https://doi.org/10.5755/j02.eie.36209 ELEKTRONIKA IR ELEKTROTECHNIKA, ISSN 1392-1215, VOL. 30, NO. 2, 2024

# Recent Progress on Digital Twins in Intelligent Connected Vehicles: A Review

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***Abstract*—As an important enabling technology in the era of Industry 4.0, the intelligent connected vehicle (ICV) facilitates robust data interaction with the outside through sensors and communication technologies, ultimately making scientific decisions based on environmental perception information. However, due to constraints such as limited communication bandwidth and computing resources, the influx of data simultaneously impedes the sustainable optimisation of the vehicle decision making process at the same time. As a novel technology that effectively connects physical and virtual space, the special ability of the digital twin (DT) is to identify characteristics within a certain lifecycle, thereby garnering widespread attention across various industries. The purpose of this paper is to review the contribution of digital twins in the application field of intelligent vehicles and explore its potential for development. First, the key technologies of ICV provide a basis for the embedding of digital twins. Then, by analysing the development process and technical composition of digital twins, readers can better understand the concept of digital twins. Finally, the application of DTs in ICV is reviewed from the perspective of vehicles, traffic facilities, and occupants. Future challenges and opportunities in this direction are described at the same time.**

***Index Terms*—Digital twins; Intelligent connected vehicle; Intelligent transportation system; Data analytics.**

## I. INTRODUCTION

As the global count of automobiles continues to increase, while changing people's travel and lifestyle, it has also caused many problems such as traffic accidents and environmental pollution. Relevant reports show that traffic accidents caused by human factors account for more than 90 % of the total proportion [1], which has a serious impact on the posture of traffic safety. Autonomous vehicles with environmental perception, intelligent decision making, and control execution now offer a solution to the human-caused traffic problem. According to Strategy Analytics [2], autonomous driving will improve 585,000 lives between 2035 and 2045.

Intelligent connected vehicle (ICV) [3], the combination of the Internet of vehicles and intelligent vehicle, is an intelligent mobile space that integrates modern communication technology and network technology. ICV facilitates the sharing of perceived data among vehicles and traffic infrastructure through communication and cloud computing, allowing for more informed decision making [4]. At present, with the gradual maturity and improvement of the automatic driving industry chain, ICV has entered the stage of mass production. It is believed that the share of L2 and above-level autonomous vehicles in the Chinese market will reach 38.4 % in 2025 [5]. Despite the ability of ICVs to access extensive data from vehicle sensors and road traffic systems, the increasing complexity and heterogeneity of data processing introduce safety concerns. In particular, the system design of ICVs may struggle to fully consider all data details. In response, we propose to use digital twins to promote the design and development of ICVs.

Digital twins (DTs) refer to the exact replication of physical objects in virtual space, forming digital mirror images that, in turn, simulate the properties, behaviours, and conditions of the corresponding physical entities [6]. DTs possess the attributes of a full life cycle, meaning that this mirror relationship typically spans the whole life cycle of the physical thing, encompassing not just the manufacturing process but also subsequent maintenance, etc. [7]. Simultaneously, DTs have real-time dynamics, i.e., this mirror relationship is real-time, and when the external environment changes, its mirror will correspond to the corresponding changes to ensure that its replica of the physical object is completely replicated [8]. DTs are also bidirectional, i.e., not only does the physical object transmit data to its mirror, but the mirror can also transmit data to the physical object. This bidirectional flow facilitates the physical object in making informed decisions based on the data received from its digital twin [9]. In the ICV-orientated DT environment, vehicles and traffic systems are modelled as digital mirrors, thus forming a mirror relationship between the virtual space (server) and the physical space (road environment), which allows ICVs to make rational decisions through the data of DT. Furthermore, the full life cycle of DT for ICV is expressed in the multidimensionality and comprehensiveness of its modelling, which allows DT to predict driving safety after a certain decision to help the physical object make a more reasonable decision. The

Manuscript received 20 December, 2023; accepted 3 April, 2024.

discontinuity and timeliness of the mapping between the road environment and its digital mirror enables the real-time digital mirror to establish the corresponding mirror connection immediately after the real road changes, which is one of the manifestations of DT real-time dynamics. The bidirectionality of DTs is manifested in the fact that the mirror space and the road environment provide each other with data references, while the mirror space itself does not replicate accidents during the operation of the physical object, which means that DTs can transfer vehicles from the road environment, which is characterised by low fault tolerance and high cost, to the mirror space, which is characterised by high cost and low fault tolerance [10]. This transfer improves driving safety by mitigating the risk associated with real-world operations. In essence, the application of DT technology to ICVs holds the promise of advancing the commercial production of ICVs. Figure 1 visually represents the specific application of digital twins in vehicles.

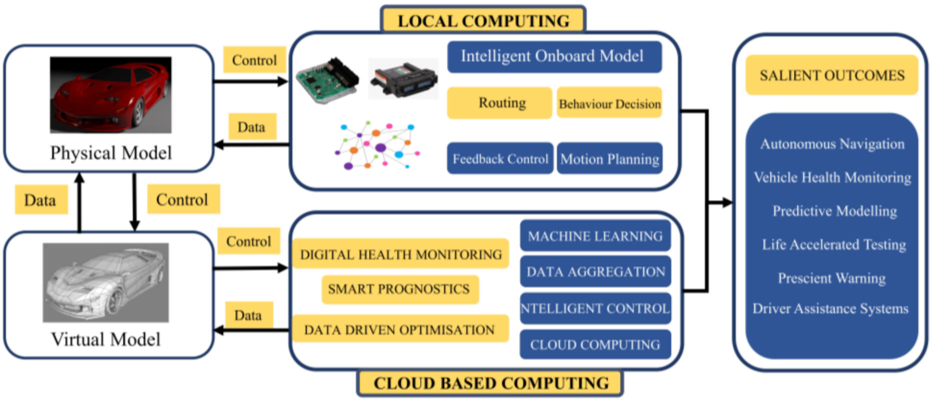

Fig. 1. The application of DT in the vehicle.

This paper is presented in three sections. Section II analyses research related to ICVs, categorising it according to the three modules of perception, decision making, and control, and the current state of the development of ICVs is described. The emergence and development of DTs is discussed in Section III. Section IV provides an overview of the application of DTs and the challenges faced by the application of DTS in ICV. Finally, the whole paper is summarised and future research directions are pointed out.

## II. BRIEF INTRODUCTION TO THE STUDY OF INTELLIGENT CONNECTED VEHICLE

The intelligent connected vehicle is a product of the fusion of mobile Internet and industrial intelligence in the automotive industry, which can share data with a wide range of heterogeneous devices, transform the car from a separate individual into a collection of many information applications [11]. This section focusses on the key technologies of smart connected vehicles, namely environment sensing, intelligent decision making, and control execution, thus providing a fundamental basis for the embedding of digital twins.

