing DTs into sustainable ITS by addressing the following cornerstone aspects: i) Why should one consider DTs in ITS applications? ii) What can DTs represent from ITS' new physical environments? And iii) How can one use DTs to address SDG related to efficiency, safety, and ecology in ITS? Our methodological approach for surveying the literature addresses these questions by categorizing contributions and discriminating their ITS elements and agents against the SDG they addressed. Thus, in this survey, we provide an in-depth and contextualized overview of the challenges when approaching ITS through DTs, including scenarios involving autonomous and connected vehicles, ITS' infrastructure, and traffic agents' behavior. Moreover, we propose a functional reference framework for developing DTs of ITS. Finally, we also offer research challenges regarding standardization, connectivity infrastructure, security and privacy aspects, and business management for properly developing DTs for sustainable ITS.**

***Index Terms*—Digital twins, intelligent transportation systems, connected vehicles, sustainability.**

I. Introduction

The transport sector is among the most important in modern societies, attracting the attention of industry and academia to continue its constant evolution alongside government initiatives. In a simplified way, we can define transport systems in three fundamental components: the agents that intervene in the system, the roads through which the agents move, generally addressed as the road network, and the operation of the system, which defines the behavior of traffic and the control systems to manage it [1]. The 2030 Agenda for Sustainable Development, approved by the United Nations (UN), defined several sustainable development goals (SDGs) that include transport as a key enabling element [2]. Sustainable transport is related to the care of life and the well-being of people through the road safety approach (Safety - SDG 3.6), the reduction of polluting emissions (Ecology - SDG 3.9), the creation and use of sustainable infrastructures (Efficiency - SDG 9.1), and the conception of sustainable transport systems that allow access to transport in a safe, affordable way for all, improving road safety (Efficiency, Safety - SDG 11.2).

The smart city paradigm proposes a complex system that, using basic infrastructure and intelligent solutions, will allow a highly efficient functioning of humanistic society in several verticals [3]. Specifically, in the field of transportation, ITS allow for achieving high efficiency and reliability in transportation systems through the interaction between cyber systems and physical transport systems in the context of smart cities. With ITS, traditional transport systems' performance is currently being improved through new Internet of Things (IoT) solutions. They collect data and use it in transportation system modeling and data analysis for real-time control, optimization, verification, and validation [4]. However, ITS are a critical and distributed infrastructure system, making their management very complex in today's cities. Therefore, planning future ITS as a service-oriented architecture goes well beyond IoT deployment. Scalability, flexibility, and security are challenging issues for future ITS [5]. In addition, human factors will significantly impact interaction primitives and system outcomes [6].

A. Motivation

In recent years, DTs have gained popularity among academia and industry as a tool for dealing with complex systems. DTs represent a physical asset in a digitized representation, which mutually communicates, promotes, and co-evolves them through bidirectional interactions [7]. Through various digitization technologies, entities, behaviors, and relationships in the physical world are holistically digitized to create high-fidelity virtual models. Virtual models rely on real-world data to formulate their real-time parameters, conditions, and dynamics. This results in a more representative reflection of the corresponding physical entities, integrating big data analysis, artificial intelligence (AI), and machine learning (ML) techniques [8]. A bidirectional, reliable, and low latency communication channel allows the interaction of physical entities and processes with its DT, exploring the advantages of cloud computing and softwarization [9]. Although DTs are being applied to different sectors and activities, the lack of standard models for physical and virtual entities, data, connectivity, and standardized architecture for DT makes their adoption and implementation slow, and their reproducibility and reusability become almost impossible beyond the borders of a specific solution.

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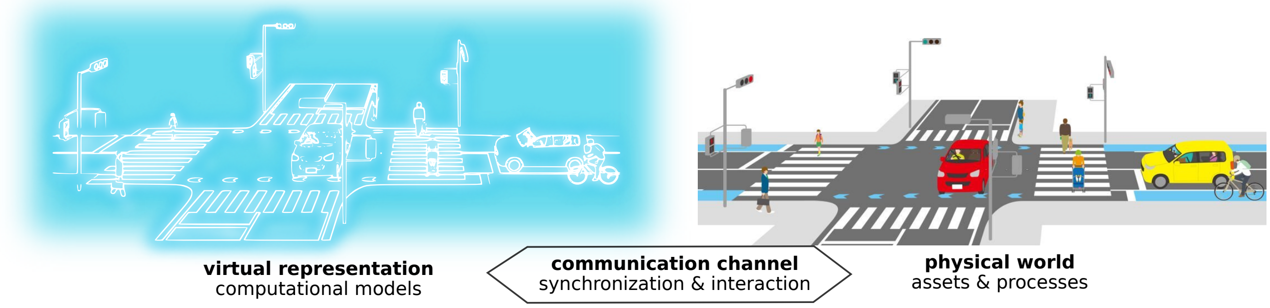


Fig. 1: The Digital Twin paradigm: illustration for ITS.

Different standardization bodies have already been trying to organize the understanding and the modeling of DT's intricate features. Their efforts focus separately on topics such as physical and virtual entities, data, connectivity, and service features [10]. On the other hand, a holistic approach, including an open-source initiative, is being pushed forward by the Digital Twin Consortium [1]. It emerged in 2020 as a conglomerate encompassing industry, government, and academia whose objective is accelerating the development, adoption, interoperability, and security of DTs and enabling technologies. The Consortium defined the DT as *"a virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity"* that allows transforming business models through understanding, optimal decision-making, and effective action, using real-time and historical data to represent the past and present and simulate predicted futures. The main functional blocks of a DT, namely the physical world, the virtual representation, and the communication channel, are illustrated for ITS in Fig. 1.

B. Contributions and Organization

Existing surveys addressing the DT field focus on characterizing DTs from modeling perspectives, architecture proposals, and the categories of services and applications most used in a field. Readers are referred to surveys that deal with foundation concepts of DTs [11]–[18]; industry verticals [19]–[22] and also in Industry 4.0 manufacturing models [23]; civil engineering [24]–[29]; agriculture [30]–[32]; energy [33]–[36]; healthcare [37], [38]; and, finally, to smart cities [39], [40]. Although DTs have been gaining popularity in transport system solutions, a survey that updates the state of the art of DTs for ITS is yet to be found in the literature. For instance, a recent comprehensive "survey of surveys" on milestones in autonomous driving and intelligent vehicles by L. Chen et al. [41] could only locate a single survey on DTs in that context, i.e., [42]. Thus, it is clear that there is a need for a comprehensive survey that collects and organizes the trends in using DTs as a transitioning element toward intelligent transportation solutions. The following points are the principal contributions of this article:

1) It gradually unveils the importance of DT technology by framing the recent advances in the UN's sustainability goals and identifying the early adopters and key areas of modern ITS that DTs will empower.
2) It presents a reference model that summarizes the lessons learned into a DT-ITS framework with its functional and non-functional requirements, and research directions that need contributions.

[1]https://www.digitaltwinconsortium.org

The methodology used is based on research questions that would outline the course of the survey, as well as the revision protocol to be applied. The survey aims to identify current trends in adopting DT throughout the vehicular transport ecosystem, identifying architectures and technologies that make these solutions more efficient than traditional approaches in the context of smart cities. Having this in mind, we posed the following research questions (RQ):

- RQ #1: *Why should one consider DTs in ITS applications?*
- RQ #2: *What can DTs represent from ITS' new physical environments?*
- RQ #3: *How can one use DTs to address SDG regarding efficiency, safety, and ecology in ITS?*

We surveyed relevant publications from 2018 to 2023 in the Scopus, Web of Science, and IEEE Xplore databases and complemented with other works from Google Scholar. We organized the selected papers and discussed them sequentially to provide answers to the RQs above. We consider ITS' twinned entities and sustainability goals on key areas empowered by DTs, providing a piecemeal approach to gradually laying solid foundations and motivations for readers to contribute with their research efforts toward sustainable DT-ITS.

The remainder of this work is organized as follows. Section II discusses the adoption of DT technology to address known problems in the design, operation, and management of transportation systems. Section III describes the research background and status of DTs as enablers of a new generation of intelligent transportation solutions. Section IV introduces a reference framework to accurately and timely develop DT-driven applications in transportation systems. Section V discusses challenges that require substantial research efforts and careful planning to enable sustainable DT-ITS. Finally, Section VI concludes this survey.

II. Precursors for DTs in ITS

DT-ITS are defined as the digital representation of the transportation system, including intelligent infrastructure, traffic participants, traffic behavior, and the surrounding environment. To achieve a fidelity representation, new advanced enabling technologies are employed for data collection, processing, privacy, and security, using accurate and real-time data collected. A key difference DTs can make for ITS is that the verisimilitude of their virtual models may allow for an early and even anticipated discovery of problems in transport systems. Thus, short-, medium- and long-term strategies can be outlined to support decision-making and achieve more robust ITS applications.

Even though DTs have marked a notable presence in academia, the industry has perceived the adoption of this technology to be slower, and this begs RQ #1 on the practical relevance of DTs for current and future ITS demands. This section presents contexts that may drive early adopters to see DTs as a graceful evolution pathway for legacy techniques in ITS instead of a disruption to current practices. Thus, RQ #1 is here addressed by focusing on i) sensing consolidation and scenario simulation; and ii) test systems using in-the-loop approaches.

A. Sensing Consolidation and Scenario Simulation

ITS are now an information-rich scenario with extensive sensing coverage of roads and connected vehicles so that human drivers can be better informed about dangerous traffic and road conditions, adverse weather conditions, and traffic congestion. DTs may become a framework to enhance current applications to meet UN sustainability goals. For instance, real-time and detailed road and traffic information allows road authorities to exercise more precise traffic control, such as lane-level traffic control and ramp merge, to improve safety and traffic efficiency. Using IoT sensing devices, combined with digital maps and road-building information models [43], DT systems can be used to consolidate road traffic systems and road health and asset-monitoring systems [44].

