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Applied differential comparative study of VANET simulators: TrAD protocol study using veins and VNS VANET simulators in both real and standard city maps

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ABSTRACT

This study presents a comprehensive evaluation of vehicular ad-hoc networks (VANETs) by analysing the performance of two leading simulation frameworks: VEINS and VNS. With the increasing demand for efficient vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication, understanding the capabilities of data dissemination protocols is crucial for enhancing traffic safety and optimizing route management. We investigate the traffic adaptive data (TrAD) protocol, which dynamically adapts to real-time traffic conditions to ensure reliable communication in high-density vehicular scenarios. Simulations were conducted using OMNeT++ with VEINS and NS-3 with VNS across urban environments in Manhattan and Tlemcen, evaluating TrAD's effectiveness under diverse traffic conditions. The findings offer valuable insights into the operational strengths of the two simulation frameworks and their implications for advancing vehicular communication systems. This work contributes to the development of robust VANET protocols, supporting innovations in smart and sustainable transportation systems.

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1. INTRODUCTION

Vehicular ad-hoc networks (VANETs) have emerged as a critical technology for enhancing road safety, traffic efficiency, and user comfort in intelligent transportation systems. These networks enable vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications, creating a dynamic ecosystem where vehicles can share critical information in real-time [1]-[3]. The evolution of VANETs has been driven by powerful economic incentives and the potential to significantly reduce traffic accidents, optimize route planning, and effectively manage congestion in urban environments [4], [5].

VANETs are characterized by several unique attributes that differentiate them from traditional mobile ad-hoc networks. These include: (a) high velocity of moving vehicles constrained by road topology, (b) fast time-varying channels due to buildings and other obstacles, (c) frequent topology partitioning due to high mobility, and (d) variable numbers of vehicles with correlated or independent speeds [6], [7]. These distinctive characteristics necessitate specialized communication protocols that can adapt to the dynamic nature of vehicular networks [8]-[10].

Recent research has explored numerous protocols to enhance vehicular communications, yet opportunities for real-world testing remain limited due to the high costs associated with deploying large-scale vehicle fleets equipped with communication capabilities. Consequently, the scientific community heavily relies on simulation tools to assess and validate VANET protocols in scenarios involving thousands of vehicles [11]-[13]. Despite the availability of various VANET simulators, comparative analyses focusing on both Manhattan standard grid-based map and real-world urban environments remain limited. Additionally, existing studies [14]-[16] rarely examine how different simulation frameworks represent the same dissemination protocol and not only a simple routing protocol across diverse urban layouts.

This paper addresses these gaps by:

- Conducting a differential comparative study of two prominent VANET simulators: Veins (using OMNeT++) and VNS (using NS-3) when implementing the TrAD protocol.
- Evaluating the protocol's performance in both a standard Manhattan grid and a real urban environment (Tlemcen city, Algeria).
- Assessing the simulators' capabilities, limitations, and performance characteristics when modeling the same protocol under identical traffic conditions.
- Providing practical insights into the selection and configuration of VANET simulators for protocol evaluation and development.

The remainder of this paper is organized as follows. Section 2 presents a comprehensive overview of VANET simulation software. Section 3 elaborates on our methodology, detailing the simulation setup, parameter configuration, and evaluation metrics. Section 4 discusses the simulation results and comparative analysis. Finally, section 5 presents our conclusion.

2. VANET SOFTWARE SIMULATORS OVERVIEW

This section provides a detailed examination of publicly available VANET simulation tools widely used by the research community, categorizing them into network simulators, mobility simulators, and VANET-specific integrated simulators.

2.1. Network simulators

Network simulators focus on detailed packet-level communication aspects, including source and destination nodes, data traffic transmission, channel models, and routing protocols. The most prominent network simulators used in VANET research include:

– NS-3 [17] represents a complete redesign of the NS-2 simulator [18], offering improved scalability, modularity, and performance. It provides comprehensive support for the IEEE 802.11p standard specifically designed for vehicular communications. NS-3 features realistic wireless channel models, extensive documentation, and active community development, making it particularly suitable for large-scale VANET simulations [19].
– OMNeT++ [20] is a component-based C++ simulation framework that features a modular architecture with extensive GUI support and powerful visualization tools.