### *A. Perception of the Environment of Intelligent Connected Vehicles*

The environment-sensing technology of ICVs serves as the foundation for other technologies, offering essential input for subsequent decision making and control processes, and is the same as the “eyes” and “ears” of the vehicle [12]. Environment sensing technology primarily encompasses two components: perception technology and communication technology, expressed specifically through the installation of multiple sensors on the vehicle body or vehicle-to-everything (V2X) technology to collect information from the vehicle’s surroundings and transmit these data to the control unit, ultimately ensuring the safety of the vehicle.

In the perception system of ICV, sensing technology is the basis for data processing and sharing, and its composition includes three parts: the information acquisition unit, the information processing unit, and the information transmission unit. The perception technology is that the vehicle collects information about the surrounding environment through its own sensors [13]. Current mainstream sensors are presented in Fig. 2.

However, the predominant approach in sensing technology is multisensor fusion, as the information collected by a single sensor is more limited and its environmental adaptability is insufficient [14]. The performance of different types of sensors and their combinations is shown in Table I.

TABLE I. PERFORMANCE COMPARISON OF DIFFERENT TYPES OF SENSORS AND THEIR COMBINATIONS.

| **Performance** | **Radar** | **Vision** | **Lidar** | **Radar Vision** | **Vision Lidar** | **Radar Vision** |
|---|---|---|---|---|---|---|
| Sensing Distance | High | Mid | High | High | High | High |
| Object Detection | High | High | High | High | High | High |
| Lane Detection | Low | High | High | High | High | High |
| Object Classification | Mid | High | Low | High | High | High |
| Location Estimation | High | Low | High | High | High | High |
| Velocity Estimation | High | Low | High | High | High | High |
| Traffic Lights/Signs | Low | High | Low | High | High | High |
| Gestures(Human)Recognition | Low | High | Low | High | High | High |
| Adverse | High | Mid | Mid | High | Mid | High |
| Low Light Performance | High | Mid | High | High | High | High |

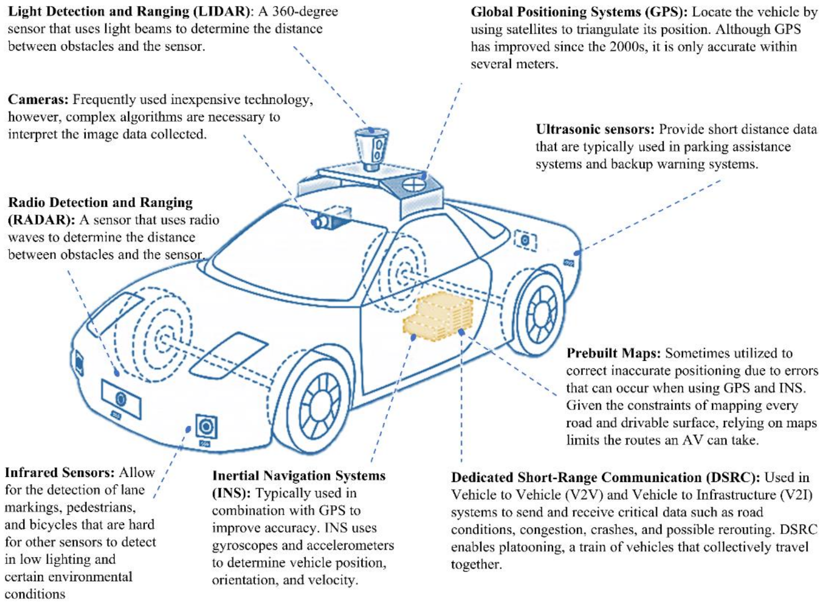

Fig. 2. Sensor ecosystem for ICV.

Currently, there are two main choices of sensor types for multisensor fusion: fusion of visual sensors and LIDAR and fusion of visual sensors and RADAR, with radar vision (RV) being the most dominant fusion scheme, due to the superior target detection capabilities of visual sensors, such as signal light recognition and lane line recognition, complemented by RADAR providing additional scene depth information, and the combination of the two can achieve the complementary disadvantages and enhance the robustness during environment perception. As in [15], vehicle detection and tracking is performed using a multisensor fusion of millimetre wave radar, as well as cameras, ensuring a high detection rate while achieving fast detection of each vehicle. According to experimental findings, the suggested system has a detection rate of 92.36 % for on-road vehicles and a false alert rate of 0 %.

Compared to a single vehicle, ICV communication technology allows them to acquire more information about their surroundings while ensuring their own high perception accuracy, which is due to the fact that they turn the vehicle from an “island” into a node in the intelligent transportation system (ITS) [16], thus gaining access to information in a broader spatial context. As shown in Fig. 3, the modes of interaction of V2X communication technology to obtain information about the surrounding environment include vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-pedestrian (V2P), and vehicle-to-network (V2N) [17]. Through V2V technology, vehicles can exchange enhanced driving information, contributing to more advanced and safer autonomous driving. For example, Wang [18] shared information between vehicles through V2V technology to achieve better trajectory planning. Luo, Xiang, Cao, and Li [19] used V2V communication to achieve automatic lane change and eliminate potential collisions in the process. The V2I technology exchanges information between the vehicle and the road side unit (RSU), enhancing vehicle safety at intersections and improving road capacity. Qian, Gregoire, Moutarde, and De La Fortelle [20] used communication between roadside facilities and vehicles to assign priorities to vehicles and coordinate vehicle movements. Pubboobpaphan, Liu, and van Arem [21] used communication between vehicles and road facilities to rationally plan vehicle speeds and reduce travel time.

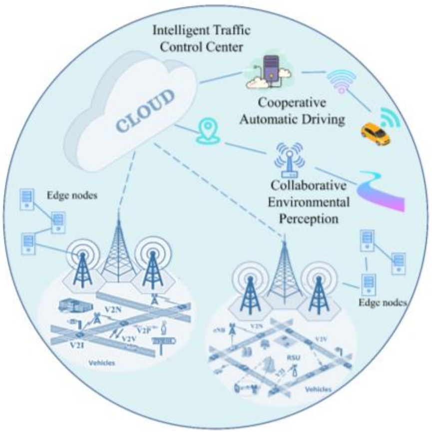

Fig. 3. V2X communication technology.

### B. *Intelligent Decision Making of Intelligent Connected Vehicles*

The role of the decision making system in ICVs is to generate safe driving instructions, such as path planning and danger warnings, based on the environmental information collected by the vehicle, the vehicle’s driving target, and its own state. Essentially, this system functions as the “brain” of the vehicle [22].