Nevertheless, the analysis of all the possible situations in a transport scenario involving several agents, vehicles, and non-vehicles is diverse, making their evaluation very difficult from the current model of traffic control centers. Presently, simulators are used as flexible and efficient tools for ITS for predicting scenarios, but it is well known that they need proper traffic representation. The strong coupling between the vehicle, the environment, and other agents is oversimplified. Moreover, the amount of computational resources demanded for modest scenarios is presently a bottleneck for ITS. Liu et al. [45] proposed a new pipeline to create artificial scenes and generate virtual datasets based on parallel vision theory with low modeling time and high-quality labeling.

DTs have been proposed in the operational design domain (ODD) analysis of such systems for security validation in autonomous systems. Sun et al. [46] proposed an architecture design to improve the ODD of autonomous vehicle systems. In this way, it is possible to capture the operational constraints of the generic components of the road environment, such as road type, traffic volume, and weather conditions. Determining which ODD to use for an automatic driving system function can be compared to finding the driving environment condition boundaries that satisfy particular evaluation criteria based on potential scenarios, allowing more realistic environment models to be created. To represent structural, physical, and behavioral information in a virtual environment, Yu et al. [47] developed a game engine-based DT system that provides physics and graphics engines for 3D modeling, image rendering, and physical simulation.

The physics-based models derived were well-behaved to solve physical processes and systems for a long time. However, many complex systems escape such quantitative analytical descriptions or the correct selection of input variables [48]. The high computational demand required to solve such models makes them unsuitable in most cases for real-time ITS applications. Thanks to a large amount of data and the rapid development of AI/ML solutions, data-driven models are presented as an excellent complement to physics-based models, mainly in supporting optimization and simulation tasks. This is why a balanced perspective of both approaches is needed for complex transportation systems. Combining both represents the most successful way to construct DT-based models for ITS. Compared with conventional transportation simulation, DTs have the potential to improve precision, ease of implementation, and digitization of procedures [49].

The predictive power of the so-called data-driven models, like AI/ML solutions, depends on historical data for training. Thus, it is severely limited by the number of (rare) events that have occurred before. For sustainability goals related to safety, predicting rare events is crucial. Some agent-based modeling approaches work best in providing plausible scenarios for situations that have not occurred before. However, they still need to be more effective in their predictive power [50]. Recent trends in symbiotic simulation studies emphasize its combination with machine learning. Despite its success and usefulness, very few works focus on applying a hybrid system of this type in microscopic traffic simulation. The application of ML models in microscopic traffic simulation is limited to predictive analytics or offline simulation-based prescriptive analytics. Therefore, DTs enabled by data-driven models help to dynamically update the parameters of the deep learning model for real-time traffic simulation [51].

A pay-as-you-go approach can be adopted economically from legacy systems to DT-oriented ITS. Digital twins will become increasingly interoperable. Early DT designs focused on individual domains. New DT interoperability standards will facilitate the composition of larger-scale DT assemblies from a library of designs. Standards will accelerate efforts to reuse DT components across multiple designs in ITS. Moreover, new wireless communication technologies, especially vehicle-to-everything (V2X) communications, will play a decisive role in DT interoperability. V2X is already crucial in the modern ITS test system, so we argue this is an important precursor for DT adoption.

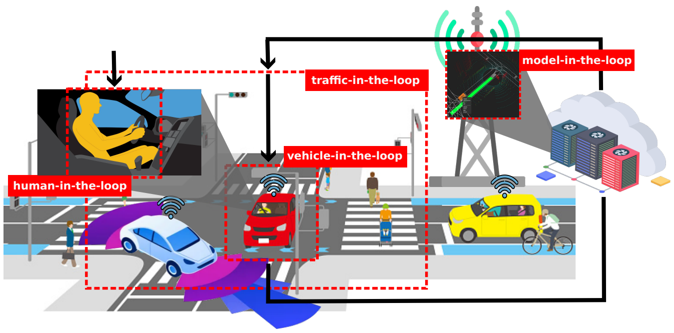


Fig. 2: Current in-the-loop ITS' test systems and simulations involving agents, communications, and intelligent infrastructures

B. Test Systems using In-the-loop Approaches

To support the V2X road test, Han et al. [52] designed a live transmission system on the road, which simulates the information of non-V2X-equipped road vehicles through the V2X array node. A road sensing system was used to collect information from the vehicle data to be used in procedures for reconstructing scenarios based on V2X and extracting road scenarios. Playback of critical scenes could be considered a type of DT test; the reliability of the test results largely depends on the validity of the test scenario. A critical scenario extraction method is proposed to meet the test requirement. Like the live broadcasting function, for the playback function, the test scenario is expressed by a C-V2X message and disseminated via node array to simulate V2X application scenarios.

The DT-oriented test system can consolidate simulation efforts and thus has been increasingly used to meet vehicle navigation and security requirements [53], in many cases using simulation loop schemes such as model-in-the-loop (MIL), scenario-in-the-loop (ScIL) [54], [55], vehicle-in-the-loop (VIL) [56], and human-in-the-loop (HITL) testing [57], as shown in Fig. 2. Note that in-the-loop approaches involve the physical world, assets and processes, and computational models while using communication channels for interaction. In other words, it can be seen as a prototype that fits the DT in Fig. 1.

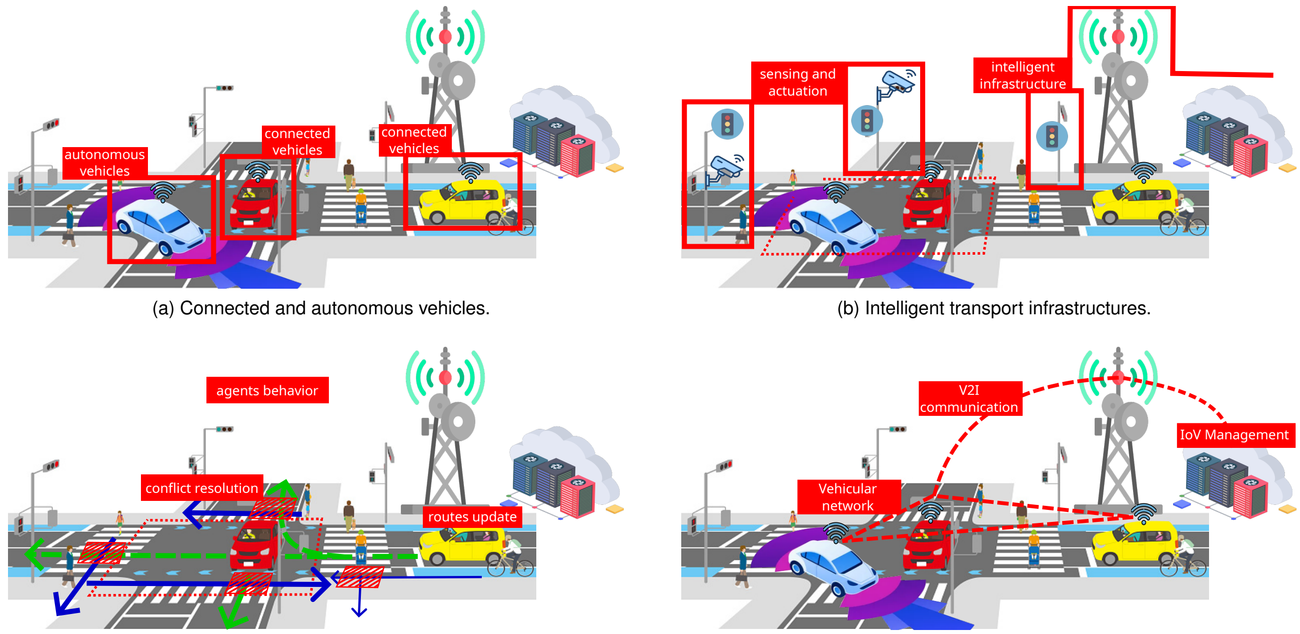
To enhance the realism of the simulation scene, many simulation platforms use game engines to render a fairly realistic 3D scene. However, rendering this way is expensive and resource-intensive, and the data obtained from some types of virtual sensors is very different from the real scene. This problem was addressed in [58], which proposed an injection simulation framework capable of customizing roads and traffic scenarios to achieve SIL and vehicle-in-the-loop (VIL) tests for different functional modules. The scenario generation module is based on the real road's high-precision semantic map (OSM map) and the simulator SUMO to define the test scenario. The framework could inject data into the fusion and perception layers by providing accurate simulated traffic information and LiDAR data generated in real time. Besides, Balázs et al. [55] presented a novel simulation concept for ITS called scenario-in-the-loop (SciL) testing. The SciL concept is the extended version of the traffic-in-the-loop (TiL) simulation method, created to test autonomous driving functions in critical collision situations using real targets.

A DT-based automated driving test method was proposed by Shoukat et al. [59]. Vehicles collect and release driving information through V2X communication, execute the data fusion, and upload the information to the simulation platform. With a similar approach, a mixed reality simulation environment was introduced by Szalai et al. [60] that integrates a real test vehicle into a virtual environment. Thus, the behavior of a real vehicle connected to the simulation can be tested in real time with a VIL approach. With VIL, the real movement of the test vehicle allows testing the vehicular functions at the decision and movement planning level, even at low costs for automotive manufacturers and researchers. Shuguang et al. [61] also proposed a novel VIL verification method based on vehicle-road-cloud collaboration. In the solution, the autonomous driving obstacle avoidance algorithm is verified in the highway scene using a mixed scene. Another motivation for using DT in transforming future ITS applications has to do with vehicular and pedestrian mobility. Understanding the global behavior of urban transportation allows the construction of projections for decision-making stakeholders, i.e., traffic management entities and public policy formulators. The classic features of human mobility, such as daily variation, have already been addressed by DTs to mitigate restrictions imposed on both mobility and agent rationality when classic mobility models are generated [62].

