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VANETs' research overview updated: past, present and future

José Anderson R. de Souza [**Federal University of Campina Grande** | ***joseanderson@copin.ufcg.edu.br***]
Elmano Ramalho Cavalcanti [**Federal Institute of Paraiba** | ***elmano.cavalcanti@ifpb.edu.br***]
Teles de Sales Bezerra [**Federal University of Campina Grande** | ***teles@copin.ufcg.edu.br***]
Reinaldo C. de M. Gomes [**Federal University of Campina Grande** | ***reinaldo@computacao.ufcg.edu.br***]

Centro de Engenharia Elétrica e Informática (CEEI), Universidade Federal de Campina Grande (UFCG), . Aprígio Veloso, 882, Universitário, Campina Grande,PB, 58429-900, Brazil.

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Abstract The automotive industry has been undergoing significant changes, from electric and autonomous cars to the implementation of technologies for efficient and safe communication between vehicles. Vehicular Ad Hoc Networks (VANETs), in synergy with the Internet of Things and Artificial Intelligence technologies, contribute to increasing the safety and efficiency of land transport systems, aiding in the reduction of environmental pollution, and providing multiple applications to users. This article offers a historical perspective of research in VANETs, analyzing about 600 articles published between 2007 and 2021 in important conferences and journals. A systematic methodology was adopted for the selection and analysis of the articles, focusing on criteria such as thematic relevance, research methodologies employed, and significant contributions to the field. The most promising areas, main tools, and methodologies used in the studies were identified. We detected trends in the topics addressed and their future perspectives. Additionally, a detailed discussion on the main research problems found and a comparison with other studies were carried out, highlighting gaps and persistent methodological flaws in research. Specific issues, such as the lack of standardization in simulation methodologies and the need for more realistic approaches, are emphasized. Finally, perspectives for future research in VANETs are explored, suggesting promising directions, such as the development of enhanced security protocols, integration with emerging cloud computing technologies, and exploration of new applications in smart urban scenarios.

Keywords: Vehicular Ad hoc Networks, Survey, Vehicular Network, Applications, Future Research

1 Introduction

The contemporary world is witnessing an unprecedented transformation in the automotive sector and communication technologies. Vehicular Ad Hoc Networks (VANETs) emerge as a promising field, bringing with them a vast array of applications ranging from improvements in transportation safety and efficiency to innovations in entertainment and urban sensing [Cavalcanti *et al.*, 2018]. This article delves into a historical and comprehensive analysis of VANET research, focusing on identifying trends, the most used methodologies, and the predominant tools in the study of these networks.

Aligned with Internet of Things (IoT) and Artificial Intelligence (AI) technologies, VANETs promise not only to increase the safety and efficiency of land transportation systems but also to contribute to reducing environmental pollution and enriching user experiences with a multitude of applications [Domingos *et al.*, 2016]. However, effectively implementing a vehicular network is crucial, requiring the identification and selection of key parameters for simulations, experiments, or formal analyses.

The conducted research analyzed about 600 articles published between 2007 and 2021 in significant conferences and journals, identifying the most promising and recurrent areas, as well as the main tools and methodologies used in the studies. From this analysis, trends in the addressed topics and their future perspectives were detected. Moreover, we discuss the main research problems found and compare them with other studies, emphasizing the gaps and flaws that continue to be employed in studies.

Vehicular networks represent a promising path for new research and the strengthening of academic knowledge, disseminating potential solutions that can assist in the daily lives of users and the general population. Among the main challenges and characteristics of VANETs, future perspectives to be considered for the vehicular network interface include security and privacy, intelligent processing techniques, vehicular edge computing, and clustering in VANETs [Kurkowski *et al.*, 2005; Andel and Yasinsac, 2006; Sarkar and Gutiérrez, 2014].

Throughout the research, the contributions of this study will be detailed, encompassing advancements and innovations in VANET technology. It will also highlight which methodologies have been fundamental in shaping current practices and the tools that have emerged in this evolving field.

Significantly, we will highlight the integration of technologies, such as the IoT and AI in VANETs, detailing how these integrations enhance the functionality and efficiency of vehicular networks. Moreover, this study addresses critical gaps in current research and identifies potential methodological flaws that persist in contemporary studies, proposing pathways for future investigations.

Additionally, this research will explore the evolution of network architectures within VANETs, examining how emerging technologies have influenced their design and implementation. It will delve into advancements in security protocols and data transmission efficiency, which are crucial for ensuring robust and reliable vehicular communications. The study will also cover the practical applications of these technologies in urban and rural settings, demonstrating their impact on real-world traffic management systems.