Decision making algorithms of ICVs can be divided into two major categories, namely, based on the a priori rules and based on learning. The decision making method based on a priori rules is that ICVs draw on a rule base that encompasses driving behaviour derived from traffic rules, driving experience, and, more so, it can choose different logical structures in the rule base to make decisions when faced with different scenarios. This approach exhibits a clear structure and does not require a substantial amount of data for model training. For example, Boss [23], an unmanned vehicle developed at Carnegie Mellon University, and Talos [24], an unmanned vehicle at Massachusetts Institute of Technology, make decisions based on a priori rules. Learning-based decision making algorithms, on the other hand, train deep neural networks by simulating the human learning process and seeking the most reasonable decision in one attempt, e.g., the authors in [25] based on deep reinforcement learning for decision making training. This approach features a simpler and clearer structure compared to rule-based decision making and imposes lower requirements on the equipment on board. The results show that on a complex three-lane road, the speed of the self-driving car under this model is increased by 2.4 % when making lane changes.

As shown in Fig. 4, the author in [26] compared and analysed patents related to branch technologies in intelligent decision making, and it can be found that the current research focusses mainly on danger warning, path planning, and other aspects. Therefore, the following section introduces the two parts of path planning and danger warning.

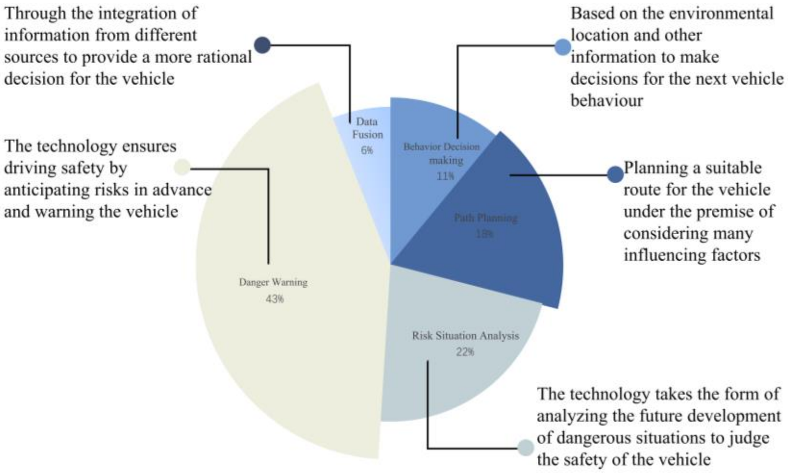

Fig. 4. Patent issues related to intelligent decision making [26].

Path planning: Path planning, also known as trajectory planning, aims to find a suitable path between the starting position and the target position, considering variables such as the path, vehicle status, traffic regulations, and other relevant factors [27].

Different search algorithms have different advantages and disadvantages, suitable for different road conditions, such as the Dijkstra algorithm [28] and the $A^*$ algorithm [29], the ant colony algorithm [30], etc. In particular, the $A^*$ algorithm is straightforward but computationally intensive, the Dijkstra algorithm is robust but less efficient, and the colony algorithm is also robust but easy to fall into the local optimum. Choosing the appropriate algorithm according to the target environment can complete the search task faster and better. Path smoothing is essential to ensure the safety of passing paths, which can smooth irregular paths. Common smoothing algorithms include interpolation-based path smoothing, i.e., passing through all the path points in the path to form longer curves, including Bessel curves [31], cubic spline curves [32], etc. Additionally, optimisation-based path smoothing, as demonstrated in [33], uses the centreline of the road as a reference, employing nonlinear optimisation to ensure smoothness. Special curve-based path smoothing techniques, such as Dubin’s curve [34], are also employed.

Danger warning: Vehicle danger warning serves as an early warning protection mechanism, anticipating potential dangers such as lane departure and front-end collisions. Its purpose is to warn the vehicle owner about potential risks and to remind the vehicle owner to pay attention to the safety of driving by issuing danger warnings [35].

The warning for lane departure addresses the issue of unintentional lane departure caused by driver fatigue or distraction. It uses sensors to assess how far between the vehicle and the traffic sign, alerting the driver when the vehicle approaches or reaches the lane sign. It does not warn the driver if he or she intentionally crosses the lane (by turning on the turn signal) [36]. As in [37], the information about the surrounding lane is detected by sector detection, and the degree of deviation is calculated using an angular relationship to judge the degree of lane deviation, and at the same time the distance to the vehicle in front is determined by identifying the shadow and tail lights of the vehicle in front. The purpose of lane change overtaking warning is to assist the driver in making a safe lane change through additional technical means, the core of which is blind spot detection [38]. The principle of operation is as follows: when the driver sends the intention to change lanes, such as turning on the turn signal, the sensor identifies the visual blind spot of the driver when changing lanes to determine whether it is safe to change lanes at this time, and sends a timely warning to the driver when danger occurs, such as in [39], where the authors use visual and radar sensors to detect the visual blind spot.

### *C. Control Execution of Intelligent Networked Vehicles*

The control execution is the vehicle after receiving the planning of the decision making system, according to the specific requirements to accurately issue commands to control driving, such as vehicle acceleration, steering, braking, etc. Its function in automatic driving is analogous to the role of hands and feet in the human body [40]. The vehicle control system issues control commands after receiving decisions from the decision making system. It consists mainly of three parts: longitudinal control, lateral control, and lateral-longitudinal cooperative control [41].

Longitudinal control of the vehicle involves coordinating the throttle and brakes to achieve precise control over vehicle speed and distance in relation to front and rear vehicles and obstacles [42]. Effective longitudinal control allows for a timely response to dangerous scenarios, enables efficient collision avoidance, and reduces the likelihood of traffic accidents. Furthermore, in ITS, the longitudinal control of different vehicles can enhance the efficiency of vehicle travel during peak urban car usage, consequently reducing the probability of traffic congestion. Longitudinal control can be categorised into direct [43] and indirect control structures based on different algorithmic structures. The former achieves control of the vehicle's brake pressure and throttle opening solely through the controller, while the latter involves setting up upper and lower position controllers to manage vehicle control. Due to the complexity of longitudinal vehicle control, which involves multiple aspects, hierarchical control has become the mainstream method. Hierarchical control effectively alleviates challenges in system development. For example, the authors in [44] use a hierarchical regulation based on model predictive control (MPC) for vehicle speed control, the algorithm combines a simple longitudinal inverse vehicle model and adaptive regulation of MPC, which can automatically avoid high-frequency oscillations by using the engine braking torque under various driving conditions.