By revisiting RQ #1 ("*Why should one consider DTs in ITS applications?*"), we can conclude that DTs are a pathway for fragmented assets like sensing, computation, and communication so that simulation and testing techniques can be appropriately consolidated into a single framework for designing and operating future transportation systems. The rise of domain-specific languages (DSL) for modeling virtual entities has significantly promoted the adoption of DTs, which are a powerful tool for the agile development and evaluation of ITS applications. This evolution in design methodology has made it possible to analyze all possible scenarios swiftly and manage transport systems more efficiently. This way, DTs can help meet the most critical goals for raising sustainable transport systems.

III. Key Areas Empowered by DT in ITS

This section introduces a comprehensive survey on DT-ITS to answer RQ #2, considering now the main actors of the future transport ecosystems. From the selected papers, the ITS new physical environments benefiting from DTs are as follows: Connected and autonomous vehicles, intelligent transport infrastructures, ITS agent behavior, and the Internet of vehicles. The context for these key application areas is illustrated in Fig. 3, which expands the perspective and concepts brought in Fig. 1 for the physical world. To address what can be represented by DTs in such areas, the twined elements and the sustainable goals spanned by the surveyed papers are also presented in comparative charts embedded in Tables I, II, and III.



(a) Connected and autonomous vehicles.

(b) Intelligent transport infrastructures.

(c) ITS' agents behavior.

(d) Internet of Vehicles.

Fig. 3: Key application areas empowered by DT in ITS.

A. Connected and Autonomous Vehicles

New vehicle concepts began to emerge in parallel with other branches of technology, making connected cars a reality today in hybrid scenarios like the one illustrated in Fig. 3a with connected and autonomous vehicles. Implementing advanced driver assistance systems (ADAS) plays an essential role in the safety of the entire traffic system. ADAS systems improve the vehicle's safety for its occupants and other road users. Today, the most common assistance only suggests drivers take the best actions. However, solutions capable of taking control of the vehicle to avoid an accident or minimize its consequences are becoming more common. DT-enabled solutions can be applied for ADAS systems to reach more efficient levels in the assistance provided to drivers.

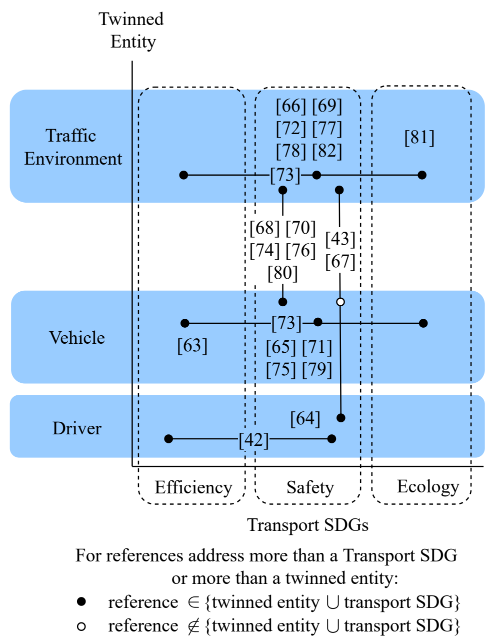
Wang et al. [66] proposed a framework that uses DT to provide drivers with recommended speed information through an onboard interface, allowing more efficient vehicle control. A DT of the traffic scenario, including the physical road infrastructure and the transport agents, was developed in the cloud. Models of a ramp merging use case roll interacted with the physical world through vehicle-to-cloud communication. This work was extended by Liao et al. [43], adding the modeling of the human behavior of the driver. With the support of this DT, a reduction in average speed variation was obtained, which shows that the cooperative fusion approach of the sensor system used is safer than in the reference scenarios without driver assistance. In addition, reducing polluting emissions and fuel consumption was verified, complying with lines of action for creating sustainable transportation.

In ADAS systems, adaptive cruise control (ACC) adjusts the longitudinal speed of vehicles to maintain a safe distance from the vehicle in front, increasing safety, enhancing driving comfort, and reducing fuel consumption. However, the functionalities of ACC limit the following drivers' styles, resulting in a lack of confidence in ACC systems and limiting their adoption. A method supported by DTs, which learns from drivers' natural vehicle tracking behavior, was proposed by Wang et al. [72]. The model generates a vehicle acceleration profile that adapts to the driver's preferences, resulting in a personalized ACC system contributing to collision avoidance. HITL experiments on a driving simulator validated the solution. Techniques that use DTs to validate HITL teleoperation in transportation systems were proposed by Kuru [69]. A case study of personalized adaptive cruise control is also used by Wang et al. [70] to evaluate the potentialities of the game engines platform in creating complete models of connected and autonomous vehicles (CAV).

Although ADAS are today a reality in solutions from several vehicle manufacturers, these systems suffer from unnecessary warnings or propose strange actions for drivers, especially in complex traffic scenarios. Moreover, false positives cause driver distraction and confusion, posing additional safety concerns and undermining such systems' credibility. Mindful of this problem, Tang and Jiang [67] proposed a solution that infers the driver's perception through gaze tracking to improve the driving assistance system. Based on historical observations, the proposal mimics the driver's prediction of unobservable agents in the driving environment, warning the driver only if an agent represents an unperceived imminent collision threat.

Only real-time information from the target vehicle can be perceived when ADAS solutions are based solely on object detection sensors. The last can result in historical data being unable to predict vehicle behavior due to the short detection time horizon. To improve the sensor fusion process used in ADAS systems, a new sensor fusion methodology that integrates images obtained by cameras and the knowledge learned by DTs executed from the cloud was introduced by Liu

TABLE I: Summary of main research on DT-empowered CAV.



Ref.	Year	Contribution
[63]	2018	An AI-based solution to precisely and perfectly measure the traffic situation in real-time and the driver intention to improve traffic efficiency
[64]	2018	A framework in which behavioral models of drivers are shared among connected cars to predict potential future actions of neighboring vehicles.
[65]	2019	A solution to predict driving patterns, typical routes, and driver habits, designed to augment customization of smart cars and user driving experience.
[66]	2020	Recommendation of speed information through an onboard interface for road merge scenarios
[67]	2020	A driving assist system that reduces unnecessary warnings by taking into account the driver's perception of the driving environment
[68]	2020	A sensor fusion methodology, integrating camera image and DT knowledge from the cloud to help intelligent vehicles make better decisions
[69]	2021	Human-on-the-loop haptic teleoperation for human control of remote vehicles collaboration
[70]	2021	A DT simulation architecture based on Unity game engine that integrated analytic external tools
[71]	2021	A framework for vehicular DTs that facilitate the data collection, data processing, and analytic phases.
[43]	2022	Recommendation of speed information, an extension from [66]
[72]	2022	Learn from individual driver's naturalistic car-following behavior and outputs a desired acceleration profile that suits the driver's preference
[73]	2022	Extension from [68]
[74]	2022	A motion planning scheme to handle the crash mitigation in scenarios with unavoidable collision
[75]	2022	Evaluation of driving risks according to the stability and trajectory deviation of the vehicles
[76]	2022	Moving vehicles tracking and recognition algorithm by video to predict the vehicle movement integrating VR and DT
[77]	2022	A traffic accident prevention and prediction system established based in IA through data provided by a DT
[78]	2022	A co-pilot intelligent decision safety system to achieve better supervision of autonomous driving systems with online cloud learning
[79]	2022	A consensus motion control algorithm to generate the vehicle speed trajectories in non-signalized intersections
[80]	2022	An efficient collaborative autonomous driving scheme to minimize the cost for completing the driving process.
[42]	2022	A study on driver DTs and its key enabling aspects.
[81]	2022	A virtual reality enabled by DT for on-road emission monitoring for developing and evaluating eco-driving strategies.
[82]	2023	A shared controller for safe and human-friendly cooperative driving based on predictive risk assessment.

et al. [68]. The authors predicted the lane change behavior of vehicles around the ego vehicle to validate the solution. HITL simulations occur in an intelligent vehicle simulation environment based on a game engine. In addition, an information visualization method based on augmented reality (AR) was adopted as part of the DT to display the predicted information found on the cloud. The work was extended in [73], where a multi-layer perceptron algorithm is proposed with modified lane change prediction approaches. Simulation results revealed that the proposed model could significantly improve highway driving performance regarding safety, comfort, and ecological sustainability.

In autonomous vehicle scenarios, DT approaches regarding driving strategies in dynamic environments have been studied to guarantee the safety of the entire transport system. Driving is a social activity that involves endless interactions with other agents on the road, so locating these agents and predicting their possible future actions in the environment is essential for the safety of all agents. A crash mitigation algorithm that directly incorporates a generalized crash severity index model for vehicle-to-vehicle collisions of multiple impact patterns was proposed by Li et al. [74]. The algorithm tries to adapt the vehicle position before the collision to minimize the impact's severity. The algorithm was tested in a real-vehicle intersection crossing scenario and validated through DT simulations. Wang et al. [75] designed a road driving safety analysis based on extracting vehicle movement information using drone images. In this way, scenes of vehicle movement in the virtual world and analysis of vehicle driving risks can be built. The results showed that driving risk analysis based on the DT method could more accurately monitor various status indicators in the vehicle movement process.