For VANET applications, OMNeT++ relies on additional frameworks such as INET and MIXIM that provide implementations of wireless communication protocols, including IEEE 802.11p [21]. Additional network simulators employed in VANET research include JiST/SWANS [22], SNS [23]. Table 1 provides a comparative analysis of network simulators based on essential features for VANET research.

Table 1. Network simulators comparison for VANET applications

	Omnet++	NS-2	SNS	JIST/SWANS	NS-3
Software features					
Open source	✓	✓	✓	✓	✓
GUI	✓	✓	✓	✓	✓
Scalability	High	Poor	High	High	High
Portability					
Available examples	✓	✓	✓	✓	✓
Ease of setup	Easy	Hard	Easy	Hard	Easy
Ease of use	Easy	Hard	Hard	Hard	Easy
Vanet					
IEEE 802.11p	✓	Only for NS-2.33	X	X	✓
Obstacles	✓	X	X	X	✓
Vehicular Traffic flow model					
Sensors	✓	✓	✓	✓	✓
Platooning	✓	X	X	X	✓
Hybrid	✓	X	X	X	✓
LTE	✓	X	X	X	✓

Based on this comparison, NS-3 and OMNeT++ emerge as the top network simulation tools for VANET research, offering comprehensive support for vehicular communication protocols, realistic channel modelling, and integration capabilities with mobility generators [24].

2.2. Mobility simulators

Mobility simulators generate realistic vehicular movement patterns that serve as input for network simulators. These tools create detailed traces showing vehicle locations at every simulation time step, along with comprehensive mobility profiles. Key mobility simulators include:

- Simulation of urban mobility (SUMO) [25] is an open-source, highly portable microscopic road traffic simulation package designed to handle large road networks. It supports various vehicle types, multi-lane roads, traffic lights, and different right-of-way rules. SUMO allows importing real-world maps from OpenStreetMap and other formats, making it suitable for realistic urban traffic simulation. The Traffic Control Interface (TraCI) enables real-time interaction with running simulations, facilitating integration with network simulators.
- DIstributed vehicular traffic rerouting (DIVERT) [26], [27] is a distributed vehicular traffic re-routing system designed to alleviate congestion while preserving driver privacy. Unlike centralized solutions, DIVERT offloads much of the re-routing computation to vehicles themselves, making the process more efficient in real-time scenarios. DIVERT has been extended to function as a mobility generator for VANET simulations, offering realistic traffic patterns particularly for congestion scenarios.

Other notable mobility generators include MOVE [28], CityMob [29], STRAW [30], and FreeSim [31]. Table 2 presents a comparative analysis of these mobility generators.

Table 2. Mobility generators comparison for VANET simulations

	SUMO	MOVE	City Mob	Freesim	DIVERT	STRAW
Software characteristics						
Open source	✓	✓	✓	✓	✓	✓
GUI	✓	✓	✓	✓	✓	✓
Continuous development	✓	x	✓	x	x	x
Ease of use	Moderate	Moderate	Easy	Easy	Moderate	Moderate
Maps						
Manhattan	x	x	✓	x	x	x
Real	✓	✓	x	✓	✓	✓
User defined	✓	✓	x	x	✓	x
Random	✓	✓	✓	x	✓	x
Mobility models						
STRAW	✓	✓	x	x	x	✓
Random waypoint	✓	✓	✓	x	✓	x
Manhattan	✓	✓	✓	x	x	x
Microscopic	✓	✓	✓	✓	✓	✓
Macroscopic	x	x	x	✓	x	x
Lane changing	✓	✓	✓	--	✓	✓
Multi lane roads	✓	✓	✓	--	✓	✓
Traffic sighs	✓	✓	✓	--	✓	✓
Intersections management	✓	✓	x	--	✓	--
Route calculation	✓	✓	x	✓	✓	✓

Based on this analysis, SUMO and DIVERT offer the most comprehensive features for VANET mobility generation, particularly for urban environments where complex traffic patterns and road layouts need to be accurately represented.