This article presents a comprehensive survey of recent studies, highlighting the adequacy of performance metrics and preferences made during research, which may render results sensitive to validation compared to related studies or even the unreliability of the research outcomes, depending on how the study was conducted. Finally, open challenges and promising research directions are indicated. This article is expected to become a guide for newcomers and professionals interested in vehicular networks.

2 Related surveys

In the field of vehicular network environments, the literature presents a limited number of studies addressing the selection of parameters for simulation or experimentation and correlating results to outline application trends and future research directions.

A notable contribution is the work of Weber *et al*. [2021], which conducted an updated review of VANET simulators, assessing current resources and their suitability for evaluating new scenarios in related research. Despite ongoing challenges in identifying current and future simulators, their findings suggest Veins as a particularly apt tool for supporting emerging technologies. Our study extends the timeframe of analysis from 2007 to 2021, discussing the state-of-the-art, main challenges, and future perspectives in VANETs.

Ashraf *et al*. [2021] introduces the Node Redeployment Shrewd Mechanism (NRSM) for wireless sensor networks (WSNs). This mechanism aims to overcome network coverage challenges frequently affected by improper placement of sensor nodes. The article explores variations in several NRSM parameters such as pulse emission rate, maximum frequency, and detection radius. The performance of NRSM is compared with algorithms like the Fruit Fly Optimization Algorithm (FOA), Jenga-inspired optimization algorithm (JOA), and Bacterial Foraging Algorithm (BFA), in terms of average coverage, computation time, standard deviation, and network energy reduction.

Ashraf *et al*. [2020] addresses significant challenges faced by wireless sensor networks, mainly related to network coverage due to improper sensor node placement. To overcome these challenges, a mechanism named Bodacious-instance Coverage Mechanism (BiCM) is proposed. BiCM aims to improve network coverage by reorganizing sensor node positions. Furthermore, the study explores variations in several BiCM parameters such as pulse emission rate, maximum frequency, grid points, and sensing radius, identifying optimized parameters. Simulation results show that the tuned BiCM outperforms the Fruit Fly Optimization Algorithm (FOA) and standard BiCM in terms of average coverage rate, computation time, and standard deviation.

Ahmad *et al*. [2020] presents the BiCM, a novel mechanism to enhance network coverage in WSNs. BiCM is designed to overcome challenges faced by WSNs due to improper sensor node placement, affecting coverage and network performance. The article also investigates variations in several BiCM parameters like pulse emission rate and detection radius. The performance of BiCM is compared with FOA and a tuned version of BiCM, in terms of average coverage, computation time, and standard deviation.

The study by Cavalcanti *et al*. [2018] covers the period between 2007 and 2016, offering insights into the credibility of simulation-based studies and the broader VANET research field. They analyzed approximately 283 articles, with 147 published in the first five years (2007-2011) and 136 in the second (2012-2016).

2.1 Comparative Analysis

This research extends the understanding of published works in the field of VANETs by integrating systematic reviews of emerging technologies and their practical applications, setting it apart from the studies by Cavalcanti in 2018 and Kurkowski in 2005. To facilitate the understanding of the technical terms used throughout this article, a list of terms and abbreviations will be presented in Table 1.

Table 1. List of Abbreviations

Abbreviation	Definition
AI	Artificial Intelligence
APP	Application layer protocols and services
DATA	Data management
DTN	Delay Tolerant Network
IoT	Internet of Things
I2I	Infrastructure-to-Infrastructure
MAC-PHY	MAC and Physical layers issues
MANET	Mobile Ad-hoc Networks
MOB	Mobility issues
OBU	On-Board Unit
PERF	Performance comparison analysis
ROUT	Routing protocol
RSU	Roadside Unit
SERV	Complementary services
TOOL	Tools and testbeds
VANET	Vehicular Ad-hoc Network
WSN	Wireless Sensor Networks
V2V	Vehicle-to-Vehicle
V2I	Vehicle-to-Infrastructure
V2X	Vehicle-to-Everything

In contrast to the previously mentioned studies, which concentrated on the technologies and methodologies of their time, this research includes the latest technologies and significant advancements from publications involving the applicability of the IoT and AI within the context of VANETs. Table 2 presents a comparative analysis of prior research. Cavalcanti *et al*. [2018] conducted a comprehensive analysis of the challenges and research methodologies in VANETs up to the publication date, whereas Kurkowski *et al*. [2005] assessed the credibility of simulation studies in mobile ad hoc networks (MANETs), without considering subsequent technological advancements.