Yang et al. [83] proposed a DT method for executing multi-vehicle experiments, using a combination of physical and virtual vehicles to perform coordination tasks. For this, a sand table testbed was developed with its DT in the cloud, where devices enable human-machine interaction, all visualized in a mixed-reality solution. The study explores the concept of cloud vehicles, allowing the control of vehicles in the first person from the driving simulator. Another study on the prediction of driving states of vehicles to enhance the accuracy of traffic safety was conducted by Lv et al. [76]. In this solution, the vehicle simulator and the virtual environment system are built based on vehicle dynamics through virtual reality technology. A DT of the vehicle was built based on various sensors and a Gaussian process algorithm.

DT solutions have widely addressed the safety of transport agents. A method of predicting and preventing traffic accidents based on DTs and artificial intelligence to guarantee the safety of drivers and pedestrians was proposed by Lv et al. [77]. A neural network-based object tracking algorithm is applied to DTs for video analysis for traffic accident detection. The solution used computer-aided design (CAD) software to model transportation drawings on 3D models. Intelligent security systems have also been proposed by Lu et al. [78] to create virtual entities that act as co-pilot systems. Solutions of this type are designed to make the real-time evaluation, response, and recording of failures possible. With digital co-pilot systems, it is possible to provide analysis and feedback and record incorrect decisions, which helps in the self-adaptation of the system. Other design and implementation methodologies of DTs for safety validation and automotive safety have been proposed in [65], [71].

Cooperative driving at non-signalized intersections has been a popular topic in intelligent transportation systems research. In these new intersections, the driving strategies adopted by AV represent a crucial point for the safety of the agents interacting in the conflict zone of the intersection. Wang et al. [79] proposed a DT architecture for AV and human-powered connected vehicles where the software modules and their algorithms are developed in the digital world. The vehicle's DTs are displayed to the driver using AR, enabling them to engage in cooperative driving behavior with other CAVs at non-signalized intersections. The simulations were performed using game engines, where HITL simulations are conducted with the guidance provided by AR. With the development of a DT-enabled architecture to facilitate collaborative and distributed autonomous driving, Hui et al. [80] introduced the concept of collaboration-as-a-service, designing a DT for each AV. With this architecture, a collaboration mechanism based on auction games was developed to decide the lead DT and the tail DT in each driving group. In addition, DTs can replace AVs to make collaborative driving decisions in virtual networks in advance, where frequent information exchanges between AVs in physical networks can be avoided. Kumar et al. [63] also deduced the driver intention from collecting various data and a virtual vehicle model in the cloud.

Accurately predicting a driver's behavior remains a challenging problem in road safety. Cheng et al. [64] proposed a framework to address this problem, in which driver behavioral twins are shared between connected cars to predict the potential actions of neighboring vehicles, thus improving driving safety. The behavior of a vehicle is determined by its driving context, which includes road conditions, nearby agents, infrastructure, and even the driver's state of mind. However, the driving context perceived by the human driver may differ from that perceived by the vehicle, making it even more challenging to predict driver behavior. The proposal collects historical driving data to build a driver behavior profile model for each vehicle, which can be used to predict its future behavior in different driving contexts. A virtual platform was developed in a game engine platform to eliminate the effect of unrelated factors.

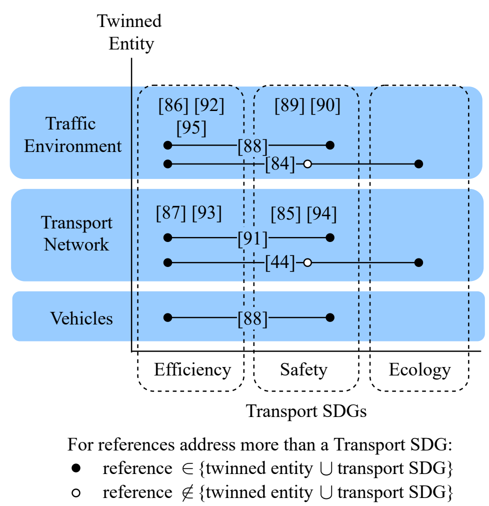
In this regard, it is essential to build a unified human-centered intelligent driving system that considers the proactivity and sensitivity of the human driver. The digitization of the human driver must be able to model habits, personality traits, and decision patterns, which are crucial characteristics that define a human driver. Hu et al. [42] introduced the first driver DT model. The proposal attempts to bridge the gap between existing automated driving systems and fully digitized ones and assist in developing a complete cyber-physical human driving system. With the driver DT model, it is possible to monitor the physiological state to help prevent accidents due to distraction or sudden illness and improve driving safety. Key features of this driver DT include multimode state fusion, custom modeling, and time variation. This system provides the autonomous vehicle with improved personalization, allowing it to drive like a human being.

B. *Intelligent Transport Infrastructures*

Sustainable urban road planning should strive to meet current and future traffic-related demands and achieve financial, environmental, and social benefits, a complex and interdisciplinary subject. Intelligent and adaptive transportation infrastructures, as shown in Fig. 3b, are one of the bases for achieving truly sustainable transportation solutions. A toolchain for visualizing detailed road traffic data from multimodal sensors was proposed by Neuschmied et al. [84]. The approach was based on an audiovisual analysis of the traffic scenario. It provides a holistic view, including tracking and counting traffic participants, detecting potentially dangerous situations, and analysis of sources of noise pollution. A spatial data management system extracts information with a geographic information system (GIS), and a web-based viewer allows interactive visualization in the context of a high-definition DT of the traffic environment. Likewise, Jiang [44] proposed a DT-based urban road planning approach employing multi-criteria decision-making and GIS. The urban planning framework considers land use, traffic congestion, driving route selection habits, air quality, and noise. The approach could obtain functional, economical, and environmentally friendly urban road planning. Unlike previous studies, the proposal considers the construction of new roads and includes the analysis of existing old roads. Another DT system based on GIS technology was proposed by Wang et al. [85] to provide a new way of surveying and mapping in the transportation industry and transform the horizontal and vertical design of highways into computer-aided design. Also, Guo et al. [86] proposed a 3D digital system based on roadside sensing of a cooperative vehicle infrastructure system, allowing the visualization of road traffic in real time.

DT systems for road traffic, road health, and asset monitoring can be built using IoT devices combined with digital maps and road construction information models. Mao et al. [88] offer a future roadmap for developing IoT systems to construct DTs of intelligent roads. The CitySim database, formed from the vehicular trajectories obtained through videos recorded by drones, was created by Zheng et al. [89] to facilitate the research and development of security-based applications. CitySim facilitates research towards DT applications by providing relevant assets such as 3D base maps of

TABLE II: Summary of main research on DT-empowered intelligent transport infrastructures.



Ref.	Year	Main Contribution
[85]	2021	An analysis of the modeling process of the road traffic DT system to verify the feasibility of the practical application using geographic information.
[86]	2021	A platform for real-time roadside sensing that uses the Robot Operating System to create 3D virtual road traffic environments.
[87]	2021	A DT platform for the digital twinning of roads.
[84]	2022	A toolchain for visualizing detailed road traffic data from multimodal sensors (cameras, LIDAR, microphones, and geographic information).
[44]	2022	A sustainable urban road planning approach that uses data from multiple sources in the physical world to assist new road construction and old road widening.
[88]	2022	An IoT-based system for smart roads to enable the construction of a DT of the traffic and road system and various applications
[89]	2022	A video-based trajectory dataset (CitySim) generated from drone recordings, intended to facilitate safety research by providing traffic trajectories.
[90]	2022	A drone sensing scheme with machine vision methods used to extract traffic flow micro-data including driving trajectories and vehicle speeds.
[91]	2022	A model-free method by using the macroscopic road network images and stacking multiple Conv-LSTM layers to form an encoding-decoding structure to predict spatiotemporal congestion caused by accidents.
[92]	2022	Develop a framework for a DT smart freeway.
[93]	2022	A scheme to integrate third-party controllers to dynamically generate and calibrate traffic flow in simulation scenarios in SUMO.
[94]	2022	A framework for DT in intelligent intersection modeling to consolidate real-time monitoring, control, and management of road intersections.
[95]	2023	A novel Blockchain-based smart parking scheme in DT empowered VSNs with privacy protection.

recording locations and signal times. CitySim's trajectories were generated through a five-step procedure that ensured trajectory accuracy. In addition to base maps, CitySim provides signal timing data related to signalized intersections. The calibrated traffic patterns and 3D base maps are used in a collaborative simulation that integrates microscopic traffic and driving simulations.

A DT system for traffic flow perception and risk identification has also been proposed to improve ITS infrastructure. A road and traffic trajectory model for highway entrances and exits was proposed by Liu et al. [90]. The model is also built based on drone information and computer vision methods to extract microdata of traffic flow, including driving trajectories and vehicle speeds. Moreover, Ji et al. [91] designed the DT of a road network to observe the traffic operation from a macro perspective. The information obtained was used for the spatiotemporal prediction of congestion induced by accidents, acting to mitigate the adverse effects while responding to traffic accidents promptly. Based on the simulation and identification of such conflicts, traffic scenes can be simulated to support the decision-making of traffic management centers.

Taking advantage of the DT in the almost real-time interaction between physical and cyber entities, Fu et al. [92] proposed a framework for the DT of an intelligent highway. The solution's efficiency was evaluated through a case study based on simulations with SUMO, mapping the driver-vehicle-roads set in a cybernetic system. The simulator allows the creation of microscopic models to model individual driving behaviors and the complex interactions between adjacent vehicles and mesoscopic models that focus on the heterogeneity of driver and vehicle behaviors in probabilistic terms. Also, to improve the monitoring of road infrastructures, Marai et al. [87] proposed deploying a system on roads that creates a DT of the road by constantly sending data to the Edge.