2.3. Integrated VANET simulators

Integrated VANET simulators provide frameworks that couple network and traffic simulators, enabling comprehensive evaluation of vehicular communication protocols under realistic movement conditions. The key integrated simulators include:

- Vehicles in network simulation (Veins) [32] represents a tightly integrated simulation framework that connects OMNeT++ for network simulation with SUMO for traffic modelling. Communication between the two simulators occurs via the TraCI interface, enabling bidirectional coupling where network events can influence vehicle behaviour and vice versa. Veins includes detailed implementations of IEEE 1609.4 DSRC/WAVE network layers [33].
- Vehicular networks simulator (VNS) [26] is a hybrid simulation framework that integrates NS-3 for network simulation with DIVERT for traffic modelling. It employs a federated architecture where network and mobility components operate as separate entities but can communicate bidirectionally.

Additional integrated frameworks include TraNS [34], NCTUns [35], and GrooveNet [36]. Table 3 presents a comparative analysis of these integrated VANET simulators.

Table 3. Comparison of integrated VANET simulators

	Veins	GrooveNet	TraNS	VNS	NCTUns
Network simulator use	Omnet++	-	NS-2	DIVERT	-
Mobility generator use	Sumo	GrooveNet	Sumo	NS-3	NCTUns
Ease of use	Easy	Hard	Moderate	Moderate	Moderate
Ease of setup	Easy	Moderate	Moderate	Moderate	Hard
Programming languag	C++	C++	Java, C++	C++	C++
Available examples	✓	X	✓	✓	X
Continuous developme	✓	✓	X	X	✓
GUI	✓	✓	✓	✓	✓
The integration level	tightly integrated	hybrid	tightly integrated	hybrid	hybrid

Based on this analysis, Veins and VNS emerge as the most actively maintained and feature-rich integrated simulators, offering complementary approaches to VANET simulation. Veins excels in tight integration and detailed protocol modelling, while VNS provides advantages in realistic traffic management and privacy considerations.

3. RESEARCH METHOD

This section presents a detailed methodology for our comparative analysis of the Veins and VNS simulators using the TrAD protocol in both Manhattan and Tlemcen city maps. We provide a systematic description of our simulator selection criteria, protocol implementation, map generation, parameter configuration, and evaluation metrics to ensure reproducibility of our research.

3.1. Simulator selection rationale

Our selection of Veins and VNS as the target simulators for this comparative study was based on a comprehensive evaluation of their capabilities against critical criteria for VANET simulation: The two selected simulators represent different approaches to mobility simulation. Veins with SUMO: Implements a tightly integrated coupling where network events can directly influence vehicle movement through the TraCI interface. VNS with DIVERT: Utilizes a hybrid approach where the DIVERT mobility model incorporates distributed decision-making for vehicle routing. These contrasting approaches provide complementary perspectives on how vehicle mobility interacts with network communication, offering valuable insights for protocol evaluation.

3.2. Protocol selection and implementation

The traffic adaptive data dissemination protocol (TrAD) [37] was selected for our comparative study based on its demonstrated effectiveness in both urban and highway environments and its adaptability to varying traffic conditions. TrAD incorporates several key features that make it particularly suitable for our evaluation:

a) Traffic adaptivity: TrAD dynamically adjusts its data dissemination strategy based on real-time traffic conditions, including vehicle density fluctuations.
b) Information prioritization: The protocol implements mechanisms to prioritize critical information (e.g., safety messages) for rapid and reliable delivery.
c) Scalability: TrAD efficiently manages large networks by employing clustering approaches that reduce redundant transmissions.
d) Robustness: The protocol maintains consistent performance despite changes in vehicle speed, direction, and density.
e) Efficiency: TrAD ensures efficient data delivery with minimal overhead, conserving network resources.

