VANET Simulators:An Overview and Comparative Analysis

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***Abstract*— Intelligent Transportation Systems (ITS) utilize Vehicular Ad Hoc Networks (VANETs) for real-time data exchange, road-safety enhancement, and coordinated operation of connected and autonomous vehicles. The high mobility, frequent topology changes, and heterogeneous communication modes in VANETs necessitate advanced simulation environments for robust development, testing, and performance evaluation. This study reviews approximately 70 recent scholarly works to comparatively analyze five prominent VANET simulators (SUMO, OMNeT++, ns-3, Veins, and MATLAB-based platforms), assessing architecture, protocol support, scalability, and mobility integration. It identifies each tool's strengths, limitations, and appropriate use cases ranging from traffic modeling to network and cross-layer evaluation. Three key open challenges are highlighted: interoperability, more realistic mobility modeling, and AI-enabled hybrid simulation, and the findings are intended to guide the design of more realistic, flexible, and better-integrated VANET simulation frameworks.**

Keywords—VANET, Simulator, Comparative Analysis, Intelligent Transportation Systems

I. INTRODUCTION

A Vehicular Ad-Hoc Network (VANET) is the challenging and self-organized distributed communication network that is fundamentally established by moving vehicles, each of which serves as a dynamic node characterized by variable speed and fluctuating traffic dynamics. This network plays a crucial and pivotal role as a key component of intelligent transportation systems (ITS), enabling robust communication not only between vehicles but also between vehicles and various infrastructure components such as traffic signals and road signs. ITS, delineate a range of services that enhance vehicular communication, such as a cooperative awareness service that promotes mutual knowledge among vehicles and an environmental notification service that provides critical alerts about road conditions and hazards [1]. To facilitate urban mobility modeling, SUMO (Simulation of Urban Mobility) plays an instrumental role, and the resultant findings contribute to a holistic assessment of propagation models and an evaluation of diverse routing strategies aimed at ensuring timely and efficient dissemination of vital data among vehicles. Several academic papers and studies have facilitated an in-depth comparison between various routing protocols, assessing their performance under different conditions in various simulation scenarios. Among these studies [2]. presented an extensive modeling framework for VANETs that is particularly useful for understanding vehicle interactions. In their study, the ad hoc on-demand distance vector (AODV) and Dynamic Source Routing (DSR) protocols were closely compared within realistic urban scenarios that exhibited varying levels of node mobility and vehicle density, thereby allowing for the observation of the behaviors and efficiencies of both protocols in a practical setting [3]. The most widely used routing protocols are scrutinized, encompassing three reactive (AODV, DSR, and DYMO) and three proactive (DSDV, FSR, and OLSR) variants, thereby providing comprehensive insights into the advantages and limitations inherent to each protocol type, as well as their applicability in real-world vehicular communications and scenarios[4]. The significance of simulation in vehicular ad-hoc networks, have been proposed since the 1970s as a pioneering concept in transportation technology, and recent implementations are now expected to offer a wide array of intelligent transportation features, including but not limited to accident prevention, improved traffic efficiency, and enhanced access to entertainment and vital information. Over the years, vehicles have evolved into highly complex computer systems that not only modify driver behavior but also monitor and control various aspects of vehicle operation with remarkable precision [5]. A well-designed VANET network system can provide a multitude of benefits, including significantly safer driving experience, efficient traffic monitoring and control mechanisms, and even semi-automated driving capabilities. For example, safety applications, such as collision avoidance systems and congestion reduction strategies, have been rigorously proposed and investigated within the framework of VANETs [6]. Moreover, VANETs serve as emergent and realistic simulation tools, with the requirement for realistic mobility patterns to comprehensively evaluate protocol performance [7]. This, in turn, supports a comprehensive methodology for a diverse range of protocols and scenarios, ensuring that future developments in VANETs can meet the demands of increasingly interconnected vehicle networks and intelligent transportation systems [8].

II. RELATED WORK

The interest in VANET applications has grown significantly over the past two decades, leading to the development and continuous improvement of numerous simulation tools. In this study, approximately 70 scholarly works were examined to identify and analyze various simulators currently available in the field. Some of these include[1-15].

Existing VANET simulators have been widely utilized and cited in academic research, reflecting their importance in modeling vehicular communication systems. Each simulator varies in design focus, capabilities, and research adoption, which is often indicated by its citation counts. Fig 1 illustrates the number of citations, which serves as a useful metric to assess the popularity, credibility, and overall impact within the VANET research community.