This research not only updates existing knowledge on VANETs but also introduces a practical perspective on how new technologies can be effectively integrated to solve contemporary traffic and security issues. The practical, application-oriented approach significantly differentiates this work from earlier reviews, which were more limited in scope and depth.

3 Overview of Vehicular Ad Hoc Networks

This section elucidates the fundamental characteristics, opportunities, and challenges associated with VANETs. We underscore key areas such as network architecture, mobility models, propagation and routing protocols, and principal categories and applications specific to VANETs.

Network simulators play a crucial role in the validation, evaluation, analysis, and comparison of communication protocols across various layers of the protocol stack. For effective simulation, these simulators must encompass implementations of protocols and services across the physical, link, network, and transport layers. Two pivotal components integral to wireless ad hoc network simulation are the propagation model and the mobility model [Boucetta *et al.*, 2021].

3.1 VANETs Architecture

The architecture of vehicular networks, known as vehicular ad hoc networks, is characterized by an intricate network of vehicles connected in a wireless ad hoc format. Key components integral to VANETs include RoadSide Units (RSUs), On-Board Units (OBUs), proxy servers, administrative servers, a range of applications, vehicles, a vehicle registration authority, and location-based applications [Arif *et al.*, 2019]. A detailed representation of the vehicular network taxonomy is depicted in Figure 1.

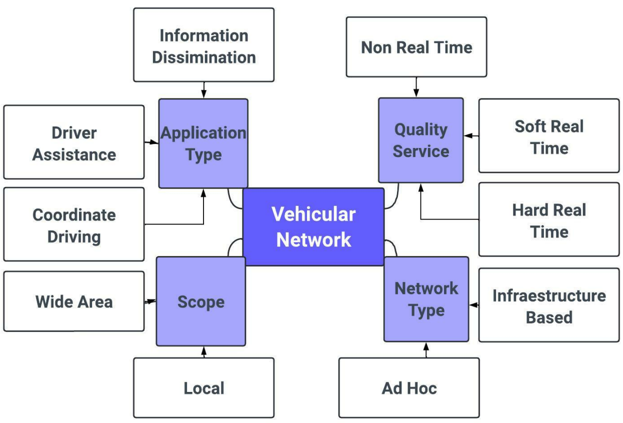

Figure 1. Taxonomy of Vehicular Network.

Within an urban VANET setting, the inclusion of RSUs is a typical manifestation of roadside infrastructure. In such environments, we can identify three primary modes of communication: Infrastructure-to-Infrastructure (I2I), Vehicle-to-Vehicle (V2V), and Vehicle-to-Infrastructure (V2I), as illustrated in Figure 2. Furthermore, with the emergence of the IoT, the concept of Vehicle-to-Everything (V2X) communication has gained prominence, encompassing a broader range of interactions within the network.

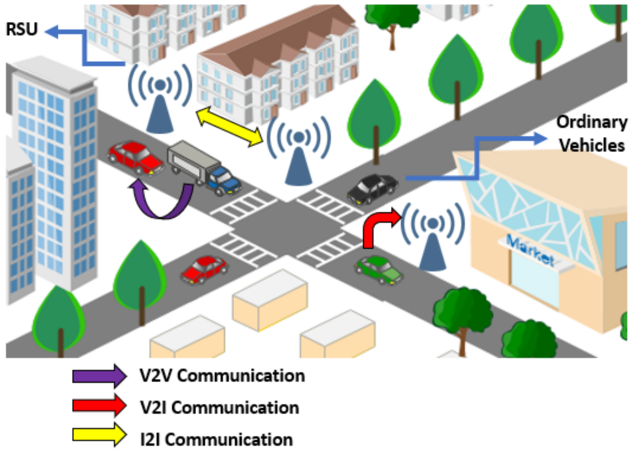

Figure 2. VANETs Architecture.

3.2 Mobility Model

A pivotal element in the structure of vehicular networks is the mobility of vehicles. Independent of whether the vehicles traverse urban streets or highways, their movement adheres to specific patterns. As elucidated by Cavalcanti and Spohn [2013], a mobility model is essentially a mathematical framework that delineates the movement patterns of mobile entities, such as vehicles.

Hartenstein and Laberteaux [2009] asserts that vehicular mobility can be modeled based on trajectories and flows. The generation of mobility models from real-time traffic data is essential for producing specific and accurate results [Sommer and Dressler, 2008]. These models are categorically divided into two types: microscopic models, which focus on individual vehicle mobility, and macroscopic models, which address the mobility of vehicle groups. The vehicular mobility model is adept at simulating vehicle behavior, incorporating aspects such as road topology, traffic conditions, and the proximity of other vehicles.

