Survey of Simulation Testing and Evaluation Technologies for Internet of Vehicles: Postprint

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Abstract

Before large-scale deployment of V2X networks and their widespread application in the intelligent connected vehicle domain, comprehensive and in-depth testing and evaluation of their performance and functionality are required, with evaluation and analysis through simulation technology being the current mainstream approach. Based on the testing and evaluation requirements in V2X research and application processes, this study summarizes mainstream network simulators and traffic simulators, categorizes existing V2X simulation platforms, and investigates and comparatively analyzes typical platforms. According to the application characteristics of V2X networks, it examines and summarizes factors affecting simulation performance, including vehicle mobility models, channel propagation models, and driver behavior. Typical evaluation metrics for V2X functionality and performance testing are summarized from the perspectives of network simulation metrics and V2X application-related metrics. Finally, future development directions of V2X simulation testing are discussed.

Full Text

Preamble

Survey on Simulation Testing and Evaluation Technologies for Internet of Vehicles

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Abstract: Large-scale deployment of Internet of Vehicles (IoV) and its extensive application in intelligent connected vehicles require comprehensive and in-depth testing and evaluation of performance and functionality. Simulation-based evaluation and analysis has become the mainstream testing approach.

Starting from the testing and evaluation requirements in IoV research and application processes, this article summarizes mainstream network simulators and traffic simulators, classifies existing IoV simulation platforms, and conducts comparative analysis of typical platforms. Based on the application characteristics of IoV, it systematically examines key factors affecting simulation performance, including vehicle mobility models, channel propagation models, and driver behavior. The paper also summarizes typical evaluation metrics for IoV functional and performance testing from the perspectives of network simulation indicators and application-related metrics. Finally, it discusses future development trends in IoV simulation testing.

Keywords: Intelligent and Connected Vehicles; Internet of Vehicles; Testing and Evaluation; Traffic Simulation; Network Simulation; Metrics

0 Introduction

With the rapid development of the new generation of technology revolution centered on the Internet and artificial intelligence, autonomous driving technology continues to achieve breakthrough progress, making intelligence and connectivity important directions for automotive development. The "Made in China 2025" initiative has identified intelligent connected vehicles as a key focus area. Internet of Vehicles (IoV) technology is one of the critical technologies for transforming traditional automobiles toward intelligence and connectivity, and constitutes an essential component of the intelligent connected vehicle architecture. In recent years, it has garnered significant industry attention and in-depth research. Currently, the most prominent IoV technologies include the DSRC protocol based primarily on IEEE 802.11p and the C-V2X protocol based on cellular technology (including LTE-V and evolved 5G-V2X), enabling four communication modes: vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-human (V2H), and vehicle-to-network (V2N). These technologies encompass various application scenarios such as traffic information collection, real-time traffic condition monitoring, emergency information dissemination, assisted driving, cooperative driving, platooning, remote vehicle operation, high-precision map downloads, and entertainment multimedia.

To ensure that intelligent connected vehicles can operate safely, reliably, and efficiently under various road traffic conditions, weather environments, and usage scenarios, extensive testing and validation are required, involving a complex evolutionary process. Therefore, testing and evaluation constitute an indispensable and critical component in the research, development, and application of intelligent connected vehicles, serving as an essential means for large-scale deployment of IoV infrastructure and equipment and their widespread application in intelligent automobiles [1]. IoV is essentially a special type of Mobile Ad Hoc Network (MANET). On one hand, it inherits the characteristics of traditional MANETs, including high-speed node movement and frequent network topology changes. On the other hand, it possesses distinctive features that differentiate it from conventional MANETs [2,3], primarily including: vehicle nodes are constrained by static road geometry; vehicle node movement is influenced by real-time traffic conditions (congestion levels, traffic light status, traffic control, etc.) and driver behavior; and wireless channel quality is affected by multiple factors such as relative vehicle speed, roadside building obstruction, and multipath effects. Precisely because of these characteristics, when researchers and developers conduct functional and performance testing of IoV protocols or autonomous driving applications in real-world road environments, they must undertake large-scale deployment of IoV infrastructure and terminal equipment on roads and vehicles. Furthermore, when studying the interactions and mutual influences between IoV technology and traffic elements or network channel transmission, it is necessary to construct various test scenarios across different road environments including urban, highway, and rural settings. Therefore, although real-world environment research and testing of IoV is the most direct and effective method, it is constrained by testing costs, site availability, personnel scale, difficulty in highly reproducible test scenarios, and safety concerns. Consequently, simulation-based testing, evaluation, and research and development of IoV remains a primary technical approach.