Lateral control of the vehicle: Lateral control of the vehicle involves adjusting the steering wheel angle taking into account the position of the vehicle, longitudinal speed information, road curvature, and other factors influencing the decision. This adjustment ensures that the vehicle follows the expected trajectory planned by the trajectory planning module, promoting smoothness in the driving process and preventing significant deviations from the trajectory [45]. At present, many scholars for lateral control research algorithms are as follows: the more classical proportional-integral-derivative (PID) control method, the principle of the algorithm is relatively simple, the application of engineering is more mature, and the control parameters are generally determined by the method of trial and error. The authors in [46] proposed a distributed proportional integral derivative control algorithm to solve the problem of uncertainty and time-varying communication delays due to the existence of uncertainty of variable chi-square parameters when the fleet is travelling. Another classical algorithm in control theory is sliding-mode control, known for its efficacy in disturbed environments. The authors in [47] used sliding mode control to solve the path planning problem to achieve smooth motion of the vehicle by introducing sliding hyperplanes in the lateral direction.

Lateral and longitudinal cooperative control of the vehicle: In the vehicle travel process, lateral control or longitudinal control alone cannot fully address the vehicle's travel situation, as the two are inseparable [48]. Therefore, lateral-longitudinal cooperative control can better meet the control needs of ICVs. An ideal transverse-longitudinal controller should exhibit robustness and fully consider the correlation between transverse and longitudinal control, preventing interference from longitudinal speed or transverse displacement on the accuracy of the other direction [49]. For example, the authors in [50] proposed transverse and longitudinal control based on adaptive neural control, i.e., designing a neural network-based controller for the simultaneous control of transverse and longitudinal motions of an autonomous vehicle using a type-2 fuzzy set (IT2FS)-based activation function. The highest tracking errors of 0.04 m (for lateral path following) and 0.02 m/s (for longitudinal velocity) were found by modelling the simultaneous control of lateral and longitudinal motions. On the other hand, the authors in [51] designed two algorithms for transverse and longitudinal directions by linearising a nonlinear model and thus using an MPC strategy, where the MPC algorithm for transverse dynamics uses a predefined reference trajectory and the state of the system to compute the vehicle commands so that it follows the trajectory and satisfies the constraints imposed. Simultaneously, the vehicle longitudinal velocity controller computes commands to maintain the vehicle velocity in line with the reference.

## III. GENERATION AND DEVELOPMENT OF DIGITAL TWIN

As a pivotal technology in the Industry 4.0 era, the digital twin, characterised by the fusion of information and physical elements, signifies a new phase in the advancement of intelligent systems. Originating from diverse technologies such as the Internet of Things (IoT), sensors, artificial intelligence, machine learning, etc., it exhibits versatile applicability across domains such as smart manufacturing and product development [6], [52]. In particular, since 2017, Gartner has consistently identified DTs among the top 10 strategic technology trends annually and positioned them as one of the top 10 most promising technology trends for the next decade. BITKOM, the German Association for Information Technology and New Media, predicts that DTs will be of great value in the manufacturing market, exceeding €78 billion by 2025 [53]. This section takes a look at its development history, evolution of conceptual connotations, and key technology components.

### *A. History of Digital Twin*

The concept of DT was first introduced in 2003 by Professor Grieves, who categorised digital twins into physical products, virtual products, and their connections [54]. In 2011, Professor Grieves formalised the name of the digital twin definition by quoting the relevant definition from John Vickers' article. In the same year, the inaugural paper on DT was published, illustrating its application to predict the service life of structural components of aircrafts [55]. Later, in 2012, NASA redefined the DT [56] as a physical model based on historical and real-time data, which can reflect multiphysics, multiscale, multiprobability, and ultrafidelity analogue simulation processes, and used it in the design of space vehicles. Subsequently, the U.S. Air Force also defined the DT, expanding the NASA-based "aircraft or system oriented" to "system oriented to complete the modelling" and "mapping" to "mapping and prediction". The year 2014 saw the release of the first white paper on DT, broadening its application from aerospace engineering to a diverse array of industries [54]. This signaled the superior versatility of DT, garnering attention within academia. By 2015, General Electric released a cloud service platform, Predix [57], which uses big data, IoT, and other advanced technologies based on DT to achieve real-time monitoring, timely inspection, and predictive maintenance of engines. Siemens also achieved notable results by employing DT in product development, specifically in assisted manufacturing and virtual commissioning [58]. In addition, Singapore has emerged as a trailblazer in proposing the use of DT technology to build innovative smart cities, thus improving urban management, accelerating development, optimising urban structures, and fostering city stability. By proposing a city model called “Virtual Singapore”, it helps users in make long-term rational decisions in city management, urban planning, etc. IDC’s release of IDC Future Scape: Global Smart City Forecast 2023 - China Insights concluded that by 2024, approximately 70 % of Chinese cities will adopt DT technology to promote sustainable urban development and improve the efficiency of city operations. The significant milestones in the evolution of DT technology are visualised in Fig. 5.

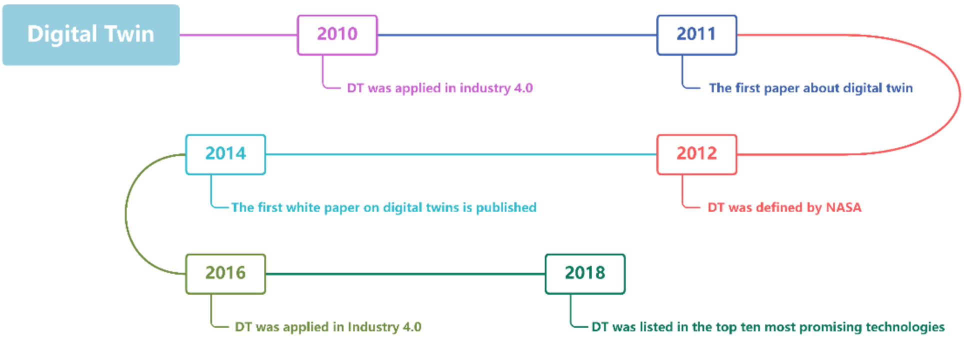

Fig. 5. DT timeline diagram.

### *B. Definitional Evolution of Digital Twin*

The concept of DT has undergone continuous refinement since its inception, and a universally recognised definition has yet to emerge [8]. At the beginning of Grieves’ concept of DT, he argued that DT consists of three dimensions: physical, virtual, and the connecting part of the two, and explored the synchronisation of the connecting part [54]. Then Tao and Zhang [59] for the application of DTs in simulation, based on the three-dimensional DT model, proposed that a complete DT consists of five dimensions: the physical part, the virtual part, the connection, the service system, and the data processing. Among them, the service system is equivalent to an integrated service platform to meet the individual needs of the users. Gartner offers a different perspective, defining the DT with four key elements: digital model, linked data, identification, and real-time monitoring capability, which improves the accuracy and completeness of the model by leveraging the bidirectionality of the data between the physical and the virtual to ultimately achieve the description of the physical entity [1].