Vehicular networks exhibit a variety of mobility patterns, contingent upon the simulation or experimental environment in which they are implemented. Notably, these networks are characterized by the high mobility of vehicles and numerous nodes that move at varying speeds, especially in urban areas [Mateus, 2010].

3.2.1 Synthetic Map

Synthetic models constitute a prominent category in vehicular network simulations. These models are pivotal for simulating environmental effects realistically by developing mathematical models that mimic real-world scenarios. However, as highlighted by Souza [2018], synthetic models may encounter limitations when applied to practical, real-world settings. The essence of these models lies in understanding

Table 2. Comparative Analysis of Advancements in VANET Research

Aspect	Kurkowski et al (2005)	Cavalcanti et al. (2018)	Current Investigation
Technological Focus	Limited to the analysis of simulations in MANETs.	Covered VANETs up to 2018, with an emphasis on protocols.	Integration of the latest innovations in IoT and AI into VANET communications.
Methodology	Evaluation of the credibility of simulations.	Analysis of literature at events and conferences in the field.	Systematic review with rigorous selection criteria, incorporating new articles published in recognized scientific journals in the study area.
Practical Applications	Limited theoretical discussion on future applications.	Description of potential applications of VANETs.	Proposals and directions for practical implementation using new technologies to demonstrate the feasibility of the research.
Content Update	Based on technologies and concepts up to 2005.	Included advancements up to 2018.	Inclusion of studies post-2018, reflecting on technological evolution and its future implications.

a specific movement pattern, developing a corresponding mathematical model, and then recreating this movement in simulations. Nonetheless, as Harri *et al*. [2009] indicate, the complexity of modeling certain movements, particularly their interactions, can lead to models that are either too intricate or impractical for implementation.

The road topology plays a crucial role in achieving realistic outcomes in vehicular movement simulations. Factors like the layout of streets, the frequency of intersections, and traffic density greatly influence mobility parameters and metrics. These factors include the speeds of cars (minimum, maximum, and average) and the vehicle density on the simulated map, as elaborated by Fiore *et al*. [2007]. Synthetic mobility models can be categorized based on various criteria:

- *User Defined:* This approach involves defining the road or urban topology through graph vertices and their interconnecting edges.
- *Random:* This model generates a random graph, enabling implementations based on existing models, such as the Manhattan grid, Spider, or Voronoi patterns.
- *Maps:* Here, the topology is derived from actual maps, incorporating various topological patterns like GDF, TIGER, or Arcview.
- *Multilane:* This type includes topologies with multiple lanes, facilitating simulations of lane changes when necessary.

Additionally, intersection management is integrated into synthetic models, enhancing vehicle handling and behavior during intersection approaches. Common scenarios in these models include crossings governed by stop signs or traffic light junctions, as discussed in the works of Fiore *et al.* [2007] and Souza [2018].

3.2.2 Realistic Map

In vehicular mobility models, there are two primary classifications: microscopic and macroscopic. The macroscopic perspective encompasses movement constraints such as roadways, intersections, and traffic signals. It also involves the creation of vehicular traffic scenarios, incorporating elements like traffic volume, flow patterns, and the initial distribution of vehicles [Harri *et al*., 2009]. Conversely, the microscopic approach zeroes in on the individual movements of each vehicle and how it behaves in relation to other vehicles.

A novel method to understand these models is by delineating them into two functional segments: Movement Restrictions and Traffic Generator. Movement Restrictions describe individual vehicle movements, typically based on topological maps. This includes larger scale elements like streets and buildings (macroscopic) and smaller scale elements like individual cars, pedestrians, and roadway constraints (microscopic). Traffic Generator, on the other hand, simulates diverse traffic flow types and manages their interactions within the specified environment [Souza, 2018]. This includes macroscopic factors like traffic densities and flows, as well as microscopic aspects such as inter-vehicle distances and acceleration patterns.

3.3 Propagation Model

Signal propagation models are integral in simulations or experimental settings involving vehicular networks, where they simulate the behavior of electromagnetic waves. The effectiveness of message transmission within these networks depends on variables like the distance between nodes, signal strength, and potential interferences, as shown in Figure 3.