The construction of IoV simulation platforms relies on two fundamental components: network simulators and traffic simulators. Network simulators are used for packet-level simulation of traffic data transmission and reception between IoV nodes, as well as backend load, routing, links, and channels [7]. Traffic simulators are primarily used to generate realistic vehicle trajectories that serve as input for network simulators. IoV simulation involves both traffic simulation and network simulation, but it is not a simple superposition of the two. Currently, mainstream IoV simulation platforms are generally based on deep coupling of these two types of simulators to make the simulation environment more realistic. Specifically, realistic vehicle trajectories are generated in traffic simulators based on different vehicle mobility models and input into network simulators. Through the interaction between the two, the performance of different network protocols under various vehicle mobility models can be validated.

Currently, multiple network simulators can be applied to test communication performance between vehicle communication nodes, such as NS2 [8], NS3 [9], JiST/SWANS [10], OMNeT++ [11], QualNet [12], OPNET [13], and GTNetS [14]. All support various wireless network communication protocols and include or can be extended to support node mobility models. Additionally, many mature traffic simulators exist, such as SUMO [15], VISSIM [16], PARAMICS [17], TransModeler [18], TRANSIM [19], and CORSIM [20]. Many popular IoV simulation platforms are developed based on these simulators, but they employ different solutions for deeply coupling the two types of simulators. Based on differences in coupling approaches, this paper categorizes common IoV simulation platforms into four types: separated, embedded, joint, and integrated.

1.1 Separated IoV Simulation Platforms

Separated IoV simulation platforms refer to simple unidirectional linking between traffic simulators and network simulators, where trajectory files generated by the traffic simulator are input into the network simulator for wireless communication simulation between nodes, as shown in [Figure 1: see original paper]. Examples include CARLINK/CMU [21], CORSIM/QuelNet [22], and MITSIMLAB/NS2 [23]. The advantage of this approach lies in its simple operation and easy implementation. However, the disadvantages are also obvious: once vehicle trajectories are determined in the traffic simulator, they become unmodifiable in the network simulator, which clearly differs from reality. In actual environments, vehicle trajectories will certainly be modified based on network communication results. This approach severs the relationship between the two simulators and essentially runs them separately, enabling only simple IoV simulation tasks. Consequently, this approach is rarely used today.

1.2 Embedded IoV Simulation Platforms

Embedded IoV simulation platforms utilize existing network simulators, traffic simulators, or middleware to embed corresponding required modules to build a complete IoV simulation platform. There are three primary embedding schemes, as shown in [Figure 2: see original paper].

a) Embedding traffic simulation modules into network simulators. This is the most widely used scheme in embedded platforms. As mentioned earlier, existing network simulators already integrate simple node mobility models; adding more complex, realistic vehicle mobility models on this basis can achieve the desired functionality. Examples include STRAW/SWANS [24], ASH [25], and NS3 extension [26]. Compared with embedding various complex network protocols and communication modes into traffic simulators, this approach is less costly and easier to implement.

b) Embedding wireless network simulation modules into traffic simulators, such as TSM [27]. This scheme is not common in practical applications, mainly because the operational difficulty is relatively high, requiring independent development of numerous complex network protocols and communication modes, with no guarantee of wireless network communication stability.

c) Utilizing extensible simulation middleware (such as ARTiS) to embed both traffic simulation modules and wireless network simulation modules, such as MoVES [28]. The benefit of this approach is that the programming for both modules can be implemented within a single program, facilitating more timely information interaction and feedback, but it consumes substantial human resources and time.

1.3 Joint IoV Simulation Platforms

Joint IoV simulation platforms make full use of existing network simulators and traffic simulators, linking them bidirectionally and using middleware for information interaction, as shown in [Figure 3: see original paper]. Platforms such as CARISMA/NS2 [29], TraNS [30], Veins [31], MobiREAL [32], iTETRIS [33], and SimIVC [34] all adopt this approach. Unlike separated simulation platforms, vehicle trajectories in these platforms change in real-time during simulation. If a vehicle node receives a message from another vehicle node during simulation that requires changing its current operational state (for example, receiving an emergency braking message from a vehicle ahead), the network simulator sends a request to the traffic simulator (network feedback). After receiving the request, the traffic simulator adjusts the vehicle node' s operational state and then sends the vehicle node' s latest position and speed information back to the network simulator (traffic feedback). The greatest advantage of this approach is achieving real-time information interaction between the network simulator and traffic simulator. Although simulation speed and efficiency are not as high as embedded and integrated solutions, since mature network simulators and traffic simulators are used, they can support a large number of wireless network communication protocols and complex vehicle mobility models, offering high simulation precision. This approach is widely used in current IoV simulation research.