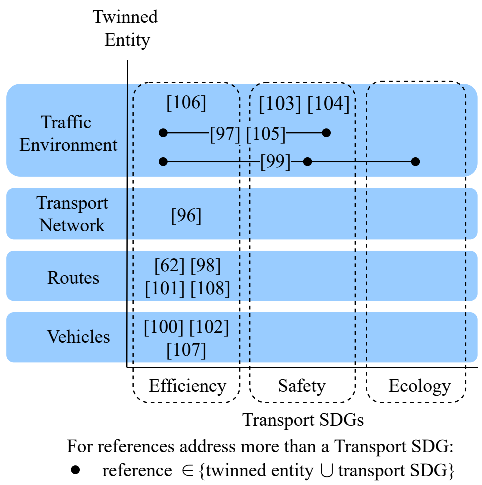
C. Agents' Behavior in ITS

DT-enabled solutions have been recently proposed to meet the challenges of urban mobility that directly influence the operation and management of ITS, improving route selection or conflict resolution at intersections as shown in Fig. 3c. Chen et al. [96] developed a mobility network based on DT to extract accurate profiles of bus stations. The data obtained was used in analytical operations to perform transport management autonomously. A co-simulation framework that combines vehicle and traffic simulation was proposed by Shi et al. [97]. The framework employs a deep learning algorithm with video data to complete the input–model–output full-chain autonomous driving co-simulation testing method system.

Fan et al. [62] proposed a mobility DT to predict users' movements based on the current urban state. This solution predicted trajectories that respond to different conditions by filtering or augmenting the historical database concerning specific simulation tasks. The system encoded the daily variation of human mobility at the metropolitan level, automatically extracting the mobility trends of the city and then predicting long-term and long-distance movements at an approximate level. The coarse forecasts are then resolved at a satisfactory granularity level through a probabilistic path recovery method, which offloads most heavy calculations to the offline phase. Furthermore, Wang et al. [104] developed a mobility DT defined as an edge cloud-based framework powered by artificial intelligence to serve mobility services. The solution consists of large blocks in physical space (i.e., human, vehicle, and traffic) and their associated DTs in digital space. The proposal was evaluated through a case study of a personalized adaptive cruise control system. Through a cloud-based ADAS, the vehicle DT provides visual orientation and control commands towards the vehicles connected in a HITL simulation.

Obtaining real-time information on the actual traffic flow is another fundamental aspect of ITS. Hu et al. [105] mod-

TABLE III: Summary of main research on DT for agents behavior in ITS.



Ref. Year	Main Contribution
[98] 2019	Introduce a modeling scheme for the mobility based on a time series behaviors of EVs to evaluate the charging algorithm and pile arrangement policy.
[96] 2021	A DT mobility profiling framework to learn node profiles on a mobility network, capturing the complex spatiotemporal features in traffic scenario.
[99] 2021	A connected-corridor application for dynamic, real-time, data-driven traffic simulation models to dynamically attain high-fidelity vehicle record information.
[100] 2021	A vehicle path planning scheme based on virtual vehicle density, where the cloud gives different rewards to different road sections to reduce latency.
[101] 2021	A simulation model for bus routes, to modeling processes of several passenger services.
[102] 2021	A model to construct the bus operation chain, giving feedback of the whole process of demand-responsive transit service.
[103] 2021	A intelligent vehicle behavior analysis framework that uses deep learning and Kalman filtering to track vehicles.
[97] 2022	A data-driven co-simulation framework for vehicle dynamics, sensors, and traffic environment modeling, using SUMO and CARLA.
[62] 2022	A two-stage human mobility predictor that extracts citywide mobility trends as crowd contexts and predicts long-term and long-distance movements.
[104] 2022	A mobility DT defined as an AI-based data-driven cloud–edge–device framework for mobility services.
[105] 2022	A DT-assisted real-time traffic data prediction method by analyzing the traffic flow and velocity data monitored by IoV sensors and transmitted through 5G.
[106] 2022	Technical methods of DT for urban transportation process integration: creating architecture, analyzing system function, and digital technology integration.
[107] 2022	An anticipatory algorithm for a real-world dial-a-ride problem that uses a DT framework for analysis and optimization of the algorithm.
[108] 2023	Uses a genetic algorithm for obtaining an in-depth understanding of the bus dynamics.

eled the traffic flow for creating a DT for real-time traffic prediction according to speed and traffic flow data monitored by distributed traffic cameras. Collecting data in large cities to understand the transport impacts of transport services has been one of the main tasks of transport researchers and engineers. By analyzing traffic data supported by DTs, traffic managers can optimize traffic scheduling and formulate transportation policies. The DT of the transportation system of a medium-sized city was proposed by Khalil et al. [109], considering several modes of transportation, such as public transportation, shared transportation services, and private vehicles. This DT evidenced new opportunities, creating an environment for policy learning with reinforcement learning using open data sources and agent-based simulations. A DT was also proposed by Abhilasha et al. [99], which leverages real-time data streams to model the current traffic state and provide dynamic feedback on traffic. In this case, the robustness and feasibility of the proposed DT architecture were demonstrated using a testbed. The testbed allowed the injection of control signals in real-time and volume data flows in the traffic simulation model for the execution of the models and the evaluation of the dynamic performance metrics.

Choosing the best urban traffic route, shortening travel time, and alleviating traffic pressure are other critical aspects of transportation systems. Thus, a route planning scheme DT-enabled was proposed by Hui et al. [100] to facilitate traffic management, considering the personalized users' demands. In the solution, DT vehicles interact with each other from the cloud to make route planning decisions in advance. According to the traffic density of the different road sections, rewards were established to encourage the vehicles to obey the scheduling instructions. Moreover, Wang et al. [106] presented an urban transportation project where the technical methods of the DT of the urban transport process are addressed, making the architecture, analysis of the system function, and integration of digital technology available for such projects. As a case study, the best path system design method was provided by building the frame structure. The field detection module was used to perform the virtual driving test and the detection data processing to ensure route selection accuracy.

For the electric vehicle (EV) industry, the driving experience is highly dependent on the availability and accessibility of vehicle charging infrastructure. As the number of charging piles increases, carefully designed arrangements of resources and efficient infrastructure utilization are essential for this industry's future development. Zhang et al. [98] proposed a DT by modeling the mobility based on the behaviors of a time series of EVs to evaluate the charging algorithm and the grid layout policy. The DT EV behavior and route choice are dynamically simulated based on time-varying driving operations, travel intent, and charging plan in a full-scale simulated charging scenario. With a DT mobility model, the EV behaviors and interactions were simulated to study the efficiency and quality of charging on both the supply and demand sides. Furthermore, the performance of different proposed charging scheduling algorithms and charging stack deployments was evaluated by simulating traffic and charging on a large scale of inter-connected EVs.

Several solutions powered by DTs have been proposed for the public transport sector to improve route planning. Creating DTs of real bus routes requires the development of suitable approaches for modeling individual processes. Zhukov and Moroz [101] proposed a simulation model of bus routes aiming to clarify the approaches to model the processes of getting on and off passengers, the parking time of vehicles at a stopping point for passenger exchange, and the waiting time of passengers to board the vehicle. To address demand-sensitive traffic (DRT) problems, Deng et al. [102], with the support of DT, performed the representation of a DTR system to explore essential details of this system. The proposal describes the bus transit process between two stations, suggesting that DT-based solutions contribute effectively to the construction of the travel chain for the traveler.

In trajectory calculus problems, the performance of the different anticipatory algorithms when the dynamism in the system increases is also a fundamental question. Ritzinger et al. [107] proposed a framework based on DTs, allowing sophisticated algorithm performance analysis and re-optimization strategies. Special attention was given to the communication and data synchronization between the real environment and decision-makers, which is vital when dealing with dynamic vehicle routing problems. The DT-based module implements a state machine where all possible vehicle states and transitions are defined, and computational experiments are performed on a set of test instances generated based on information and data from the real environment. Similarly, Li et al. [103] proposed a behavior analysis framework for intelligent vehicles based on a DT that supports the detection of abnormal behavior. In the solution, the tracked vehicle was assigned to a DT virtual scene, and the behavior of each vehicle was tested according to custom detection conditions configured in the scene. The solution in [103] was an innovative and efficient scene-building toolchain and production process, integrating high-definition mapping, data collection, photogrammetry, and process generation technology.

D. Internet of Vehicles

The Internet of Vehicles (IoV) leverages advancements in sensing and communication to build an environment in which vehicles are conceived as (i) powerful multi-sensor platforms; (ii) embedded computational features; and (iii) elements capable of communicating with other vehicles and road infrastructure as shown in Fig. 3d. With the potential to deploy compute-intensive applications, edge computing is combined with IoV powered by DTs to enhance intelligent transportation capabilities. Furthermore, the need for in-vehicle computing resources can be supplemented by upgrading vehicle DTs and offloading services to edge computing devices.

Xu et al. [110] implemented a multi-user download system where the QoS is reflected through the services' response time. The approach applied a service offload method with deep reinforcement learning for IoV powered by a DT. With this method, performing comparative experiments with real-world service data is feasible to assess the efficiency and adaptability of service offloading. Xu et al. [111] also applied a DT in an ITS to simulate the offloading strategies, building a virtual representation of the system that examines the states of the roadside units. Zhang et al. [112] proposed a new vehicular edge computing network to create an edge management framework that improves multi-agent learning efficiency through DT technology while improving replicability performance between virtual and physical networks through a learning approach. A distributed multi-agent learning scheme minimizes the download cost of vehicular tasks under strict delay constraints and dynamically adjusts the state mapping mode of the DT network.