As DT research id delved into specific applications, various new concepts have emerged. For example, Tao, Zhang, Cheng, and Qi [60] proposed the concept of digital twin workshop (DTW) based on the concept of DT, which consists of four parts: physical workshop, virtual workshop, workshop service system, and workshop twin data, and concluded that it is characterised by virtual-real fusion, data-driven, all-encompassing integration and fusion, and iterative optimisation. DTW has played an important role in the promotion of smart manufacturing. Zhuang *et al.* [61] contributed the concept of product digital twin, emphasising the reconstruction of the full-element and the digital mapping of a working process or state of a product in the virtual space. They illustrated its system composition, implementation pathway, and explored the developmental trajectory of digital twins. In addition, the concepts of organism DT and experimental digital twin have also been proposed [62], [63].

### *C. Technical Components of Digital Twin*

Digital twin is a process that involves gathering information from a physical object, transferring it to the virtual space for modelling and data analysis, and subsequently feeding back the results to the physical object to aid in decision making. This comprehensive application arises from the cross-integration of multiple technologies. Accordingly, this section outlines the digital twin mechanism from four key applications perspectives.

Data collection and transmission: Qi *et al.* [64] argued that the core of DT is a high-fidelity virtual model and only with an accurate understanding of the physical world can its accurate correspondence with the virtual model be realised. Therefore, achieving accurate physical perception and information collection is crucial. As a large amount of data is required to maintain the model at each stage of data twinning, more accurate data collection through distributed combinations of different types of sensors can provide data support for the DT system to achieve a perfect reproduction of the physical object. In this paper, the combination of sensors for ICV is discussed in Section II. Furthermore, the timely transfer of data is a crucial factor in maintaining the real-time aspect of the DT. Real-time is an important feature of DT and its importance to the whole system is self-evident. High-bandwidth fibre optic technology enhances data transmission by providing greater bandwidth, thereby reducing delays and improving the real-time performance of the system. In addition, cloud servers fulfil the requirements for data storage and management. Cloud-based data processing adeptly captures the characteristics of a product’s entire life cycle, enhancing database performance.

Construction of multiscale and multidomain models: Since DT needs to map physical entities and processes to virtual environments, the accuracy of the DT model directly affects the effectiveness of the representation, so it is very important to explore ways to improve the accuracy of the modelling. By using appropriate modelling algorithms to achieve feature extraction of data, the need to build multiscale and multidomain models can be better achieved. Simultaneously, DT modelling offers the advantage of cost reduction and facilitates modification of simulation parameters, mitigating the laborious adjustments needed for physical models. Model construction comprises geometric modelling for object appearance, behavioural modelling to describe object behaviour, and rule-based modelling for logic. Faced with intricate physical entities, these models can be considered distinct units, combined as necessary for multiscale and multidomain modelling. In addition to ensuring model construction accuracy, validation is essential. As argued by the authors in [64], optimising the model and reducing variability requires verification, validation, and accreditation (VVA). Given the dynamic nature of the virtual counterpart of the DT that evolves with the physical world, adjusting the virtual model through correction techniques is crucial. This ensures closer alignment with the actual state of the physical object, preventing the gradual accumulation of deviations.

Service application: DT service technology is mainly expressed as a response according to the actual needs of physical objects, such as process planning, equipment health management. This technology achieves its objectives by analysing data to furnish a foundation for guidance or assist in decision making for real objects. Illustrated by a complex system cluster, this technology enables precise, real-time decision making for physical objects. It achieves this by processing comprehensive and accurate real-time data, addressing the service demands throughout the entire life cycle of the product. Simultaneously, it offers guidance and suggestions for the general health operation by delving deeply into relevant information when addressing individual modules. In addition, this technology can also share data for other models without prerequisite information or share data for components that are difficult to develop, such as building a unified service platform for management, and users can use the corresponding services on demand.

Physical-virtual connection: The interaction of DT includes three types: physical entity-to-physical entity interaction, which is mainly manifested as direct communication between the two; virtual model-to-virtual model interaction, which is mainly manifested as information sharing between the two; and the most popular interaction between the physical object and the virtual model, where the physical object transmits the information collected by the sensors to the virtual model at the appropriate frequency to ensure that the virtual model is updated synchronously with the real world to ensure the efficiency of the model, while the virtual model also transmits the analysis results to the physical side in real time to assist decision making. This physical-virtual model makes DT efficient and dynamic [65]. Ensuring a robust connection between virtual and real requires unified communication interfaces and protocol technologies. Interface compatibility improves connection stability, while implementing appropriate security technologies is crucial to protect connection stability and security, ensuring data confidentiality.

## IV. APPLICATION OF DIGITAL TWIN IN DRIVERLESS VEHICLES AND FUTURE PROSPECTS

Autonomous vehicles are widely considered one of the most promising technologies for improving the safety and efficiency of road travel. The seamless integration of information space and physical space, a feature inherent in digital twin technology, enables the detection of any changes in real-world objects by sensors. These changes are promptly reflected in their virtual counterparts. This feature makes DT promising for vehicle-orientated applications such as vehicle simulation testing and fault detection [66]. In addition, digital twins offer qualitative advantages in optimisation algorithms and their real-time connectivity features help reduce production and service time or costs, introducing novel data analysis, prediction capabilities, and creative applications.

Consequently, current research on digital twin-based smart connected cars has garnered significant attention. For example, Vietnamese electric vehicle maker VinFast collaborated with Cerence to introduce a digital twin-based smart connected car, using the Cerence Connected Vehicle Digital Twin platform for cloud connectivity and personalised services. This section analyses applications related to the three modules of human, vehicle, and traffic environment within the DT framework.

### *A. Digital Twin Application for Vehicle*

In the era of Industry 4.0, amid the continuous evolution of the information industry, DT technology has found widespread application in the automotive sector, covering vehicle design, production, testing, and essential body technologies [67]. When addressing vehicles, the focus is primarily on constructing comprehensive models, either of the entire vehicle or specific parts, tailored to meet individual user requirements.