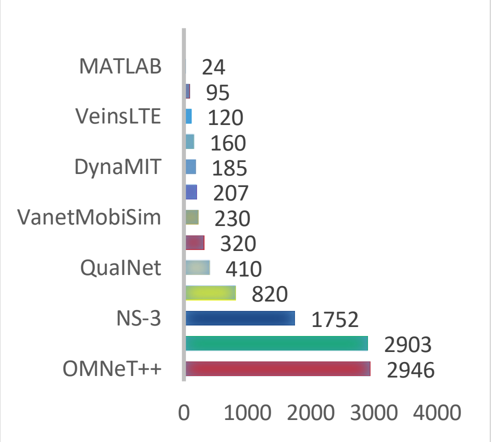

Fig 1. Overall impact of major VANET simulators based on citation count.

III. TYPES OF VANET SIMULATORS

Vehicular Ad Hoc Network (VANET) simulators can be broadly categorized based on their primary simulation focus and integration capability. The main types include mobility simulators, network simulators, and integrated co-simulation frameworks. Mobility simulators such as SUMO (Simulation of Urban MObility) are responsible for modeling realistic vehicular movement, traffic dynamics, and road environments, which are essential for generating accurate mobility traces. Network simulators like OMNeT++ and ns-3 emulate the communication behavior of vehicular nodes by implementing wireless protocols, channel models, and routing algorithms [10-13]. In addition, MATLAB-based simulators and custom toolboxes are increasingly used for algorithmic prototyping, performance evaluation, and hybrid control analysis. The choice of simulator depends on the research objective mobility optimization, communication performance, or cooperative system testing and often involves multi-tool integration to achieve high fidelity and realism in VANET studies[13].

A. Microscopic Simulators

Microscopic simulators effectively capture the intricate dynamics of individual vehicles as they travel along specific streets, showcasing the highest levels of detail and precision. The position, speed, and heading of each vehicle were updated at every simulation step, allowing for an accurate representation of the traffic flow and individual movements. This approach facilitates a deeper understanding of how vehicles interact within an urban environment, providing valuable insights for transportation planning and management [14].

Diverse scenarios can be conveniently entered and defined using textual description files, allowing for flexibility and adaptability in simulation scenarios [15]. Simulators serve as tools that focus on the high-level characteristics of traffic flow. They represent aggregated relationships among quantities such as density, flow, and average speed, without a detailed account of individual vehicle dynamics [16].

Although macroscopic models enable large-scale assessments owing to their computational efficiency, they generally lack the capability to depict granular interactions between vehicles, making them less suitable for analyses in which individual vehicle behaviors influence the study outcome [17]. In the context of Vehicular Ad-Hoc Networks (VANETs), the interplay between vehicle mobility and communication performance necessitates a finer level of detail than that provided by macroscopic models [18].

B. Hybrid Simulators

Hybrid simulators merge real hardware with simulations to provide realistic and repeatable performance testing. VANET operations can be tested using real hardware in the loop. If implemented on the devices, hybrid simulators allow one to test sensor processing, routing, congestion control, and adaptive data dissemination in a range of scenarios. Once VANET applications are implemented on hardware, hybrid simulators systematically verify their behavior and limit the time, complexity, and costs of the validation phase [19]. The protocol performance depends on the tested radio environment. Hybrid simulation enables propagation-channel, radio-channel, and general radio-environment analyses in the development, fine-tuning, and validation of physical-layer techniques; its models support the assessment of transceiver and physical-layer performance and their impact on upper-layer protocols [20].

IV. POPULAR VANET SIMULATION TOOLS

Extensive analyses have focused on realistic vehicular mobility patterns in VANET simulations. Popular tools include MOVE for generating vehicle movements from user-defined road maps or OpenStreetMap data; NS-3, a robust network simulator offering researchers high flexibility in configuring communication protocols; and SUMO, a microscopic and multi-modal traffic simulation package[13].

Models and simulators found in the literature generally consist of a realistic vehicle movement generator and a network simulator that supports scenarios involving the 802.11p/WAVE protocol [21]. In recent years, SUMO has been one of the most prominent microscopic urban mobility frameworks available, evidencing considerable interest within the research community and providing vital resources. Over the last decade, the demand for accurate, realistic, and scalable multi-hop VANET simulators has escalated concomitantly with an increase in relevant application proposals. Although numerous realistic tools exist, no single simulation tool satisfies all requirements [22].