1.4 Integrated IoV Simulation Platforms

Integrated IoV simulation platforms refer to standalone IoV simulation platforms that integrate both traffic simulation modules and wireless network simulation modules, such as NCTUns [35], Gorgorin [36], GrooveNET [37], AutoMesh [38], and VSimRTI [39]. These platforms have the highest coupling tightness between traffic simulation modules and wireless network simulation modules, resulting in faster simulation speed and higher efficiency. The disadvantages lie in greater difficulty, longer development cycles, and since they are developed independently, their simulation accuracy is difficult to compare with mature network simulators and traffic simulators.

2 Typical IoV Simulation Platforms

1) TraNS

TraNS combines the NS2 network simulator and SUMO traffic simulator to build a more realistic simulation environment, supporting vehicular communication technology through the IEEE802.11p protocol stack. Its framework structure is shown in [Figure 4: see original paper]. TraNS is an open-source IoV simulation platform offering two operation modes. The first is a network-program-centric mode, primarily for network programs that do not affect the real-time mobility of vehicle nodes, such as data exchange and music downloads. The second mode is an application-centric mode, specifically for applications that affect vehicle behavior during traffic simulation runs, such as emergency alerts and collision avoidance applications. TraNS is developed using Java and C++ and can work on both Linux and Windows platforms. In the application-centric mode, vehicle trajectories are not pre-generated in the traffic simulator but are dynamically generated during simultaneous operation of both simulators. TraCI (Traffic Control Interface) is utilized to achieve this coupled simulation. To control vehicle node mobility, the TraCI interface uses atomic mobility commands such as stop, change lane, change speed (increase/decrease), etc. The application module interacts with the driver behavior model and adjusts the mobility attributes of instantiated vehicles when necessary.

2) Veins

Veins is an open-source framework for wireless communication simulation in vehicular mobility environments, with its framework structure shown in [Figure 5: see original paper]. It supports and extends two mature simulators: the event-based network simulator OMNeT++ and the traffic simulator SUMO, providing a comprehensive set of models for IoV simulation. Veins also uses the TraCI interface, with the two simulators connected via TCP sockets, enabling bidirectional coupling simulation of road traffic and network traffic. Vehicle movement in SUMO is mapped as node movement in OMNeT++ simulation. Key features of Veins include: scientifically simulating multiple vehicle mobility patterns; supporting detailed models of IEEE 802.11p and IEEE 1609.4 DSRC/WAVE network layers, including multi-channel operation, QoS channel access, noise, and interference effects; supporting models for cellular networks such as LTE; importing entire scenarios from OpenStreetMap, including buildings, speed limits, lane numbers, traffic lights, access and turn restrictions; and supporting shadowing models caused by buildings or vehicles.

3) iTETRIS

iTETRIS, developed under the European FP7 program, is a standards-compliant open-source IoV simulation platform that conforms to ETSI standards, with its framework structure shown in [Figure 6: see original paper]. iTETRIS integrates and extends two widely cited open-source platforms for vehicle mobility and wireless communication simulation: SUMO and NS3. It supports exhaust emissions, noise, and ADAS models, and supports wireless network communication protocols such as IEEE 802.11p and WiMAX. The iTETRIS architecture is highly modular. Through open APIs, it can integrate various network simulators and traffic simulators, and manage the operation of both simulators through the iCS module. Its open-source nature and modular architecture facilitate future platform expansion.

4) NCTUns

NCTUns is a hybrid IoV simulation platform primarily composed of a graphical user interface, simulation engine, Car Agent, and Signal Agent. It integrates vehicle mobility simulation modules and wireless network communication simulation modules, using Tunnel Network Interface (TNI) to provide a fast feedback loop between the two modules. It supports multi-core processors and parallel programming. NCTUns supports various protocols for wireless network communication, including IEEE 802.11b/e wireless LAN, IEEE 802.16d/e WiMAX wireless networks, multi-interface mobile nodes for heterogeneous wireless networks, and IEEE 802.11p/1609WAVE wireless vehicular networks.