Propagation models are broadly categorized into deterministic and probabilistic types. Deterministic models calculate the signal strength based on specific environmental factors, mainly focusing on the distance between the transmitting and receiving nodes. This model simplifies the complexity of signal propagation by primarily considering the linear distance in its calculations [Van Eenennaam, 2008]. Alternatively, probabilistic models offer a more nuanced approach to simulating radio wave propagation. They incorporate a range of input parameters, making them more suitable for depicting realistic environmental conditions. This type of model is es-

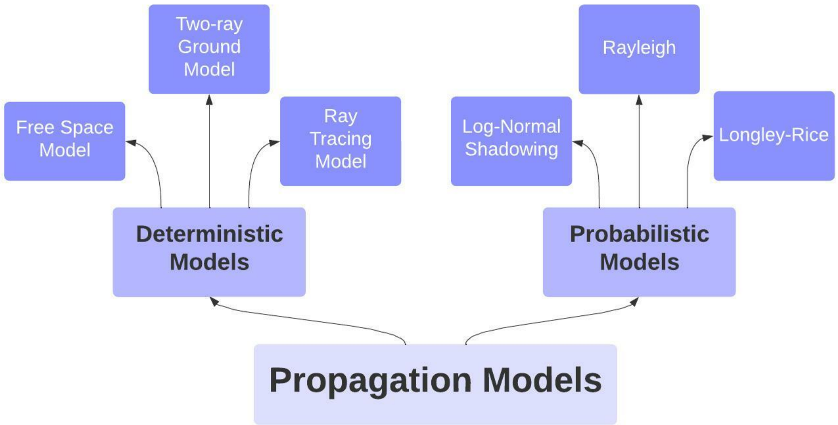

Figure 3. Types of Propagation Model.

sential for achieving accurate simulation results that closely mimic real-world scenarios.

3.4 Routing Protocol

Routing protocols are vital in communication networks, including VANETs, where they significantly enhance network performance. These protocols primarily function to establish the most efficient route between a source and a destination[Sharma *et al.*, 2021]. Due to the high mobility of nodes in VANETs, maintaining and adapting routes is particularly challenging.

- **Unicast Routing:** This is the most basic form of routing, involving direct packet transmission from a source to a destination. VANETs often employ a wireless multihop transmission method, where data packets are relayed through intermediate nodes to reach their destination efficiently. Another method within unicast routing is the carry-and-forward approach, which involves temporarily storing data packets to mitigate network congestion, although this method typically results in slower data transmission compared to multihop transmission.
- **Multicast Routing:** In multicast routing, data packets are sent from a single source to multiple destinations within a multicast group. This approach is efficient for scenarios where the same data needs to be disseminated to multiple nodes. Geo-Cast Routing, a form of multicast routing, specifically targets nodes within a predefined geographic area, enhancing efficiency in spatially focused communications.
- **Broadcast Routing:** This method is used when information needs to be disseminated to all nodes within the network uniformly. Common uses include transmitting traffic updates, weather conditions, and emergency alerts. However, broadcast routing can lead to high network bandwidth consumption and may result in the duplication of packets.

Routing protocols in VANETs can be further categorized into two types: topology-based routing and geographic routing. Topology-based protocols rely on the state of network links to route packets, whereas geographic protocols use location information to direct the packets. These can be further divided into proactive, reactive, hybrid, non-DTN (Delay and Interruption Tolerant Network), DTN, and hybrid approaches (Figure 4).

3.5 Applications of VANETs

VANETs have fostered the development of a variety of applications that significantly improve vehicular technology, traffic management, and transportation systems [Deshmukh and Dorle, 2016]. These applications are typically based on the collaborative systems structured in VANETs' network infrastructure [Hamdi *et al.*, 2020]. They can be broadly categorized into four major areas (Figure 5): efficiency, entertainment, safety, and urban sensing.

- **Efficiency Applications:** These applications are designed to enhance vehicular traffic management and road conditions. By optimizing traffic flow and monitoring road networks, efficiency applications aim to streamline vehicular movements, reduce congestion, and improve overall traffic efficiency.
- **Entertainment Applications:** Leveraging the connectivity offered by VANETs, entertainment applications provide various services like internet access, online gaming, and multimedia content streaming for vehicle users. These services are often facilitated through Wi-Fi networks along roads or via cellular data networks, offering passengers and drivers alike various recreational options during transit.
- **Safety Applications:** A key focus of VANETs is to bolster road safety. Safety applications aim to diminish the risk of accidents, particularly at critical points like intersections or during risky maneuvers like overtaking. These applications provide drivers with real-time alerts about potential hazards, traffic conditions, and other relevant safety information. They also play a crucial role in the operation of self-driving vehicles and vehicles equipped with intra-vehicular sensors, enhancing V2V and V2I communications for safer driving experiences.
- **Urban Sensing Applications:** As VANETs integrate with IoT and smart city technologies, urban sensing applications have emerged. These applications utilize vehicles equipped with various sensors to collect data on environmental factors like rainfall, road conditions,