The impact of DT on the automotive manufacturing industry is profound, with applications extending across the product lifecycle, encompassing design, production, manufacturing, and maintenance. During the design and development phase, DT technology helps designers test products within virtual spaces, facilitating cost effective product enhancements. For example, conducting aerodynamic or engine power tests in the virtual realm reduces the costs associated with producing prototype cars. Additionally, the use of virtual models helps designers quickly identify product defects during the design stage, mitigating the workload for subsequent revisions. In the manufacturing phase, virtual simulations model products, production plants, or assembly lines. Visualising production processes such as welding and painting provides instantaneous feedback, enabling factories to quickly identify faults and avoid additional costs. Simulating assembly of parts helps prevent defects on the assembly line, optimise the utilisation of limited resources, and improve production capacity and efficiency. Additionally, the traceability features of virtual product models facilitate tracking and analysing issues in the production process. The bidirectional flow of data between the real space and virtual models enables timely problem solving, saving both time and costs associated with physical testing. In particular, the FAW JieFang J7 vehicle plant achieved a substantial improvement in product quality and production efficiency by modelling all its equipment and production links. In the post-sales maintenance phase, the virtual model of a sold vehicle is compared with the original, identifying potential faults and facilitating the replacement of damaged parts. Simultaneously, data on vehicle performance is collected in diverse driving scenarios to inform the development of next-generation vehicles. For example, Tesla aggregates daily data reports from each vehicle using a DT simulation programme to identify abnormalities and facilitate the vehicle learning process [67].

Autonomous vehicles require extensive data collection in real-world road scenarios to meet production safety standards. However, actual road tests face challenges such as high costs, difficulty in scenario reproducibility, and variations in traffic rules across different countries. These challenges have somewhat impeded the deployment speed of intelligent network vehicles. In contrast to traditional virtual simulation testing, DT-based testing relies on modelling in the real environment, aligning more closely with actual scenarios and yielding more realistic and reliable test results. Furthermore, compared to real road tests, DT improves safety, testing efficiency, and cost effectiveness. Due to reproducing special scenarios in real space has the disadvantages of high cost and long cycle time, while building suitable driving scenarios for testing through digital twins can effectively solve the above problems. This is because the test scene is generated based on the actual road surface, while it can modify the test parameters in real time to better simulate the driving environment under extreme weather, which is conducive to verifying the effectiveness of the automatic driving algorithm. As shown in Fig. 6, traffic flow at intersections is modelled and analysed. Currently, many companies are committed to the research of digital test platforms, such as the rFpro company through the digital simulation of the real environment, the modelling of different highways, enriching the test scenarios of automobile companies [68]. Furthermore, many scholars have also carried out extensive research in this area, such as the authors in [69] based on DT to set up a test environment facing different scenarios to evaluate vehicle safety, through analysis of vehicle speed and lateral load transfer in 13 scenarios. The effectiveness of driving risk assessment is illustrated and the authors in [70] based on DT to test the low latency characteristics of vehicle decision making in the 5G environment. The cyclic scenario method was used to verify that the method resulted in an average one-way delay of less than 5 ms.

Fig. 6. Simulation modelling of real-time traffic flow at intersection [71].

Currently, ICV often makes decisions through environmental information collected from multiple sources, and the complexity of the data inevitably leads to greater computational pressure on the on-board computing devices while making the decisions more reasonable. To address the challenges of cost and energy consumption associated with in-vehicle computing devices, solutions such as cloud computing and edge computing have been proposed for data processing [72], [73]. DT-supported ICV can obtain higher computational efficiency and better quality of service by modelling different traffic units and reasonably allocating resources in cloud servers and edge computing devices (ECDs). In interactions with cloud servers, decision making is facilitated by constructing the corresponding DT models within the cloud infrastructure. Communication between vehicles and the cloud ensures compliance with low latency requirements and enables larger data storage capacity [74]. On the other hand, when engaging with edge computing, the distributed arrangement of ECDs allows DT-empowered ICV to optimise resource allocation. The modelling of various independent ECDs ensures a balanced load distribution throughout each ECD [75].

In addition, the ability to achieve high-quality and accurate trajectory prediction has become an important basis for judging the performance of ICV. Currently, common trajectory prediction models, such as long short-term memory (LSTM) [76], are used to forecast future vehicle trajectories. However, inter-vehicle interactions under complex road conditions or the sudden appearance of traffic participants can greatly interfere with the measurement accuracy of the model. While ICV empowered by DT can achieve on-line fine-tuning to meet the need for high accuracy of trajectory prediction by exploiting the feature of low latency to enable further optimisation of models like LSTM. The authors in [77] enable adaptive fine-tuning of the LSTM model to meet the need for real-time accuracy by using the deep Q-learning algorithm in the DT model. The trajectory prediction scheme proposed by this method can maintain the prediction accuracy of the safe formation and reduce the updating delay of the neural network by up to 40 %. However, the interaction between DT and ICV relies on extensive data support from various road devices. Any inaccuracies in the data, caused by systematic errors or signal loss, can impact trajectory prediction. To address this issue, the authors in [78] achieve error recovery of the predicted trajectories based on DT by correlating positioning data with sensory data and providing timely error feedback.

### *B. Digital Twin Application for Transport Facilities*

Currently, amidst the ongoing advances in digital technology, transportation infrastructure is undergoing rapid evolution, and DT, serving as a technology that bridges the real and virtual realms, holds promising applications in the intelligent transport sector. This technology has the potential to empower intelligent transportation systems (ITS) with scientific advances, facilitating the industry's transition toward intelligent and dynamic development [66]. In the field of intelligent transportation, DT has the ability to promote decision optimisation and explore the potential of ITS through its real-time visualisation and virtual-reality combination technology, so as to achieve a deeper understanding of road information and traffic demand. At the same time, DT uses simulation modelling to optimise the road network, and through its virtual modelling advantages, it can provide ITS with solutions to traffic issues, improve the efficiency of decision making, alleviate the problem of traffic congestion, increase the capacity of the road network, and reduce the occurrence of traffic accidents.

Traffic infrastructure serves as the cornerstone of an intelligent transport network and smart city development. A well-designed traffic infrastructure enhances information exchange between vehicles and roads, thus improving driving efficiency. The use of DT in the transport infrastructure can make the original single infrastructure components form a network of the overall infrastructure, which can not only make decisions on the urban traffic environment from a holistic point of view, but also improve the traffic situation in local areas, to achieve the most comprehensive and detailed understanding of real-time traffic. Consider adaptive traffic signal control as an example, where the integration of vehicle networking technology adjusts signal waiting times at intersections based on vehicle numbers, effectively reducing traveller waiting times. However, in the face of complex and congested urban road conditions, traffic delays are inevitable. In view of this situation, by combining digital twin technology, the traffic flow data of different intersections can be analysed in real time, and the traffic lights of downstream intersections can be optimised and adjusted according to the waiting time of vehicles at upstream intersections. It can reduce vehicle waiting time to avoid traffic jams and realise the fine management of smart cities. The authors in [79] propose an adaptive traffic signal control (ATSC) based on DT, while using historical traffic data for calibration to further reduce traffic signal delays in congested environments. ATSC that uses DT in 87.5 % scenarios has a better level of services. Furthermore, the amalgamation of DT with smart cities has promising application prospects [80]. The results show that the accuracy of the system constructed in this paper reaches 97.80 %, which is at least 2.24 % higher than the DL algorithm adopted by other scholars. For road scenarios, the phenomenon of urban congestion caused by pedestrian-vehicle mix or indiscriminate lane occupancy is endless. By combining roadside facilities, data collection can be achieved, and then through the control of traffic signals or traffic trajectory planning and other technologies to empower the smart city, improve resource management and resource use efficiency, such as the authors in [81] use real-time data from roadside equipment to provide feedback to the real-time monitoring platform for the road system, facilitating effective responses to emergencies.