A. Accelerated SUMO

Within the expanding field of vehicular ad hoc network simulations, it is highly desirable to effectively integrate mobility and communication simulators that can appropriately schedule various timing events. This integration is commonly achieved using sophisticated traffic simulators, such as SUMO, which are instrumental in generating node movement patterns based on detailed street plan data [23]. As vehicular networks evolve, the importance of communication aspects becomes increasingly pronounced. For this specific purpose, researchers often turn to a network simulator, ranging from the lightweight and user-friendly NS-2 or NS-3 to the more intricate and versatile OMNeT++ framework [12]. These simulators can accurately reproduce wireless communication technology and effectively model macroscopic behavior. This process is essential for maintaining the efficiency and reliability of vehicular communication networks in real-time applications [24]. The Simulation of Urban Mobility) is a microscopic, flexible, and open-source traffic simulation package designed to handle large road networks. The current implementation of SUMO supports a range of traffic and road types, including motorways, inner-city roads, rural roads, and road intersections [25].

B. *Network Simulator 3*

NS-3 has been meticulously developed as an advanced network simulator specifically tailored for IPv4 and IPv6 networking environments. Its main focus is on supporting research initiatives and educational programs that aim to enhance the understanding of networking concepts[26]. This powerful tool utilizes both C++ and Python, which provide researchers and developers with the capability to program virtually any type of network experiment one can envision [27]. NS-3 features a comprehensive array of models designed for various network devices, communication protocols, transmission channels, and Internet protocol stacks. Additionally, it includes technology-specific models that cater to a diverse range of wireless technologies, such as WiFi standards 802.11a/b/g/n, WiMAX, LTE/EPC, and point-to-point communication links. This extensive modeling capability enables users to simulate and analyze complex network scenarios with significant accuracy and effectiveness [28]. Unlike NS-2, NS-3 does not support all protocols and is currently under rapid development. It models propagation effects, including propagation loss, propagation delay, and radio energy consumption [29].

As a solid research tool, NS-3 facilitates the investigation of untested networking protocols, large-scale testbed experiments, and the study of hard-to-reach network conditions in which real hardware is not viable [30].

C. *OMNeT++ Simulation Tool*

Is an open-source, component-based, discrete-event network simulation framework. All components are arranged in modules written using the C++ programming language, and OMNeT++ provides sophisticated support for simulation experimentation, including advanced graphical runtime configuration and topology editing capabilities [31]. Extensions for inter-vehicle communications are available and include pre-implemented components for the IEEE 802.11 access mechanism, several vehicle mobility models, and common vehicular applications.

D. *Major Veins System*

Veins is an open-source framework that enables traffic mobility modeling (road traffic simulation) and network simulation with bidirectional coupling between SUMO and OMNeT++/INET. Veins offers additional support for WAVE/IEEE 802.11p and cellular network simulation and works with any INET version since 3.x.

E. *The important features include:*

- Co-simulation of road traffic and network traffic with a bidirectional coupling between SUMO and OMNeT++
- Support for IEEE 802.11p and WAVE
- Complete road traffic model provided by SUMO
- Support for arbitrary network protocols through INET
- Support for LTE / 5G extension SimuLTE
- Support for realistic and complex road traffic networks from the OpenStreetMap project
- Large set of example scenarios and models
- Mid-simulation creation and removal of vehicles
- Parameterization of vehicles during simulation
- Support for various generative applications

Within a scenario, the TraCIScenarioManager module listens to SUMO over the TraCI protocol for events such as vehicle creation and destruction. When a vehicle enters the simulation, the TraCIScenarioManager creates a corresponding OMNeT++ compound module to represent it. The WAVE application, a compound module, consists of an IEEE 802.11p Network Interface Card, an IPv4-based ColombosRsu module comprising a WAVE beaconing component, and an application. The constraints ensure that only exact versions from the same INET release series are paired with Veins. Ongoing development aims to overcome this limitation [31]. The framework is compatible with OMNeT++ version 6.0 and supports all recent INET version 4.x releases. Veins offers bidirectional coupling between SUMO and OMNeT++, facilitating synchronized traffic and network simulations. The latest version (5.2) supports OMNeT++ 6.0, INET 4.5.4, and SUMO 1.24.0. Many users utilize Veins to integrate current cellular network simulation extensions, such as SimuLTE and Simu5G [32].