To meet ultra-low network latency demands of in-vehicle internet applications, IoV enables edge devices to share their communication, computing, and storage resources through intelligent edge cooperation. However, efficiently allocating such resources using machine learning techniques and artificial intelligence requires a large amount of training data and high computing power that is impossible to achieve in a resource-constrained onboard unit or a roadside unit. Liu et al. [113] proposed a DT-enabled intelligent edge cooperation scheme, enabling optimal resource allocation and intelligent edge cooperation. The proposal aims to minimize the delay to meet the requirements of time-sensitive applications in ITS. A detailed analysis of the computational and communication resources between the physical world and the virtual space was carried out by introducing the DT technology. Through this DT, network resources are managed and allocated from a global perspective, which promotes collaboration between edge servers and improves the utilization of idle system resources effectively.

A DT-powered framework designed for IoV, focused on vehicular task offloading functions, was also proposed by Yuan et al. [114]. The DT of the network devices is mapped in real-time to represent latency states and power consumption. Since vehicular networks' latency and power consumption come from wireless communication and computing offloading, a wireless communication model was developed to optimize offloading decisions and thus minimize latency and power consumption. The solution was implemented in an IoV assisted by MEC to improve the quality of communications and guarantee QoS. Lastly, Liu et al. [115] proposed a DT transport system based on virtual reality for the IoV. In the solution, the basis of the vehicle in the simulation system is the traffic flow information collected in the real traffic scene. The objective was focused on the collaborative control of vehicles at traffic intersections based on V2X communication to perform collaborative decision-making of multiple vehicles and guarantee vehicle safety.

In heterogeneous vehicular networks (HetVNets), base stations can exploit the massive amounts of data vehicles collect to complete federated learning tasks. Hui et al. [116] proposed a scheme enabled by DTs for multitasking federated learning in HetVNets. For this, the training capabilities of the base station are analyzed, considering the available training data, the declared price, and the training experience. The task requesters and the base stations create their DTs in the cloud, where a game-based scheme attempts to achieve efficient matching between the requesters and the base stations in the DT networks. Also, in HetNets, optimizing the connection throughout the vehicle journey between the vehicle and its DT is challenging due to the uneven distribution of vehicles in the networks and the dynamics of heterogeneous wireless links. To address this problem, a learning-based heterogeneous network selection scheme in DT-empowered IoV was proposed by Zheng et al. [117]. The proposal jointly considers the dynamics of wireless conditions, vehicles' mobility, and heterogeneous access links' characteristics. As a result, vehicles can reuse the knowledge they have learned from previous tasks to solve new tasks faster or use better solutions. New vehicles incorporated into the network can also use the experience of expert vehicles to implement their knowledge system rapidly.

E. Discussion: A Context Analysis

By revisiting RQ #2 ("*What can DTs represent from ITS' new physical environments?*"), we conclude that DTs can represent almost all the elements of the ITS ecosystem, including autonomous and connected vehicles, transport infrastructures, and behavior of ITS agents, boosting ITS applications closely related to the fulfillment of the SDGs. In numbers, from the total papers evaluated in Section III to respond to the RQ #2, DT-based solutions for autonomous and connected vehicles represent 37%, intelligent infrastructure applications 22%, and applications concerning the agents' behavior in ITS 22%. Even though DT-ITS solutions are being used to address the main areas of ITS, it is evident that the automotive sector leads this section with a strong commitment to using DT in vehicle manufacturing. Besides, regarding the adoption of DT-ITS to meet the demands of the SDGs, 42% of the works address problems of improving efficiency in the use of ITS resources, safety problems are addressed in 56%, and solutions that consider the ecological aspects of ITS 7%. The low interest in solving ecological problems in ITS using DTs is striking. Only four publications address ecological issues in some way, and in most of them, the environmental approach is a collateral result of research focused on efficiency or safety. This behavior should be understood as an alert for DT-ITS researchers and practitioners to address ecological problems in ITS solutions more responsibly. In numbers specific to each ITS area, studies related to safety lead the area of CAV with 91% of the works, while studies for ITS efficiency lead with 86% the area of the behavior of ITS agents. As mentioned above, the SDGs are addressed in a more distributed way for intelligent transportation infrastructure, with ecological problems being addressed less. Finally, it is worth noting that starting in 2021, publications of research work and projects addressing DT-ITS solutions will considerably increase.

IV. DT-ITS Reference Framework

An important observation about the surveyed literature presented in the previous sections is the lack of architectural frameworks to develop DT for sustainable applications in modern ITS. Therefore, to summarize our findings and address RQ #3, this Section collects elements to propose a concise reference model for DT-ITS. In addition, discussions on DT-ITS functional and non-functional requirements are also presented. Figure 4 illustrates a systematic framework to accurately and timely develop DT-driven sustainable applications in transportation systems. The framework consists of 4 layers and considers the International Telecommunications Union in the ITU-T Y.dt-ITS recommendation draft [118]. Each of the layers and the interaction mechanisms between them are presented below.

1) The physical layer: This layer represents the elements of the transport ecosystem and the processes of combination and integration. The physical layer includes all the transport items for realizing a full-cycle process of intelligent transport. Thus, this layer is in charge of the cutting-edge processes in the operation of any DT-driven application, namely, sensing and actuation. Dynamic behaviors, events, and processes are detected and transmitted to higher layers to create DT-based models. The transmission uses communication interfaces and other enabler technologies that allow close interaction between physical and virtual entities. Similarly, DT-based models generate signals or instructions through actuators within their platform to trigger physical behavior [88]. The physical space is represented through various functional blocks [104].

- The intelligent infrastructure represents the first functional block, which includes design tasks, physical infrastructure maintenance, and system operation management with a macro approach. The deployment of specific sensors for the civil infrastructure is used in the monitoring processes, and others are specific to the transportation area for operational management. The actuation processes have an essential component of human intervention, especially in those cases directly related to the design and maintenance of the infrastructure.
- The second functional block comprises the traffic agents. This block includes vehicles (e.g., connected and autonomous vehicles, assisted driving, and conventional). For them, the most used sensors are the geolocation modules, perception sensors (e.g., LIDAR, radars, cameras), and the information from the intra-vehicle network. The action focuses on the greatness of vehicle control (e.g., steering system, acceleration, brakes, and others) in the case of fully autonomous vehicles or with some level of autonomy. In contrast, in the case of conventional vehicles, the action is carried out by the drivers. Non-vehicle agents, including drivers, pedestrians, and cyclists, also known as vulnerable road users (VRU), are also represented in this block. The sampling processes for these participants are carried out actively through the human-machine interface and passively with in-cabin sensing, environment sensing, or wearable devices. The action processes for non-vehicle participants are fundamentally aimed at drivers through driving assistance systems, which can act more precisely and thus influence the entire transport system. Other action methods for pedestrians, cyclists, or passengers are used on the roads through their wares or signaling systems.
- The last functional block deals with traffic behavior and other behaviors that act directly on the transport system, such as the mobility characteristics, the drivers' profile, and the actions of local regulatory agencies. The sensing in this block is closely related to information obtained by the previous functional blocks in those cases where the information of the transport environment is used to compute traffic and mobility information. Others depend exclusively on the relationship between traffic management companies, regulatory agencies, and authorities to

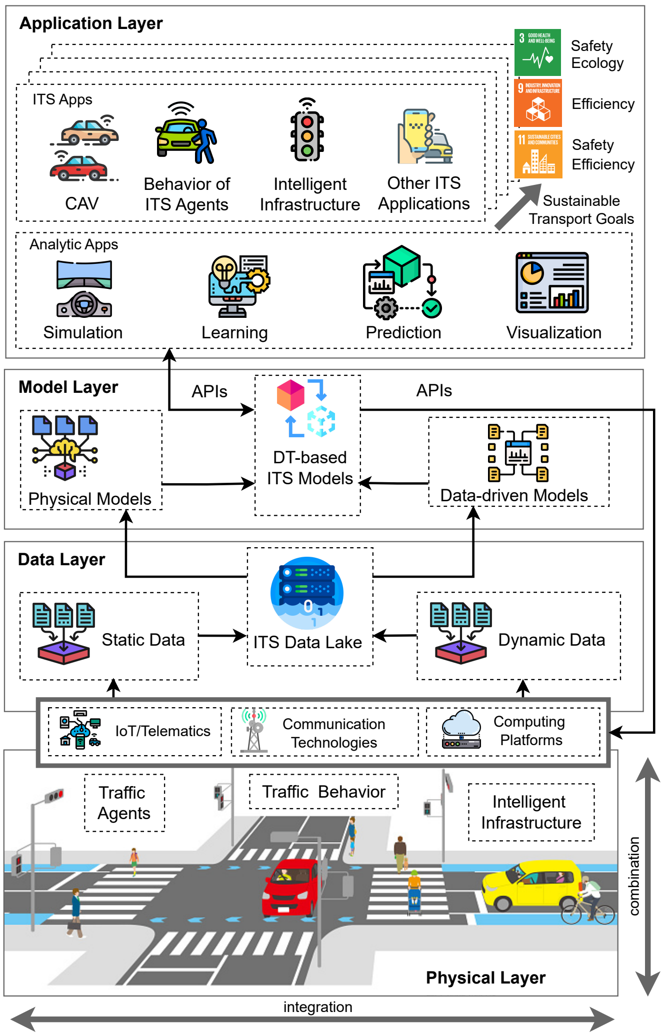


Fig. 4: DT-ITS reference framework.

keep up-to-date with policies and practices specific to each scenario.