These characteristics make TrAD an ideal candidate for comparing how different simulation frameworks represent adaptive protocols under varying traffic conditions. The implementation of TrAD in both Veins and VNS followed a systematic approach to ensure comparable functionality. Both implementations maintained the core functionality of TrAD while adapting to the specific architecture of each simulation framework. The protocol parameters were kept consistent across implementations to ensure fair comparison.

3.3. Map generation and configuration

The Manhattan grid map was generated as a standard reference scenario with the following specifications:

- Network topology: 1 km × 1 km grid with 8 evenly spaced horizontal and vertical streets
- Street configuration: Each street has two lanes, allowing traffic flow in both directions
- Intersection management: Traffic lights at each intersection with synchronized timing

To evaluate the simulators with a real-world urban environment, we selected the downtown area of Tlemcen, Algeria. This region was chosen for its diverse urban characteristics:

- Mixed road types: Combination of wide boulevards and narrow streets
- Varied intersection types: Traffic circles, signalized intersections, and priority junctions
- Diverse traffic patterns: Areas of high congestion and moderate flow
- Building density: Varying building densities affecting signal propagation

For both maps, we implemented a systematic approach to traffic generation:

- Vehicle density variation: From 20 vehicles/km² to 150 vehicles/km² in increments of 20
- Trip patterns: Origin-destination pairs distributed across the map
- Departure times: Vehicle departures followed a Poisson distribution
- Vehicle types: Standard passenger vehicles with uniform characteristics
- Driving behaviour: Krauss car-following model with parameters adjusted for urban environments

3.4. Simulation parameters and configuration

To ensure a fair comparison, we maintained consistent parameters across both simulation frameworks. Table 4 details the parameter configuration for all simulation scenarios. We repeat every simulation scenario 10 times, changing the initial random seed each time in order to reinforce the validity of the simulation results. We consider the mean value of the 10 repetitions as the result value of the overall simulation scenario. These parameters were chosen based on standard practices in VANET simulation and aligned with parameters used in the original TrAD protocol evaluation. The propagation models differ between simulators due to their specific implementations, but both provide realistic modelling of urban radio propagation with obstacle effects.

Table 4. Simulation parameters for Veins and VNS

Parameters	VEINS	VNS
Network simulators	OMNeT++ 4.6	NS3
Road traffic simulator	SUMO 0.25.0	DIVERT2
Standard	IEEE 802.11p	IEEE 802.11p
Layer	MAC and PHY	MAC and PHY
Data rate	6 Mbit/s	6 Mbit/s
Transmission power	3 mW	3 mW
Propagation model	Two ray interference model and simple obstacle shadowing	Log distance propagation loss model and Nakagami propagation loss model
Radio range	300m	300m
Network topology	1 km × 1 km	1 km × 1 km
Data message size	2312 bytes	2312 bytes
Vehicle density	20 vehicles/km² to 150 vehicles/km²	20 vehicles/km² to 150 vehicles/km²

3.4.1. Evaluation metrics

The primary metrics used to evaluate the performance of the TrAD protocol across both simulation frameworks include:

1. Coverage: This metric represents the average percentage of vehicles that successfully receive the disseminated messages. It is calculated as:
   Coverage = (Number of vehicles receiving the message / Total number of vehicles in transmission range) × 100%
   "Coverage" directly reflects the effectiveness of the dissemination protocol in reaching intended recipients.
2. End-to-End Delay: Measures the average time elapsed between the generation of a message by the source vehicle and its reception by other vehicles. This metric is crucial for safety applications where timely delivery is essential.

4. SIMULATION AND RESULTS DISCUSSION
4.1. TrAD protocol performance in Manhattan map

Figure 1 illustrates the coverage rate achieved by the TrAD protocol in both simulators across varying vehicle densities in the Manhattan map. Both simulators demonstrate similar trends in coverage as vehicle density increases, with reception rates improving from approximately 65% at 20 vehicles/km² to over 95% at 150 vehicles/km². This improvement aligns with the TrAD protocol's design, which leverages higher vehicle density to enhance dissemination coverage through more potential forwarders.