F. *VANET simulation tools*

Table 1. is a compact comparative table illustrating each tool, its typical role in VANET work.

TABLE I. COMPARATIVE TOOLS VERSION

Tool	**Comparative overview**			
	Compatible versions	***Key strengths***	***Key limitations***	***Ref***
SUMO (1.24.0)	OMNeT++ 6.0 – 6.2, Veins 5.3+, ns-3 (via TraCI export)	TraCI API (Traffic Control Interface), SUMO-GUI, Python tools	No native network stack-typically paired with network simulators (veins/OMNeT++/ns-3)	[33]
Veins (5.3/5.3.1)	OMNeT++ 6.0–6.2, SUMO 1.18–1.24	TraCI + INET Framework (OMNeT++)	Depends on OMNeT++ and SUMO versions; some learning curve integrating custom modules	[34]
OMNeT++ (6.2.2)	Veins 5.3+, SUMO 1.24, INET 4.4+, MATLAB (via FMI/Simulink link)	C++ modules, INET Framework, TraCI Interface, FMI Connector	Steeper learning curve for C++ models; and INET/other frameworks for full protocol stacks.	[35]
NS-3 (3.45)	SUMO (via TraCI4NS3 / MOVE), MATLAB (via ns3-matlab bindings)	Active development good WiFi/LTE/5G models, python bindings, widely used for reproducible research	Less out of the box mobility integration than veins (feed mobility traces from SUMO).	[36]
MATLAB (R2025b)	MATLAB + ns-3 + SUMO	FMI, TCP/IP or JSON APIs, SimEvents, Automated Driving Toolbox	Not a free/open research stack, large scale packet level VANET simulation often better in ns-3/OMNeT++;	[37]

V. KEY FEATURES OF VANET SIMULATORS

Vehicular Ad-Hoc Network (VANET) simulator serves as a sophisticated software environment specifically designed for the thorough assessment and in-depth analysis of various VANET protocols and different scenarios. These simulators typically offer a diverse range of features that are essential for accurately modeling a broad spectrum of potential VANET deployments. This section delineates several key features commonly exhibited by a typical VANET simulator; however, the precise set of features offered by each individual VANET simulator is compared in greater detail in Section 6 [38].

Vehicular ad hoc networks (VANETs) are uniquely composed of mobile nodes equipped with sophisticated onboard units (OBUs). These units play a crucial role in facilitating seamless vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication, thereby enhancing the efficiency and safety of road networks [39].

Trace file support allows users to record real traffic patterns, and a trace file generator makes it easy to replay or adjust this traffic, helping speed up development and integration.[40].

Communication within VANETs inherently resides in the wireless medium; therefore, a VANET simulator must incorporate support for wireless communication modeling. Multiple protocol stacks are often supported, ranging from models compliant with application layer protocols to the physical layer [41]. While contemporary simulators provide means to transport data, often including detailed network protocol development environments, a VANET simulator can typically extend this support to the application layer of the protocol stack [42].

Therefore, comparisons are typically performed under time-constrained environments that limit packet loss events, with an opportunity for more sophisticated radio propagation models not reflected in the simulation environment [43].

A. Realistic Traffic Modeling

Vehicular Ad Hoc Networks (VANETs) require specific mobility models that accurately describe vehicular motion and complex traffic flows. Realistic simulations must replicate utility scenarios with representative node movement patterns [44]. Early simulators for ad hoc networks such as ns-3 (Network Simulator), OPNET, SWANS, and Jist/SWANS 4 either depended on synthetic mobility or permitted trace file replay [45].

B. Network Protocol Simulation

Several studies have been published comparing routing protocols in different simulation scenarios. The comparison of AODV and DSR was conducted in realistic urban scenarios with varying node mobility and vehicle density to observe the behavior of both protocols. This study also compares DSR and DSDV with four different mobility models. Widely experimented and frequently used protocols for such studies include three from the reactive or on-demand class: AODV, DSR, and DYMO; and three from the proactive or table-driven class: DSDV, FSR, and OLSR [46].