In the current landscape of advancing information technology, there is a growing aspiration for ITS to achieve further development through the integration of technological tools such as machine learning, deep learning, and streaming analytics. Artificial intelligence technologies such as deep learning and machine learning contribute to the enhanced intelligence of ITS, while DT facilitates real-time data processing for decision making. Combining them in ITS can better capture hidden data in the traffic network and enable value-added processing of information. For example, the authors in [82] combined DT with deep learning in intelligent transport to construct a convolutional neural network-support vector regression (CNN-SVR)-based cooperative intelligent transportation system-digital twins (CITS-DTs) model, which can provide more reasonable vehicle traffic planning and alleviate traffic pressure. Compared to other algorithms, the security prediction accuracy of this algorithm reaches 90.43 %. In [83], on the other hand, the authors leverage multiple emerging technologies, including machine learning, fog computing, and edge analytics, to address challenges related to data redundancy and inefficient collaboration in systems dealing with heterogeneous information.

### *C. Digital Twin Applications for Vehicle Occupants*

With the rapid development of AI technology, as well as V2X, it is believed that a part of fully autonomous vehicles will appear in the foreseeable future. However, due to various reasons, there will still coexist many driver-controlled vehicles for a period of time. Furthermore, even for fully autonomous vehicles, consideration of the preferences of the passengers they carry plays an important role in improving the user experience. Therefore, it makes sense to build human-centred driving systems. Empowered by DT, the driver digital twin (DDT) [84] can meticulously consider user-specific preferences, increasing the user experience through comprehensive data analysis. As illustrated in Fig. 7, in addition to providing distinctly new concepts, strategies, and tactics for reaching human-centred harmonious driving, the development of DDT technology also offers new perspectives on the direction autonomous vehicles will take in the future.

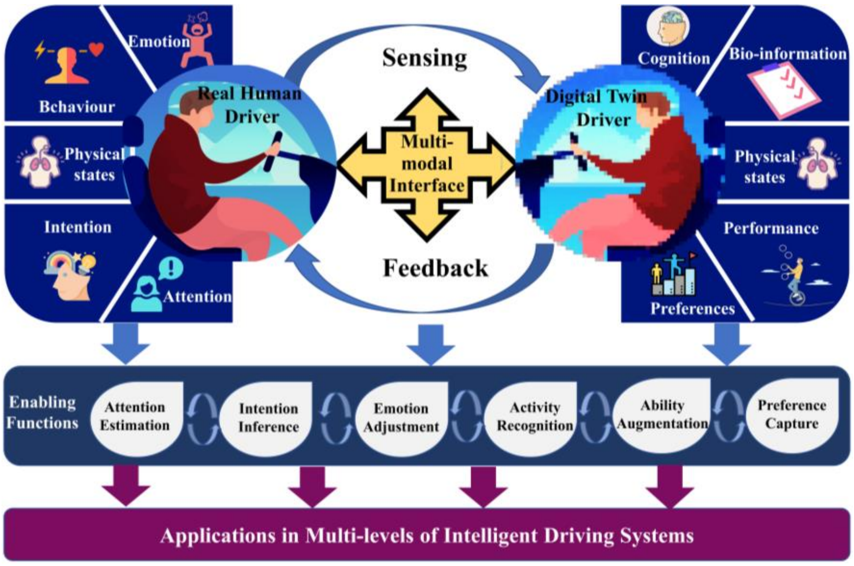

Fig. 7. The application of DT to drivers.

When creating a digital model of the user, a comprehensive array of internal and external human characteristics is captured using sensors, encompassing various state sensors (e.g., cameras, seat sensors) and human health monitoring sensors (e.g., temperature detection, heartbeat detection). At the same time, the system performs personalised modelling for distinct driving habits (e.g., driving speed, seat angle), decision making habits (e.g., habitual lane), and user emotional characteristics. This enhancement contributes to an improved user experience and increases the acceptance of highly automated vehicles. For example, the health detection system, leveraging historical data, enables better identification of divergent user behaviours among specific groups, thereby facilitating early warnings to prevent potential traffic accidents.

In addition, the full lifecycle characteristics of DT can make it possible to predict user behaviour through the collection of historical data when facing the establishment of the driver model, thus enhancing the autonomy of the system. The user-centric DDT system excels in integrating vehicle-related data with the user's state to predict driver behaviour and identify anomalies (e.g., drunk or fatigued driving). Moreover, it can serve as a decision making basis for third parties, such as insurance companies. The real-time synchronisation of the DDT model with the actual driver's attributes helps the system quickly assess the emotional fluctuations and behavioural changes of the subject, preventing potential dangers. Therefore, in addition to commercial and domestic vehicles, DT can provide a safer driving experience for engineering and even special equipment vehicles, improving driving safety and smoothness.

Since DT can better personalise the modelling of the behaviour of different users based on historical data, sharing data with each other can help users to understand the future behaviour of users around them in extreme weather (e.g., when the field of view is disturbed due to weather such as fog) and express the possible risks of different behaviours to users visually. For example, the authors in [85] used V2V technology to exchange driver behaviour information between adjacent vehicles, enabling users to avoid potential collision risks. The error rate of collision prediction in this paper is less than 2.5 %. Unlike other DT models, the driver-centric digital twin not only underscores human physiological states but also gives equal importance to psychological aspects. It aspires to realise a human-centred driving system through real-time analysis of historical data, perceiving the driver's intentions and predicting their future behaviours. The authors in [86] consider vehicle movement data in addition to traffic congestion when trying to alleviate traffic congestion problems, road capacity, but also analyses the driver's intention to allow real-time decision making to regulate traffic problem.

### *D. Challenges and Opportunities Regarding the Use of Digital Twins in this Context*

The preceding section explored the application of DT in ICV from the perspectives of vehicles, transport facilities, and vehicle occupants. While DT has significant potential to advance ICV, several challenges must be addressed to effectively commercialise this technology for DT in ICV. This section delineates the challenges and opportunities within this research domain.