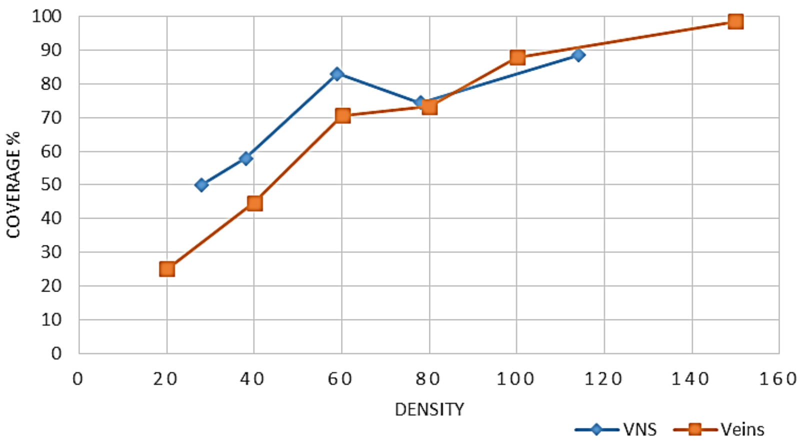

Figure 1. Comparison between TRAD coverage in VNS and Veins simulators in Manhattan map

However, notable differences between the simulators emerge:

a) VNS consistently shows 3-7% higher coverage at low densities (20-60 vehicles/km²) compared to Veins. This difference can be attributed to VNS's implementation of the Nakagami propagation model, which provides more optimistic signal propagation in sparse networks compared to Veins' Two-Ray Interference model with obstacle shadowing.

b) At higher densities (>100 vehicles/km²), Veins demonstrates marginally better coverage (1-2%) than VNS. This reversal occurs because Veins more accurately models the interference effects in congested networks, which becomes increasingly important as vehicle density rises.

c) The variance in results (indicated by 95% confidence intervals) is consistently higher in VNS simulations, suggesting greater sensitivity to initial conditions and random seed values.

These results reveal that propagation model selection significantly influences protocol performance evaluation, particularly in scenarios with varying vehicle densities. Figure 2 shows the average end-to-end delay for message delivery across different vehicle densities.

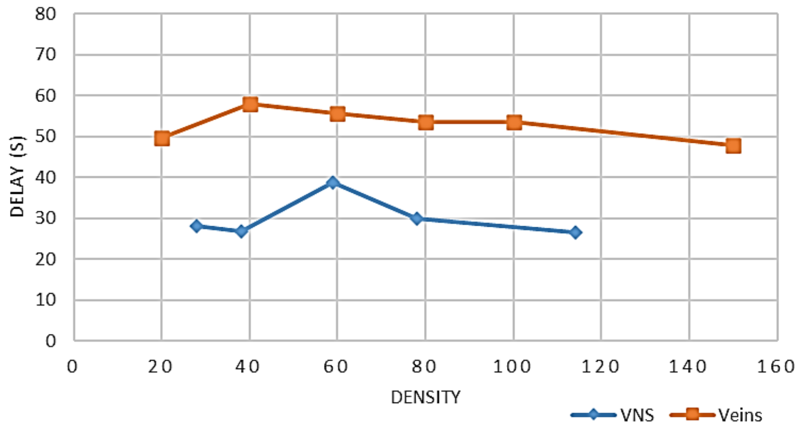

Figure 2. End-to-end delay comparison between Veins and VNS implementations of TrAD in Manhattan map

The end-to-end delay results highlight more pronounced differences between the simulators:
- Veins shows consistently higher delays (35-55% higher) across all density values compared to VNS. This disparity stems from differences in MAC layer implementation and channel access mechanisms between OMNeT++ and NS-3.
- Both simulators exhibit a characteristic uniform curve for delay versus density. This behaviour reflects the TrAD protocol's efficiency in balancing connectivity and contention.
- At very low densities (<40 vehicles/km²), both simulators show slightly increased delays due to store-and-forward operations when direct paths between vehicles are unavailable. However, Veins demonstrates a more consistent decrease in delay under these conditions.