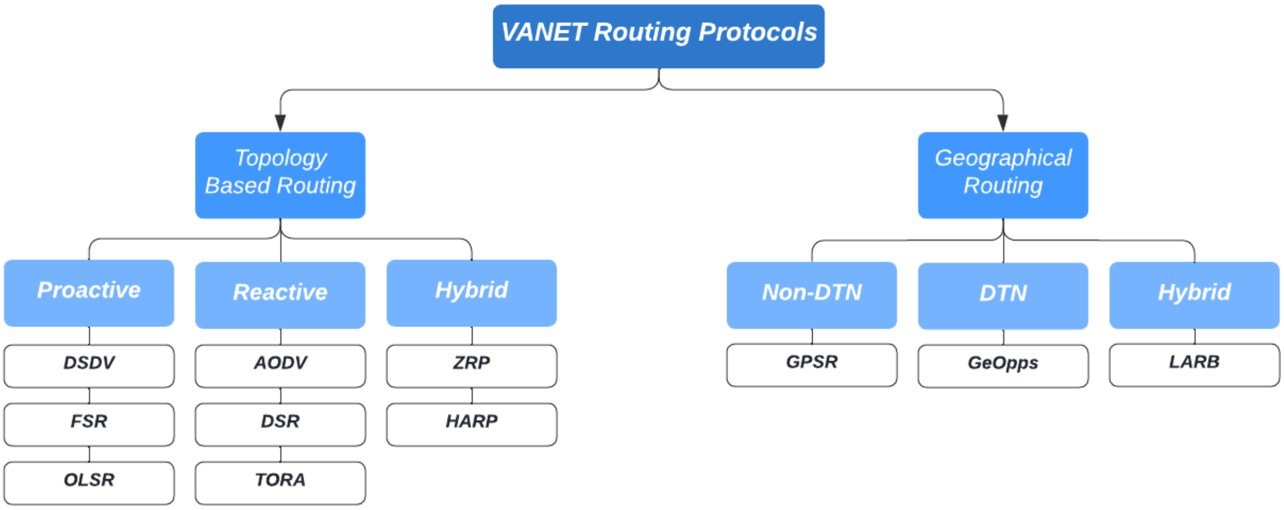

Figure 4. Taxonomy of VANETS routing protocols.

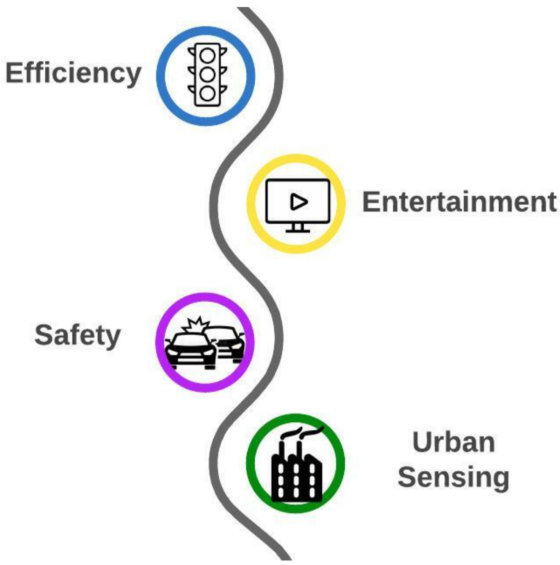

Figure 5. Applications of VANETs.

and pollution levels. This information is then communicated to relevant authorities or infrastructure components (such as Roadside Units), contributing to the improvement of urban living conditions.

4 Survey description

In this phase of our study, we focused on papers that incorporated either 'VANET' or 'Vehicular ad hoc Network' in their title, abstract, or key terms. The timeframe for these publications spanned from 2007 to 2021. The sources of these articles were primarily:

- The ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc);
- The Annual International Conference on Mobile Computing and Networking (Mobicom), including its main event and associated workshops;
- IEEE Vehicular Technology Conference (VTC);
- IEEE Transactions on Mobile Computing (TMC);
- Vehicular Communications (Elsevier), published by Elsevier.

The subsequent sections of this article aim to elucidate the following research questions regarding VANETs studies conducted up to 2021:

1. Which research methodologies have been predominantly utilized?
2. How do simulation-based studies fare in terms of credibility compared to other types of surveys?
3. What tools and protocols are most commonly employed, including simulators, propagation models, mobility models, and routing protocols?
4. Which research themes have garnered more or less interest within the scientific community?