1. Unified modelling framework.

Due to the varied responses of vehicles in different driving scenarios, none of the existing DT modelling frameworks are universal. For example, the framework proposed in [86] focusses mainly on mobile objects. Although scholars have endeavoured to introduce integrated modelling frameworks for the practical application of DTs technology, the absence of a convincing unified framework persists. This is attributed to the complexity and variability of the collected data, originating not only from pedestrians, traffic devices, and other vehicles within the ICV but also from the diverse data parameters required for modelling by the multisource sensors on the body of the vehicle and the heterogeneous systems supporting them. Consequently, a substantial volume of data lacks the desired integration capability and is challenging to encapsulate within a single modelling framework. Moreover, the non-exclusivity of the digital twin modelling framework to a specific technology or vendor, coupled with the diverse technology requirements of different customers based on their individual interests, exacerbates the challenge of achieving comprehensive modelling. In this paper, we argue that a good DT modelling framework should have a high degree of modularity and good scalability through separation and reorganisation of different parts to cope with the needs in different scenarios. Simultaneously, the framework should comprehensively account for all participants and exhibit a highly inclusive structure for multiple devices within the scenario. This structure can assimilate numerous traffic participants, enabling it to handle more complex traffic environments.

2. Challenges of DT standardisation in the transport domain.

A unified wireless communication environment is a desired objective to provide users with a more convenient and feature-rich operating environment. However, current data transmission and communication technologies for vehicles mainly include dedicated short range communications (DSRC), LTE-V2X, and C-V2X. DSRC is widely used for V2V communication or data transmission between vehicles and road test equipment, but it currently struggles to meet the demand for higher quality of service and higher transmission rates. The latter two technologies, while offering greater bandwidth, are limited in their deployment applications due to their high costs and service quality issues in fast-moving scenarios. Currently, various companies or organisations lack a standardised approach when accessing DT data application programming interfaces (APIs), and different technologies have their unique advantages and disadvantages, which results in technicians often selecting the most suitable communication technology. The development of relevant unified standards can provide better storage and management services for data while enhancing the experience of the human interaction interface. Therefore, how to find a standardised communication solution in the current complex communication environment so that it can achieve a clever balance between low cost and low latency is an important issue that needs to be resolved. And this requires not only the upgrading and iteration of technology but also the relevant departments to carry out the provisions of the unified technology.

3. High-load problem of data computation.

Cloud-edge computing is rapidly evolving with the advent of advanced machine algorithms and high-performance computing platforms. However, there is still significant room for improvement in its integration into the DT framework for efficient real-time data processing. Given that ICVs often operate in complex traffic environments, one research direction involves extracting high-quality data from multiple sources to train DTs with high-fidelity characteristics. In addition, when the huge amount of data changes in real time, how to clean the useless data in time and discover the newly generated useful data is also a challenge. Addressing these challenges requires more advanced learning algorithms capable of handling large-scale data updates and iterations, thereby optimising decision making. Furthermore, integrating Blockchain Terminal (BCT) into DT-based ICVs holds promise for mitigating redundancy and computational challenges associated with large-scale data processing.

4. Security.

The automotive industry faces significant data security risks, particularly due to its close connection with human users. Operating in a highly dynamic environment, a moving vehicle continually exchanges large-scale information with the external world, emphasising the crucial role of security and confidentiality in the communication environment. Common attacks involve attempts to disguise as registered users to infiltrate the system and disseminate false or duplicate information. Robust security measures are essential, especially for highly confidential data, ensuring its exclusive use for decision making services within the system and preventing capture by other connected devices or unauthorised access by malicious actors. In the ICV decision making processes, the data perceived by external sensors significantly influences vehicle decisions, underscoring the timely identification of the authenticity of the data as paramount. Anomaly detection through data is an effective way to deal with this threat, such as detection through supervised or unsupervised learning methods, etc. In addition, the development of communication protocols for the relevant data can also increase the security of the interaction. The trustworthiness of cloud computing platforms is a critical consideration, with public cloud platforms potentially reducing operating costs but sacrificing some control over data, whereas private cloud platforms offer enhanced security.

5. High-quality of data in transit.

Although DTs aim, to some extent, for complete and accurate synchronisation between the physical vehicle and the virtual object to effectively predict the future trajectory of the vehicle, there remains a degree of inaccuracy in trajectory prediction over long distances. This stems from small errors introduced by communication delays or vehicle measurement noise, leading to cumulative deviations that render the predicted trajectory unreferenced after prolonged simulation. For example, the authors in [87] suggest that certain fixed parameters of the model, such as the sampling interval, contribute to this prediction inaccuracy. Furthermore, in distributed edge computing environments, despite offloading some computational tasks to on-board edge servers for reduced latency, the density of base station deployments and the existence of cellular dead zones in certain areas can still introduce signal delays and severe interference, diminishing the accuracy of DTs. SpaceX’s Starlink technology is anticipated to address cellular dead zones, enhancing signal transmission quality. In addition, modifying the interference immunity and high spectral characteristics of the transmission components can also help improve the transmission environment and increase the quality of communication data, for example, by using passive reflective components.

6. High-quality communication technologies

The real-time nature of DTs is characterised by high bandwidth and low latency in the practical application of the technology, but technologies such as LTE-V2X or C-V2X in the current 5G environment face challenges in delivering an optimal user experience. Even with computing tasks offloaded through cloud-edge computing, vehicles in high-mobility contexts struggle to achieve low latency characteristics in complex road conditions. Future expectations include addressing communication challenges caused by large-scale data computation through the integration of 6G technology with mobile edge computing (MEC). This may involve leveraging technologies such as visible-light communication under 6G or strategically deploying roadside computing devices.

## V. CONCLUSIONS

The application of DT in ICV spans the entire lifecycle, encompassing product design, vehicle testing, and post-maintenance. This application contributes significantly to the digital transformation of the automobile industry while ensuring cost effectiveness. Following an overview of ICV, this paper provides a detailed exploration of the generation and development of DT, along with key technologies. It emphasises the specific application of DT in ICV, elucidating its operational mechanism and potential uses from three perspectives: vehicle, traffic facilities, and vehicle occupants. Additionally, the paper delves into key challenges associated with the use of DT technology in ICV, providing information for future implementation. A major future step of this study is to explore the application of the DT framework for ICV in multiple urban scenarios, such as environmental perception in complex scenarios such as urban intersections and urban expressways. By employing modular modelling of different types of objects (such as pedestrians and vehicles with different functions), the computing load of complex and variable data on the cloud can be reduced and the validity of the proposed digital twin framework can be verified. In addition, it can further search for which modules are better placed on cloud servers to take full advantage of the unique capabilities of the digital twin framework.

## CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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