2) The Data Layer: The data layer is based on collecting real-time data from the sensory and sampling processes produced in the physical layer, which, combined with historical data from the system, provide a sufficiently complete data lake for constructing the models used by the DTs [63]. For this, it is recommended to collect the most accurate data possible and more abundant information, giving the DT features reflecting the real environment state. Depending on the processes or physical entities that are being monitored, the data may have i) a dynamic perception of the physical space concerning the operations of the elements of traffic participants and their behaviors; or ii) a static nature more linked to the description of the environment and the infrastructure [119].

3) The Model Layer: The data lake is used to create computational models that describe the infrastructure, the agents participating in the traffic, and the operational processes of the ITS. A data processing stage is necessary for constructing these models, which is carried out in this layer to create physical and data-driven models [51]. Likewise, a stage of post-processing of the data and the combination of different sets of data and models allow for obtaining the most complex DT models (decision models) that provide a complete understanding of the data and the physical entities and processes. Once the DT model is built, it receives real-time information from the transport system to stay updated and more accurate. There is feedback to the physical layer as the DT is updated from the simulation and analysis, modifying the physical entities and processes. In this way, the DTs go beyond the simple conceptual design of ITS applications because the DT-based models are built to act as a simulator of reality. Still, they can remotely modify and manage any physical entity or process in transportation systems. The DT-based model interacts with the application layer through APIs implemented for different external applications to consume the model information.

4) The Application Layer: This layer is in charge of computing two types of applications:

- Intrinsic applications of the DT that use the models for simulation and analysis, learning tasks of intersection patterns, urban mobility, and visualizing current conditions of the transport system [104]. For most of these cases, the DT and their applications must work offline to explore different scenarios of the ITS without being tied to the elements of the physical world. The analysis tasks allow an understanding of the crucial issues of the transport system and its processes, analyzing the real world through the DT-based model. In complex systems such as ITS, when system assets interact with each other, many unexpected situations can arise that are almost impossible to analyze by operation centers or by simple system simulations. Through the DT-based model, the applications help to optimize interactions to obtain unknown information and assist in decision-making.
- External applications of particular solutions for each transport scenario are also included in this layer. These applications aim to address the main SDGs related to transportation systems. Such applications consume the model's data together with the results of simulations, analyses, and predictions for developing specific ITS applications for monitoring and managing the various facilities of the transit system and the transportation infrastructure. The DT solutions can share analytical results across visualization platforms through these applications. With them, the authorities responsible for the transportation system can detect and isolate failures in physical infrastructures, diagnose and solve problems, and recommend corrective actions. Finally, these externals can also peer with the business layers, like in the well-known framework Reference Architectural Model for Industry (RAMI) 4.0 [23], in order to automate communications with corporate clients, contractors, and service providers.

A. Functional requirements for DT-ITS

1) Efficient data collection: DT-enabled ITS are required to support bulk system data collection. DT-ITS must support efficient data collection tools and methods to collect data on all physical characteristics of the transport system. It is desirable that data collection methods offer all data in time series or that some data aggregator entity creates a time series from the data obtained. During the data collection stage, it is essential to use various tools required for the DT-ITS to support the collection of different types of transport data with different characteristics. Some data requires a higher frequency of collection (i.e., signal status, agents' location), while other data requires a higher level of real-time (i.e., traffic flow status, agents' location). It is recommended that the DT-ITS explore new data collection technologies considering the requirements of the transport applications implemented by the DT. At the same time, such data collection methods should be as lightweight as possible to reduce the occupation of network and computing resources so that it does not affect the operation of other transport system features that use data sharing. Thus, data collection is required to improve execution efficiency, reduce computing, storage, and communication costs, minimize the collection of redundant data, and use data compression when possible.

2) Efficient and unified data repository: With the transport system data collected, the DT-ITS must build a unified repository to store and manage such data. The repository must be able to extract, transfer, and upload the data collected from the ITS physical entities and processes and store the data. It is recommended to use heterogeneous databases to store the data collected from multiple structured and unstructured data. The unified repository is required to have the ability to store various types of system data, including interim data and operational data. The DT-ITS unified data repository is required to have the ability to support real-time data acquisition and access to support time-critical applications. In addition, the repository must provide a unified interface for exchanging data from the transport system with the data models created for the DT-ITS. Lastly, the data repository is required to have the capacity to efficiently manage massive amounts of data from complex transport scenarios, guaranteeing the accuracy, consistency, integrity, and security of the data.

3) Unified data models: The DT-ITS is required to define and create unified data models for various sustainable transport applications. The unified data models must be able to model the entire transport system, the agents participating, and the interactions between them. In addition, the data model must be designed to fully use the unified data repository to create various models for analysis, emulation, diagnosis, and prediction for specific application scenarios. To do this, the unified data model must have an interface to obtain the requirements of the ITS applications and report the simulations' results to the applications. For more complex scenarios, the data model is required to have the ability to provide services efficiently through a combination of multiple models. Another data model requirement is the ability to emulate and iteratively optimize transport applications that use such a model.

4) Open and standard APIs: The DT-ITS require open and standard interfaces for information exchange between the physical system and the DTs. Specifically, a southbound interface between the physical ITS and the DT data models and a northbound interface responsible for information exchange between the DT-ITS and transportation applications are necessary. The correct implementation and use of such interfaces in the DT-ITS contribute to avoiding blocking the hardware or software provider and achieving the complete interoperability of the DT-ITS. Both interfaces should have high extensibility to add more features with limited parameter changes and backward compatibility. They must also be interfaces that are easy to access and use to handle massive data and high concurrency and provide secure and reliable information exchange mechanisms.

Southbound interfaces are required to collect data from ITS scenarios. Southbound interfaces must be able to implement various collection methods, including passive and passive collection and on-demand collection. The diversity of data that can be collected in the ITS demands that the southbound interfaces support several speed options to accommodate different data requirements from applications. In addition, these interfaces are required to deliver control signaling that allows updating of the physical system depending on the outcome of specific applications. On the other hand, the northbound interface must be able to deliver the requirements of transport applications to the DT-ITS data models. Through the northbound interfaces, digital copies of the DT-ITS and data models are provided to third-party applications. In addition, these interfaces must be capable of reporting the results of the execution of the data models in the DT-ITS.

B. Non-functional requirements for DT-ITS

1) Compatibility: The DT-ITS need sufficient compatibility to apply to various transport scenarios, even managed by multiple regulatory and control entities, which may eventually be interested in various transport applications. It is necessary to support different transport scenarios containing physical and virtual devices to apply DT-ITS in numerous applications. Additionally, DT-ITS requires backward compatibility so that all updated or new functionalities (i.e., interfaces, data repository, data models) can work seamlessly with the functionalities of previous versions. The DT-ITS must work with the current transport system management implemented by transportation operators, mainly when the DT-ITS is used for operations and maintenance in complex transport scenarios.

2) Scalability: The DT-ITS must be scalable enough to support large-scale transport scenarios. The DT-ITS must be able to build a virtual twin of the large-scale physical system, taking into account, during the design and implementation stages, the complexities that a large-scale solution introduces in software design, data modeling, and embedding of new features. Consequently, it must be able to scale the virtual twin transport systems automatically according to the growth or reduction of the physical systems. Even in cases where the physical system is extended and, therefore, its complexity, the DT-ITS must maintain a stable performance. As part of scalability, it is also essential that the new functionalities of the DT-ITS can expand their capabilities with the least possible impact on existing functionalities.

3) Reliability: The DT-ITS must be highly stable to achieve reliable interaction between the virtual space and the transport system. The DT-ITS is required to have high robustness to deal with various abnormal situations. In case of manual operation error, illegal data, hardware equipment failure, or other situations, the DT-ITS must be able to handle or avoid any given error correctly. The reliability must be guaranteed, especially when dealing with DTs that implement time-critical transport applications. The data modeling must also be reliable, accurately describing the physical system's state and predicting system operating trends. Backing up essential data and functionality is also desirable, allowing the DT-ITS to restore previous checkpoints and critical historical points.

4) Synchronization: Strict synchronization of the DT-ITS with the transport system is required to represent the actual state of physical entities in real time within the acceptable delay. In the same way, the synchronization of the execution of control information from a virtual entity to a physical entity within an acceptable range must be addressed. This service requirement is closely linked to the performance of the communication network and computing platforms.

5) Security: As an essential part of current information technologies, the DT-ITS must be secure enough to avoid and mitigate security issues. Firstly, it must attend to the security of the data, maintaining the confidentiality, integrity, and reliability of the sensitive data used in the DT-ITS. Such protection must be implemented to allow trust in unified data models and data repositories. The DT-ITS is required to guarantee the security of the communication and computing infrastructure it implements. It involves software and hardware security during data collection in the transport system and processing of these data.

6) Privacy: The DT-ITS is required to protect the users' private data of the transportation system with the highest priority, complying with the country's laws based on the locations of the transport system or its DT. In addition, the DT-ITS must protect the privacy of the interaction between DTs and physical entities. The information referring to the transport system devices must be protected. The DT-ITS must be able to handle different levels of confidential data with varying levels of privacy, mainly operational data generated by transport system users.

The proposed framework is our answer to RQ #3 (*How can one use DTs to address SDG regarding efficiency, safety, and ecology in ITS?*), being the first approach to accelerate DT-ITS development. This framework even serves as a guide to define an appropriate ontology for semantics and reference implementations, allowing the expansion of DT-based solutions in the ITS ecosystem. With a functional framework that employs open standards, developers and practitioners of DT-ITS solutions can focus on the applicability of current and evolving technologies and unification strategies, developing related business model innovations. Finally, the framework allows, in a simpler way, to analyze scenarios from the perspective of cross-domain interoperability, covering all the SDGs inside and outside the transportation domain.