We analyzed approximately 600 articles, answering the questionnaire (Table 3) for each. A summary of the process is described in Figure 6, extracting all the valuable information necessary to characterize the research and highlight how the authors conducted their research. It is important to note that, due to the significant number of articles selected for the study, totaling 600 analyzed articles, it was not possible to include them in the references of this article. However, interested readers can access the complete list of articles and the collected data in the *zenodo*[1] repository, as indicated in Table 3. This measure aims to facilitate access to the complete resources of the research and ensure the transparency of the study.

Cavalcanti et al describe a list of the main research topics on VANETs, which can be grouped in eight areas, called top-level categories. There is a wide range of topics related to vehicular communications (Figure 13). For example, if an article focuses on any aspect related to the link or physical layers, such as a MAC algorithm, channel modeling, network encoding, or adaptive transmission power control, the article is labeled as MAC-PHY. At the other end is the APP class, containing all the articles that address user applications (e.g.,

[1] `https://doi.org/10.5281/zenodo.6126581`

Table 3. Detailed overview of questions in each article reviewed

Category	Description
A. Simulation Usage and Tools	
	Used simulation in the research
	Stated which simulator was used
	Used self-developed or custom simulators
	Version of the public simulator was used
B. Simulation Details and Parameters	
	Stated the size of the simulation area
	Stated the transmission range
	Stated the simulation duration
	Stated the traffic send rate
	Stated the traffic type (e.g., CBR, VBR, etc.)
C. Accessibility and Reproducibility	
	Stated the code was available to others
	Addressed initialization bias
	Addressed the type of simulation
	Addressed the PRNG used
D. Reporting and Documentation	
	Used plots to illustrate the simulation results
	Used confidence intervals on the plots
	Missed labels or units on the data

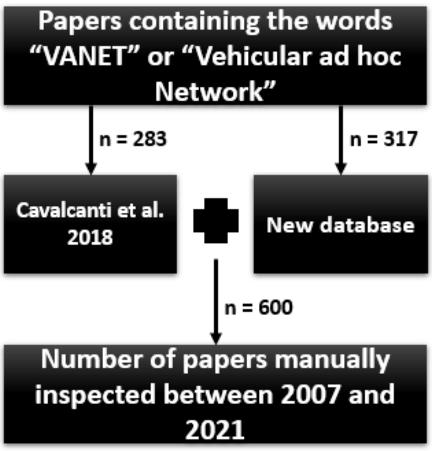

Figure 6. Number of publications by authors.

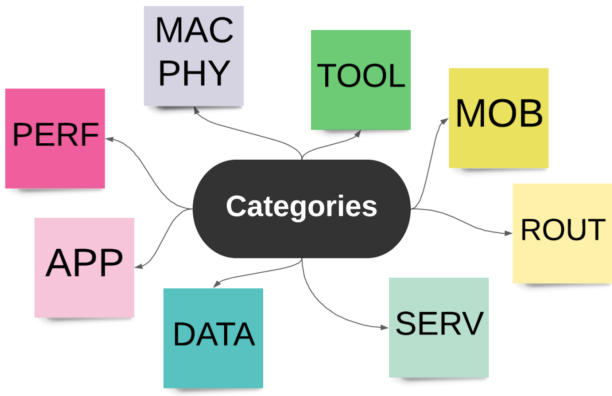

Figure 7. Classification Framework of VANET Research Topics.

collision prevention at intersections, road congestion notification, and multimedia streaming).

In their comprehensive study, Cavalcanti *et al.* [2018] outlined a classification system for VANET research, organizing the vast array of topics into eight primary categories (Figure 13). These categories provide a framework for understanding the breadth of research in vehicular communication networks.

1. *MAC-PHY:* This category encompasses studies focusing on the link or physical layers of vehicular communication systems. For instance, articles that explore MAC algorithms, channel modeling, network coding, or adaptive transmission power control are classified under MAC-PHY.
2. *APP:* This includes research that concentrates on applications for users, such as collision prevention systems, traffic congestion alerts, and multimedia streaming services.
3. *PERF:* Articles in this category are those whose primary contribution is the evaluation of protocol performance. For instance, if a study introduces a new medium access or routing protocol and then evaluates its performance, it would be categorized under MAC-PHY or ROUT, respectively, rather than PERF.
4. *TOOL:* This class is assigned to articles that describe new tools, platforms, frameworks, or architectures. In addition, to maintain simplicity, all experimental studies, particularly those related to deployment and field testing, are also included in this class.
5. *ROUT:* Encompassing studies that introduce new routing protocols.
6. *MOB:* This category is for research dealing with mobility issues, including mobility models and grouping algorithms.
7. *DATA:* Focused on studies that center around collection schemes and data disclosure.
8. *SERV:* This final category is reserved for what are

termed 'complementary services', such as Quality of Service (QoS) and security aspects in VANETs.