5) VSimRTI

VSimRTI is a comprehensive framework for evaluating new solutions in cooperative intelligent transportation systems. It enables detailed modeling of complex communication technologies including vehicle motion, V2X communication, and cellular networks. VSimRTI combines different simulators. Compared with existing fixed simulator coupling, the VSimRTI simulation infrastructure framework facilitates easy integration and interaction of simulators. Based on specific requirements of simulation scenarios, the high flexibility of VSimRTI allows the most suitable simulators to be coupled for modeling vehicle traffic, emissions, wireless communication (cellular and ad-hoc), driver behavior, and mobile applications.

Based on important factors affecting IoV simulation results, the above typical IoV simulation platforms are analyzed and compared, as shown in .

Comparison of Typical IoV Simulation Platforms

3 Factors Affecting IoV Simulation Performance

3.1 Vehicle Mobility Models

In IoV environments, vehicle movement significantly impacts network topology structure. Therefore, in actual simulation testing, selecting vehicle mobility models that can reflect vehicle movement characteristics according to real test scenarios is crucial. Generally, based on the coverage and functional characteristics of mobility models, they can be divided into three categories [40]:

a) Random motion models. These models describe vehicles as randomly moving nodes, with parameters such as movement direction and speed randomly sampled. Due to their simple implementation, these models are frequently used in MANET simulations. Literature [41] conducted simulation tests on the performance of the bypass AODV IoV routing protocol using random motion models and concluded that random motion models cannot truly reflect the movement patterns of vehicle nodes on real roads. Therefore, researchers currently rarely adopt random node motion models for simulating vehicle movement in IoV environments.

b) Actual trajectory models. Compared with using random node mobility models, node movement models based on pre-recorded actual motion trajectories represent an important step toward achieving realistic vehicle simulation. In event-based simulations, each vehicle GPS position update is reflected in the simulation as a separate event occurring at its recorded time. Literature [42] utilized quasi-steady-state traffic data from multiple weekdays and different time periods on three highways near Madrid, Spain, to construct actual trajectory models and simulated the impact of actual traffic trajectories on network topology. This trajectory-based motion model produces the most realistic vehicle movement process in network simulation. However, its practical application is limited because available trajectories are scarce and cannot reflect the trajectories of all vehicles on the road.

c) Traffic flow models. These models primarily consider multiple factors affecting vehicle movement in real road environments from microscopic, macroscopic, and macro-microscopic perspectives, modeling vehicle mobility as traffic flow. Microscopic traffic flow models use individual vehicles as basic units, primarily reflecting interactions between vehicles. Macroscopic traffic flow models reflect the overall characteristics of vehicle movement, using fluid dynamics theory to significantly reduce computational load. Macro-microscopic traffic flow models consider both macroscopic and microscopic characteristics. Currently, microscopic traffic flow models are most widely used in IoV simulation. Literature [43] addressed the problem of constructing traffic flow models for unmanned vehicles in connected environments, establishing traffic flow models under IoV environments and studying highway congestion control problems achievable in such environments.

3.2 Channel Models

In actual road networks, wireless network channel quality is affected by multiple factors such as relative vehicle speed, roadside building obstruction, and multipath effects. Therefore, modeling the characteristics of radio propagation between vehicle nodes is of great significance for IoV simulation. Commonly used IoV channel models include the following three types:

a) Free space propagation model [44]. Free space refers to a propagation environment without any attenuation, obstruction, or multipath—ideal propagation conditions. When radio waves propagate in free space, their energy is neither absorbed by obstacles nor produces reflection or scattering, with no obstacles blocking the propagation path, and the ground reflection signal field strength reaching the receiving antenna can be neglected. The free space model is the most widely used and simplest channel propagation model in IoV simulation, where radio wave loss is only related to propagation distance and wavelength, with an additional environment-dependent path loss exponent introduced to account for non-ideal channel conditions. However, simulation analysis in literature [45] shows that while the free space propagation model helps simplify IoV simulation testing difficulty, it cannot accurately describe network propagation mechanisms in real IoV environments.

b) Two-ray ground reflection model. The two-ray ground reflection model is a radio propagation model that can predict path loss during line-of-sight (LOS) propagation between transmitting and receiving antennas (typically with different heights). It is a more practical path loss approach that considers ground reflection of wireless signals, where the received signal has two components: the LOS component and a multipath component primarily formed by a single ground reflected wave. Literature [46] demonstrated that the two-ray ground reflection model can be observed in multi-vehicle scenarios and used this model to fit ray tracing data.

c) Shadowing model. In actual road networks, buildings or obstacles blocking direct line-of-sight cause attenuation of wireless signals between vehicles. The shadowing model was proposed to reproduce this effect in network simulation. Literature [47] proposed treating vehicles as three-dimensional obstacles and considering their impact on received signal power and packet reception rate for line-of-sight propagation, demonstrating the importance of this effect through experimental measurements. There are two primary methods for constructing shadowing models: one uses stochastic models, especially log-normal distribution-based random models; the other uses specific geometric models. The latter method requires a rough geometric description of the simulation scenario, which mature simulators can now provide, or can directly import real-world maps.