V. Research Directions

The need for works on ecology pointed out in Section III-E turns it into a broad research topic to investigate. However, pressing issues still need to be addressed for the non-functional requirements for the DT-ITS reference model discussed above. This section provides direction on how they could be addressed shortly and discusses new research avenues ahead.

A. Standarization

Nowadays, the pioneering solutions that use DT for transport systems follow different approaches, arbitrarily deciding their components and their relationships. Providing a functional reference framework for DT-ITS has been one of the proposals of this paper. However, the participation of standardization organizations and companies in the transport sector is necessary for a comprehensive solution, particularly non-functional requirements. The transport vertical's complete methodology is domain-dependent, requiring intricate domain knowledge to fully understand the DT implementation [120].

On the other hand, pursuing a unified and open framework with a formal structure and comprehensively defined elements of the transport system and standardized APIs would support scalable operations of DT-ITS. In general, the standardization process of the DT-ITS will contribute decisively to the creation of solutions where the interactions between the physical and virtual entities of the transport system avoid vendor lock-in, so the accessibility to heterogeneous data for accurate creation of virtual models can be made uniformly available [118]. The evaluation metrics for the performance of DT-ITS is another open research topic to compose such standards; considering that they are again diverse and dependent on the transport domain, one should focus on the representative parameters able to closely reflect the ecology, safety, and efficiency goals of ITS. To this end, extensive experimentation efforts will be required, and thus, big data analytics will be necessary to single out relevant parameters [121].

The evolution of DTs can be seen as the metaverse. DTs can be used to create the immersive virtual and persistent online emulations of 3D virtual environments promised by the metaverse [122]. Raising the metaverse standardization issue here may sound far-reaching, but it should be noticed that both the IEEE [123] and the ITU-T [124] already have initiatives toward this end. Moreover, this ITU-T Focus Group describes the metaverse as a potential enabler for innovative societal problems related to SDG, and thus, standardization of the industrial metaverse for the transportation vertical has many research avenues to be explored.

B. Scalability, Infrastructure, and Connectivity

The operation of ITS requires high-performance information technology infrastructures. This is the main way to guarantee high-fidelity two-way synchronization of the DT-ITS [125]. When considering ITS solutions empowered by DT, the mentioned infrastructures must be able to operate, manage, and execute intensive and computation-hungry machine and deep learning algorithms. The high-performance graphics processing unit considerably increases the CAPEX for implementing such systems when using edge private computing platforms. Such a situation can be circumvented with a processing-as-a-service approach, new services that leading companies in the public cloud market offer. However, using solutions based solely on public clouds also implies an increase in OPEX, making the adoption of DT-ITS not viable. Studies are needed to better separate the workloads of the virtual DT models and achieve a trade-off in allocating computing [126]. In this way, further research works are needed on the orchestration of resources in multi-tier computing. The less computationally demanding work can be kept embedded within the infrastructure of the transport system itself. In contrast, the resolution of complex ML/AI algorithms would be migrated on-demand to the cloud.

However, this orchestration effort may create other complex problems related to connectivity to reach such processing infrastructures. It has been recently demonstrated that even if a model in DT-ITS is perfectly constructed, it might still fail to predict, for instance, the trajectory of connected vehicles. In such cloud-based algorithms, measurement and processing imprecision and system latency may lead the system to leave a steady convergence and enter a chaotic region. Thus, long-term states may become unpredictable [127].

Thus, providing reliable and low latency connectivity between a DT and the physical system represents another important challenge [128], especially when many sensors need to be connected simultaneously and with real-time controlling requirements for time-critical applications. Considering the mobile agents of ITS, unlike conventional IoT communication systems, the DT requires more deterministic, higher broadband, better synchronization, and other augmented transmission capabilities to enhance DT services for diverse applications [129]. Therefore, there is a pressing need for research works deepening 5/6G ultra-reliable and low-latency communications and multi-tier computing because these two segments must come hand-in-hand for addressing DT and metaverse issues discussed above [130].

For the cabled segment of the infrastructure providing connectivity, research on using time-sensitive networking (TSN) can be an effective technique to ensure consistency between DT elements as far as LANs are concerned [131]. This can help the vertical industry to realize the network interconnection and data interworking of the integrated system in wired and wireless environments and meet the bounded business requirements of low latency, low jitter, and high reliability in various scenarios. Standards related to communication technologies, like 5G and new WLAN developments, are not explicitly proposed for DTs, but they can be reused to solve DT problems. For internetworking scenarios, some issues can be dealt with deterministic network integration along WANs [132]. Specifically, there are comprehensive cross-platform approaches designed for internetworking, such as OPC-UA [133], but their processing latency is yet a research challenge to be addressed within DT-ITS. Consequently, using these technologies efficiently and dependably is necessary, for which formal network analysis is a research avenue to be followed by DT-ITS in the infrastructure design stage [134].

C. Dependability, Security, and Privacy

In real ITS scenarios, if the digital twin becomes unreachable, it could lead to hazardous situations for human life. The DT-ITS, as using real-time data exchange, is more susceptible to threats that can make it unavailable. Threats are present in almost all components of the DT-ITS structure, and attackers can exploit vulnerabilities in physical systems, data structures, software, and data communication channels. Given such a scenario, Karaarslan and Babiker [135] analyzed the main threats for DT-based solutions and summarized the main countermeasures to be adopted to mitigate vulnerabilities in the different modules of DT systems. Among the main countermeasures, blockchain-based DTs have been increasingly adopted to protect data models and data exchange between components of the DT system [136], even in ITS solutions.

While there has been tremendous fast progress in the development of ITS, the security of such systems did not scale up at the same rate. Blockchain emerged as an essential tool in several sectors, including transportation. Its decentralized, reliable, secure, transparent, and immutable characteristics that innovate in the exchange and management of data make it a total solution to guarantee the security of ITS [137]. This research has proposed blockchain-enabled DT as a service (DTaaS) for ITS to provide a secure and reliable match between DTs and ITS. The proposal deals with the solution for the problems of the variability of the location and affiliation of the vehicle to the ITS. Thanks to the features of blockchain, secure and efficient DT-ITS service transactions, including computing, communication, and control, can be ensured.

In ITS supported by vehicular networks, the vehicle nodes are randomly distributed and move quickly, which leads to the characteristics of repeated changes in the distribution of network nodes in intelligent transportation and the uneven distribution of the network caused by vehicular density. Research is needed to improve DT-ITS security in these complex transport systems. Recent work has proposed to map the traffic situation in virtual space, using blockchain technology to protect the vehicle and identity information on the network [138], [139]. In addition to providing security, DT-ITS solutions based on blockchain contribute to reducing consensus latency in decision-making among the participants of the transport system.

D. Governance, Business, and Human Factors

The automation of the life cycle management of the DT-ITS and how the transport system users manage the DT models both need to be better developed. This management is essential because the ITS models have been well-defined from the technological side. Still, such evolution has not been the same in ITS in a business context and human factors engineering. The operation of DT-ITS solutions requires the involvement of many parties and users (e.g., government, transport groups, automotive companies, road users, etc.), so the existence of well-defined business models will facilitate access to DT-ITS resources, enabling their efficient management in multi-user and multi-operator scenarios. Moreover, a proper business layer might need to be added to our proposal in Fig. 4, like in the reference model in RAMI 4.0 [23], to automate communication across businesses. In this sense, it must consider the practitioner experiences and convenience through better-suited products and satisfaction, directly influenced by the fidelity of the results obtained through the DT-ITS [140]. In addition, the relevant legal and ethical issues in a governance model for this interdisciplinary and multi-stakeholder DT-ITS are yet to be fully understood.

Misplacing roles that humans and DTs play may result in significant problems not only for the early adopters but also for the viability of DT-ITS solutions themselves due to irreparable reputation harm caused by unrealistic expectations and strategic misalignments [141]. Therefore, in the design phase care must be taken with human factors. For DT-ITS to deserve our reliance on it, engineers and managers alike must trust frameworks, methods, and tools that will replace legacy systems. Experimental evidence and case studies as benchmark problems should be provided to gradually build up confidence that DTs are fit for purpose [142]. In this context, determining when to enable a DT-ITS to be autonomous and when to rely on humans to make decisions is another relevant question.

VI. Conclusions

Digital twins can be pivotal in revolutionizing sustainable, intelligent transportation systems (ITS). By creating virtual replicas of physical assets, DTs offer a comprehensive understanding of infrastructure, vehicles, and operational processes, with the potential to optimize energy consumption, traffic flow, and resource allocation.

Driven by the sustainable development goals (SDG) from the UN, we undertook an exhaustive survey in this paper to encapsulate the core aspects of DTs that could trigger sustainable applications in ITS aimed at fulfilling diverse (and often conflicting) objectives. We formulated and answered three fundamental research questions, paving the way for adopting DTs in ITS. From the key characteristics in the surveyed works using DT for ITS, we introduced a concise 4-layer reference framework for creating DT-ITS. We deliberated on its functional and non-functional prerequisites.

The framework is the first step towards expediting the development of DTs for ITS. The framework acts as a guide to establish an appropriate ontology for semantics and reference implementations, facilitating the proliferation of DT-based solutions in the ITS ecosystem. Moreover, we underscored several open challenges and future research avenues for developing DT solutions in ITS, indicating potential opportunities for further exploration and improvement.

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