C. Communication Models

Communication models, or radio propagation models, are also important components of any VANET simulation framework. By reproducing the spatial attenuation of the signal as a function of power, frequency, distance, and propagation environment, these models convey one of the basic fundamentals of the physical layer to the higher levels of the stack[47]. Almost all the reviewed simulators include either one or several proprietary propagation models; moreover, some incorporate standards built upon common mathematical descriptions, whose parameters may be configured to comply with specific scenarios of interest. Notably, the NS-2/NS-3 simulation platforms implement extensions that enable the use of several propagation models, including: ns3::FriisPropagationLossModel [48].

VI. EVALUTION METRICS FOR VANET SIMULATORS

The evaluation and comparison of VANET simulators have so far mainly relied on metrics such as whether the simulator is traffic- or network-oriented, whether it operates concurrently (integrated) or sequentially (restricted), and whether the traffic simulator is based on micro, meso-, or macrosimulation. Other indicators include whether real-world maps can be imported, whether the model supports high node densities, and the specific mobility models that are implemented [49]. Whether or not and to what depth a given simulation package encompasses channel-scene or data-level models or an idealized network interface can be decisive.

A. Throughput

Throughput, expressed as the average number of bits successfully delivered per second, represents the rate at which packets travel through the channel effectively. Throughput helps calculate the overall throughput ratio of a network when a queue is full and is one of the prominent parameters for measuring the data transmission capacity of a network [50]. In several experiments, it has shown that the throughput increases with the number of vehicles [51]. OPNET simulator generates vast amounts of photorealistic imagery and models radio wave propagation. The throughput obtained for this network was 3.8 Mbps for direct IEEE 802.11a wireless communication with a bit rate of 10 Mbps [52]. VanetMobiSim can generate up to 10,000 nodes and includes a user-focused interface, tools to change default settings and parameters during the simulation, and a post-simulation database file for visualization or analysis [53].

B. Latency

In the context of Vehicular Ad-Hoc Networks (VANETs), latency represents the elapsed time between message generation and its successful reception at a destination node. The standard IEEE 802.11p employs the Distributed Coordination Function for channel contention, a mechanism that can introduce variable delays before data transmission, thereby affecting overall latency [54]. Within routing protocols, measuring the time elapsed between the initiation of a Route Request and the reception of a Route Reply offers an indication of control message overhead; high values may signal network congestion and increased latency. Beyond routing, network parameters such as end-to-end delay have been found to escalate with higher node densities, emphasizing the interplay between network scale and latency [55]. Managing latency is thus critical for VANETs, especially given their reliance on timely data exchange to support applications ranging from traffic optimization to safety [49, 50].

C. Packet Delivery Ratio

Packet Delivery Ratio (PDR) is the ratio of data packets successfully delivered to their destinations relative to those generated by the sources; some packets may fail to reach their destinations due to various factors, including collisions, signal fades, and network congestion. Existing unicast routing protocols of VANET are not capable of meeting every traffic scenario. Two on-demand routing protocols selected for simulation are AODV and DSR[58]. AODV is a reactive routing protocol that establishes routes when needed, using RREQ and RREP cycles, and handles link failures by sending reports and rediscovering routes [59]. Under sparse traffic conditions featuring 3–8 vehicles per minute per road-end, PDR exceeds 99% and improves as vehicle density rises. Multipath extensions to routing protocols can substantially reduce delivery delays without generating excessive packet copies.[53- 54].

D. Scalability

The scalability attributes of a given Vehicular Ad hoc Network (VANET) system are reflective of its ability to efficiently manage larger-scale operations, where maintaining acceptable performance metrics across a significant number of vehicles ensures seamless communication and information dissemination [62]. Diverse simulation tools adopt varied strategies to evaluate and demonstrate their scalability capacities. Some simulators offer relatively straightforward assessments, such as OMNeT++ and Veins, which report scalability statistics directly based on the number of vehicles involved [63]. The MaxiNet framework enhances scalability of the Mininet-WiFi environment, managing up to 2,000 vehicles within a simulated 1,000 km2 area. SUMO conducts vehicle loading on the fly and executes the full vehicle updating process on a single processing thread, affecting the scalability of integrated simulators like OMNET++ and Veins. VENTOS supports only a single base topology; simulations that exceed this predefined scenario are not feasible[13]. VanetMobiSim differentiates itself by supporting a variety of wireless models, including NS-3 and OMNeT++. SUMO is recognized as one of the most efficient microscopic traffic simulators and is therefore well-suited to simulating extensive road networks over protracted time frames [64].