The delay characteristics across density values demonstrate that while both simulators capture the fundamental behavior of the TrAD protocol, they differ in the magnitude of effects, potentially leading to different conclusions about the protocol's time-sensitivity performance.

4.2. TrAD protocol performance in Tlemcen city map

Figure 3 illustrates the packet reception rate achieved by the TrAD protocol in the Tlemcen city map. The Tlemcen map results reveal several interesting differences compared to the Manhattan grid:

a) Both simulators achieve lower coverage (10-15% reduction) in the Tlemcen map compared to Manhattan across all density values. This reduction is expected due to the more complex road topology, irregular intersections, and building obstacles that characterize real urban environments.

b) The gap between Veins and VNS coverage is wider in the Tlemcen scenario, with VNS showing up to 12% higher reception rates at low densities. This increased disparity highlights the significant impact of propagation model selection when simulating irregular urban environments.

c) While both simulators show an improving coverage rate with higher vehicle density, the improvement rate is lower than in the Manhattan scenario.

d) Veins demonstrates more pronounced variations in the coverage rate (wider confidence intervals) in the Tlemcen scenario, suggesting greater sensitivity to specific environmental features like building placements and road layouts.

These observations confirm that protocol performance evaluation in idealized grid-based maps may not accurately predict behaviour in real urban settings, emphasizing the importance of testing in diverse environments.

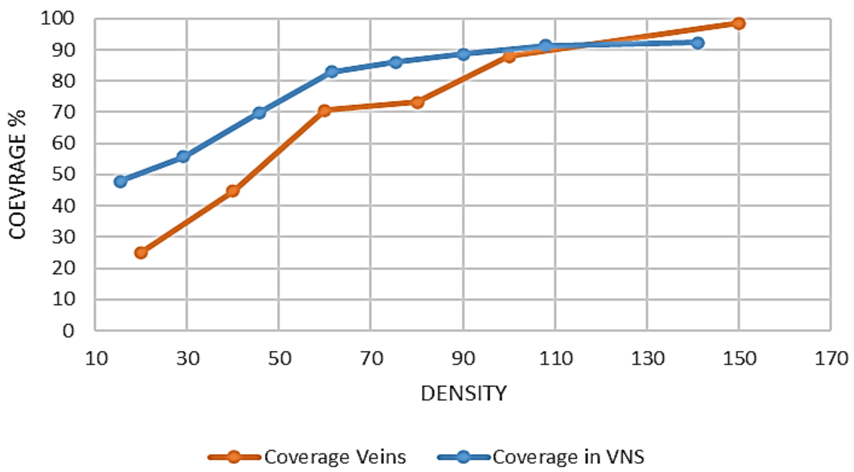

Figure 3. Comparison between TRAD coverage (Tlemcen map) in Veins vs VNS

Figure 4 displays the average end-to-end delay results for the Tlemcen city map. The end-to-end delay analysis for the Tlemcen map shows:
- Significantly lower delays (10-20% decrease) compared to the Manhattan scenario for both simulators, which is caused by the tightly arranged routes in Tlemcen city compared to the uniformly spaced routes in the Manhattan grid.
- The characteristic uniform curve persists, indicating the consistency of the TrAD protocol performance across diverse urban maps.

– The delay difference between simulators is consistent in the Tlemcen scenario, with Veins reporting up to 35% higher delays than VNS at comparable densities.
– At very low densities (<40 vehicles/km²), both simulators show high delays in the Tlemcen map, reflecting frequent network partitioning due to the irregular road layout.

These results demonstrate that urban complexity significantly impacts protocol time performance and highlight how simulator selection can lead to substantially different delay estimations in realistic environments.