3.3 Driver Behavior

In most cases, considering only vehicle mobility models and channel models is insufficient to comprehensively describe specific IoV applications, because "driver behavior" also affects IoV simulation test results. Although this factor is fundamental for accurate and realistic evaluation of IoV application performance, most current IoV simulation platforms simply assume that driver behavior matches expectations or technical system recommendations. As IoV simulation research deepens, considering driver behavior has been recognized as a very important aspect. At least before fully entering the autonomous driving stage, driver behavior significantly impacts driving decisions, as drivers may not necessarily adopt the technically optimal solution proposed by the system. In fact, driver behavior affects systems not only at the microscopic level (such as research on ideal car-following models) but also at the macroscopic level (affecting route planning and route changes).

Research on drivers shows they can be divided into four categories: a) Route changers—drivers willing to change timing and routes based on traffic information; b) Pre-trip changers—drivers willing to change routes before departure; c) En-route changers—drivers only willing to change routes before entering potentially congested sections; d) Non-changers—drivers completely unwilling to change routes.

Based on different driver reactions to optimal solutions provided by technical systems, driver behavior can be categorized as follows: a) Always compliant. This category represents all drivers who act exactly as expected, taking necessary actions according to technical system recommendations—typically the ideal condition in most IoV application research; b) Early changers. This category represents all drivers who believe early changes ($d > D$) are the best solution to avoid traffic incidents, where d represents distance from the incident and D represents a defined threshold distance. That is, incidents beyond threshold D are also considered relevant. For distant obstacles or congestion, these drivers always assume there will be no significant improvement before they arrive and choose to detour early, helping prevent secondary congestion caused by all drivers attempting to detour with short notice; c) Non-early changers. This category represents all drivers who believe only traffic incidents within a certain distance ($d < D$) are relevant, considering incidents beyond threshold D irrelevant. For distant obstacles or congestion, these drivers simply assume there will be sufficient time for resolution before they arrive and do not choose early changes; d) Never changers. All drivers in this category are very insistent on their daily behavioral habits, completely ignoring suggestions and advice. This driver category must be explicitly distinguished from the commonly used penetration rate indicator, because although these drivers do not follow any suggestions, their vehicles will certainly participate in distributed vehicle networking applications.

4 Evaluation Metrics for IoV Simulation Test Results

4.1 Network Simulation Metrics

In IoV simulation, different metrics are frequently used to evaluate network performance. Classic network simulation metrics include [48~50]:

a) Network Capacity (NC). Network capacity is one of the most important metrics for describing wireless network performance, enabling determination of whether certain applications are theoretically feasible given fundamental capacity limitations of wireless channels. Network capacity typically refers to how much data can theoretically be transmitted, usually measured in Mbit/s.

b) Throughput (TH). Throughput is the amount of data transmitted from source to target per unit time, which can be divided into node throughput and network throughput. Node throughput refers to data packets received by the target node per unit time, while network throughput refers to the average sum of data packets received by all nodes in the network per unit time.

c) Delay (DE). Delay is the time required for a data packet to be correctly transmitted from the source node to the target node, with its average value being average delay. In IoV environments, vehicles follow at high speeds with small following distances, requiring extremely low communication delay between vehicles. Therefore, this metric is particularly important for safety-critical applications.

d) Routing Overhead (RO). RO is the ratio of routing messages (protocol packets) to total communication data (protocol packets and data packets) in the network, reflecting the impact of routing protocols on network communication. The calculation formula is:

$$RO = \frac{R_{sf}}{R_{sf} + P_{sf}}$$

where R_{sf} represents all protocol packets sent and forwarded by all nodes, and P_{sf} represents all data packets sent and forwarded by all nodes.