VII. CHALLENGES CONCLUSIONS IN VANET SIMULATION

The experimental validation of VANETs is hindered by high costs and logistical complexity, making realistic simulation the only scalable option for large-scale experiments [65]. Simulation depends on mobility models to determine node positions, which must accurately capture road infrastructure, driver behavior, and traffic dynamics. Real traffic data is also required to drive simulations and produce credible results. Modeling the mobility of large-scale networks with sufficient accuracy remains an open challenge. Existing mobility models typically originate from traffic research. Macroscopic models describe traffic flow in terms of aggregate variables such as average vehicle speed, flow, and density. Table 2 illustrate the main challenges in VANET simulation, with short descriptions, their impact on VANET studies, and representative references from the literature [66].

TABLE II. THE MAIN CHALLENGES

Challenge	Description Impact		
	Description	*Impact on VANET simulation studies*	*Ref*
Scalability & performance	Running realistic large-scale scenarios (city/regional level, thousands of vehicles) strains CPU/ memory; tight coupling of mobility + network simulators increases runtime and synchronization overhead.	Limit's ability to evaluate large deployments, platooning, or city-wide services; forces simplifications that can hide emergent behaviors.	[67]
High-fidelity mobility modeling	Need for accurate micro-level vehicle dynamics, driver behavior, traffic signals, and mixed-autonomy fleets; microscopic models are detailed but costly, macroscopic models scale but lose per-vehicle interactions.	Inaccurate mobility models produce misleading communication performance (e.g., connectivity, link duration), hurting VANET protocol validation.	[13]
Heterogeneous radio / network technology integration	Modern VANETs require simulating DSRC/802.11p, LTE-V2X/5G NR V2X, and emerging 6G concepts plus multi-RAT handovers and edge-cloud interactions.	Without multi-RAT support, results may not generalize to hybrid real deployments (latency, reliability, resource allocation).	[42]
Cross-layer & application-level realism	Interactions across PHY/MAC/NET/APP layers (e.g., for video streaming, cooperative perception) are complex; many simulators treat layers in isolation or use simplified stacks.	Mis-modeled cross-layer effects (e.g., congestion → packet drops → application QoE) reduce the validity of results for safety-critical applications.	[68]
Reproducibility & standard benchmarks	Lack of standardized scenario definitions, metrics, seed/control of randomness, and versioning across simulators and toolchains.	Makes fair comparisons between proposals difficult and slows cumulative progress; published results may be hard to reproduce.	[69]
Security, privacy, and trust modeling	Simulators often omit realistic adversary models, privacy-preserving mechanisms, or trust frameworks (e.g., spoofing, Sybil attacks, privacy leaks).	Protocols validated without security considerations may fail under adversarial conditions in the real world.	[70]
Co-simulation synchronization & tooling complexity	Coupling traffic (SUMO, VISSIM) with network simulators (NS-3, OMNeT++) requires middleware, synchronization tuning, and careful event scheduling; toolchains can be brittle.	Increased setup and debugging time, risk of hidden bugs (time-step mismatch), and limits on automated experiments and CI.	[13]

VIII. CONCLUSION

VANETs serve as essential technology for building intelligent transportation systems (ITS) because they create safer and more efficient connected vehicle environments. The research examined five prominent VANET simulators, including SUMO and NS-3 and OMNeT++ and Veins, and MATLAB-based environments, through a detailed evaluation. The research demonstrated why simulation remains essential because it helps scientists study communication protocols and vehicle movements while avoiding real-world testing expenses and operational difficulties. The evaluation of these simulators through their architectural design and scalability features and network capabilities, and mobility model support showed that no single tool meets all requirements for realistic large-scale vehicular communication studies. SUMO stands as the top mobility simulator for urban traffic, yet OMNeT++ and NS-3 offer robust network-level testing capabilities, and Veins links both domains through its bidirectional coupling system.

Recent studies find out that current VANET simulation tools still face challenges in scalability, realistic mobility modeling, and interlayer accuracy. The integration of DSRC with LTE-V2X and emerging 5G technologies increases simulation complexity, necessitating hybrid and joint simulation approaches. Furthermore, the lack of uniform standards and limited reproducibility hinder consistent comparison between studies. Hybrid simulators based on artificial intelligence and machine learning have been shown to mitigate these issues by dynamically tuning parameters, optimizing computational resources, and improving both network and mobility accuracy.

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