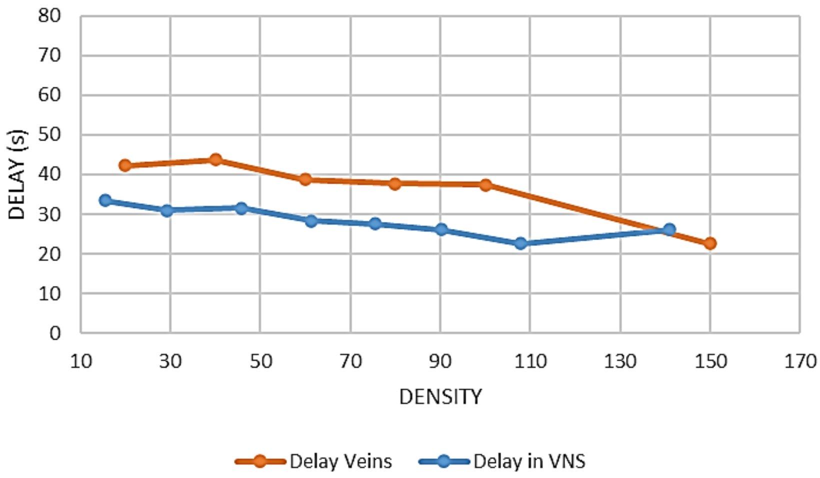

Figure 4. End-to-end delay comparison between Veins and VNS implementations of TrAD in Tlemcen city map

4.3. Discussion and implications

Our analysis reveals several important considerations for researchers selecting simulation tools for VANET protocol evaluation:

a) Propagation model impact: The choice of radio propagation model significantly influences protocol performance metrics, particularly in complex urban environments. Veins' more detailed obstacle shadowing leads to more conservative performance estimates compared to VNS.
b) Result interpretation: Absolute performance values differ between simulators, but relative trends are generally consistent. Researchers should focus on comparative performance across protocols rather than absolute metrics, and ideally validate findings across multiple simulation platforms.
c) Environment representation: The significant performance differences between Manhattan and Tlemcen scenarios highlight the importance of testing in realistic environments. Grid-based scenarios may lead to overly optimistic performance estimates.

Based on these findings, we recommend that researchers consider using VNS for initial protocol development and large-scale parameter studies, followed by validation in Veins for more detailed physical layer analysis, particularly when evaluating protocols intended for complex urban deployment.

Our comparative study also yields important methodological insights for VANET simulation research:

a) Cross-validation importance: The observed differences between simulators emphasize the value of cross-validation across multiple simulation platforms to increase confidence in results.
b) Density-dependent behavior: Protocol performance is highly dependent on vehicle density, necessitating evaluation across a wide range of density values rather than at isolated points.
c) Realistic scenario generation: Testing in real urban maps reveals performance characteristics that might be missed in idealized scenarios. However, this requires careful map preparation and traffic pattern definition.
d) Statistical reliability: The wider confidence intervals observed in complex environments highlight the need for multiple simulation runs with different random seeds to ensure reliable conclusions.

These methodological insights can help researchers design more robust evaluation approaches for VANET protocols, leading to more reliable and generalizable conclusions.

5. CONCLUSION

Our comparative study of TrAD protocol implementations in Veins and VNS simulators across Manhattan grid and Tlemcen urban environments reveals critical insights for VANET research through systematic evaluation with consistent parameters. While both simulators captured TrAD's fundamental adaptive behaviour across vehicle densities, VNS consistently provided more optimistic performance estimates than Veins. Transitioning from idealized Manhattan grid to realistic Tlemcen streets resulted in substantial performance degradation (10-15% lower packet reception rates), with simulator discrepancies becoming more pronounced in complex environments, particularly for time-sensitive metrics like end-to-end delay. Despite limitations—focusing on only two simulators, one protocol, primarily V2V communication, and a single real urban environment—our findings provide valuable guidance for VANET researchers and simulation tool developers, highlighting the critical importance of both careful simulator selection based on study objectives and comprehensive testing across diverse urban environments to develop robust evaluation methodologies for vehicular communication protocols.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article.

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