e) Normalized Routing Overhead (NRO). NRO is the number of routing packets required to send one data packet (including source sending and intermediate forwarding) to the target node, i.e., the ratio of sent and forwarded protocol packets to data packets, reflecting network routing stability. The calculation formula is:

$$NRO = \frac{R_{sf}}{P_{sf}}$$

f) Packet Delivery Ratio (PDR). PDR is the ratio of data packets received by the target node to data packets sent by the source node at the application layer, i.e., a statistical measure of correctly transmitted data packets, primarily reflecting two main characteristics of IoV: network reliability and network congestion/communication conditions. The calculation formula is:

$$PDR = \frac{P_r}{P_s}$$

where P_r represents data packets received by the target node, and P_s represents data packets sent by the source node at the application layer.

g) Received Signal Strength Indicator (RSSI). RSSI refers to the power measurement value contained in received radio signals, an optional part of the wireless transmission layer used to determine link quality and whether broadcast transmission power should be increased. Higher RSSI values indicate stronger signals; when expressed in negative form (e.g., -100), values closer to 0 indicate stronger received signals.

h) Reliability. Reliability describes whether and to what extent data transmission is expected to succeed. In many cases, the demand for reliable communication protocols conflicts with the demand for low latency and high throughput, so protocols require careful tuning to meet all or most application requirements. Reliability can be estimated in simulation by evaluating the number of failures and then establishing a reliability metric.

4.2 Application-Related Metrics

In addition to classic network-related metrics, the performance and quality of many IoV applications and protocols can be evaluated using more application-oriented metrics. For many applications, how the channel is loaded or whether delay varies between determined values is actually irrelevant (unless it exceeds real-time communication thresholds). The following three application-dependent metrics are discussed below:

a) Vehicle collision probability. This metric defines the severity of a situation, allowing messages to be prioritized or even automatically processed to prevent collisions. It is frequently used as a descriptive metric for safety-related applications, revealing the ability of relevant applications to handle emergency situations (such as sudden emergency braking by a preceding vehicle). The focus lies in accurate classification of situation criticality, reducing false alarm probability, and providing complete safety enhancement systems for IoV through research.

b) Travel time, effective average speed, and variance [52]. In research on IoV traffic efficiency-related applications, vehicle travel time, effective average speed, and variance are frequently used as primary descriptive metrics. Travel time and effective average speed reveal the ability of relevant applications to reroute vehicles under congested conditions; variance represents the dispersion degree of vehicle travel time samples, reflecting the string stability of vehicle platoons.

c) Emissions and fuel consumption [53]. In research on IoV environment-friendly-related applications, emissions and fuel consumption are frequently used as primary descriptive metrics for vehicle or fleet travel smoothness and cooperative traffic efficiency.

5 Conclusion

IoV testing is an indispensable and critical component in the research and development of intelligent connected vehicle technologies and applications, serving as an essential means for large-scale deployment of IoV infrastructure and equipment and their extensive application in intelligent vehicles. Although real-world environment research and testing of IoV is the most direct and effective method, constrained by testing costs, site availability, and personnel scale, testing and evaluation of IoV protocols and various IoV applications built upon them in simulation environments remains an important IoV testing technology. This paper systematically summarizes current domestic and international IoV simulation testing technologies. First, addressing actual requirements for IoV simulation testing and evaluation, it summarizes and analyzes current mainstream network simulators and traffic simulators, and categorizes existing IoV simulation platforms into four types: separated, embedded, joint, and integrated. It then analyzes five typical current IoV simulation platforms—TraNS, Veins, iTETRIS, NCTUns, and VSimRTI—and compares them across multiple aspects including simulation scale. Next, based on IoV application characteristics, it systematically summarizes three factors affecting IoV simulation testing performance: vehicle mobility models, channel models, and driver behavior. Finally, it summarizes typical evaluation metrics for IoV simulation test results from two perspectives: network simulation metrics and IoV application-related metrics. This paper provides important guidance for researchers engaged in simulation testing and evaluation of IoV technologies and applications. With the continuous development of cooperative autonomous driving technology in connected environments, IoV technology will gradually move from theory to application, but simulation remains an important means for large-scale testing and evaluation of vehicle networking technologies. It is foreseeable that large-scale demonstration applications of connected vehicles will provide more comprehensive real-world traffic and network data support for IoV simulation testing, thereby promoting the accuracy of IoV simulation test results. Furthermore, the construction of numerous intelligent connected vehicle closed test sites will promote the scale of real-vehicle IoV testing, serving as an important verification means to enhance the accuracy and efficiency of simulation testing platforms. Future work should focus on factors affecting IoV simulation testing performance, using real traffic data as a foundation to study the advantages, disadvantages, and applicability of various proposed vehicle mobility models and channel models.

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Note: Figure translations are in progress. See original paper for figures.