5 Survey results

5.1 Which research methodologies have been predominantly utilized?

This section explores the prevalent research methodologies employed in VANETs studies, as identified through our survey analysis (Figure 8). The primary methodologies observed include simulation, experimentation (testbeds), and formal analysis (mathematical modeling). A unique aspect of our survey was the option for respondents to select multiple methodologies if applicable to their research.

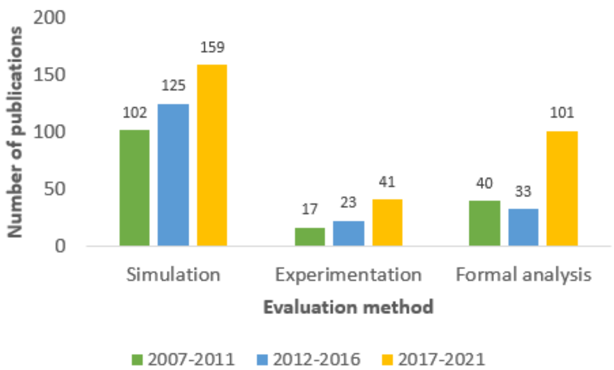

Figure 8. Overview of evaluation and validation methods.

Our findings indicate a notable trend in the utilization of these methodologies over time. Simulation, as a method for evaluation and validation, has consistently been the most prominent approach in VANETs research. Specifically, from 2007 to 2011, about 64% of the articles incorporated simulation methods. This number slightly increased to 69% in the subsequent five-year period, before decreasing to 53% in the latest data.

In contrast, there has been a significant and steady rise in the adoption of formal analysis, particularly mathematical modeling. This trend is reflective of a maturing research area where more sophisticated and theoretical approaches are being applied. Similarly, experimentation methods have also seen a gradual increase in their application, rising from 10.7% between 2007 and 2011, to 12.7% from 2012 to 2016, and further to 13.6% in the period from 2017 to 2021.

5.2 How do simulation-based studies fare in terms of credibility compared to other types of surveys?

This segment investigates the reliability and methodological integrity of simulation-based studies in VANETs by comparing findings from our survey with previous surveys by Kurkowski *et al*. [2005]; Cavalcanti *et al*. [2018]. These comparisons (Table 4) reveal a persistent lack of research artifacts like codes and data [Ashraf *et al*., 2020]. A significant finding is the persistent lack of availability of research artifacts like codes and datasets. Additionally, there has been an increase in the documentation of the simulation environment specifics, including the simulator version and the operating system used.

The study also notes that a significant proportion of articles do not detail essential simulation parameters such as the transmission range of nodes. Despite this, most studies reported the size of the simulation area, while very few mentioned the traffic pattern used. Notably, there has been a decline in the use of graphical representations to present results, suggesting a shift in the way outcomes are communicated in scholarly articles.

A significant portion of the articles reviewed, amounting to 210 out of 317 (66.24%), utilized some form of mobility model. However, only a subset of these, accounting for 48.57%, explicitly identified the specific model employed. This rate aligns closely with the findings of Cavalcanti *et al*. [2018]. Propagation models, typically integrated within network simulators, are complemented by external tools for generating realistic vehicular movement patterns. Nevertheless, there has been a noticeable decline, approximately 15%, in the frequency of studies specifying the propagation model used, as detailed in Table 5.

In their study, Hota *et al*. [2022] conducted a comparative analysis of various propagation models. Their findings highlighted that the Nakagami model exhibited subpar performance, particularly in terms of network overload metrics. Conversely, the Two-Ray Ground model demonstrated superior throughput when compared to other models like Friis, Log Distance, and Nakagami.

5.3 Which tools and protocols are most commonly employed, including simulators, propagation models, mobility models, and routing protocols?

Conducting research in the field of vehicular networks necessitates a careful selection of network and mobility simulators. This choice hinges on various factors like the researcher's operating system, whether the software is open source or proprietary, the availability of online tutorials, and the user-friendliness of the simulation environment. Preferences for well-known or widely used simulation tools may evolve over time. Figure 9 illustrates the trend in network simulator preferences over recent years.

The NS-2 simulator emerged as the most popular, used in 29.1% of the 104 articles that employed simulation, followed by OMNET++ (16.5%), NS-3 (15.1%), and MATLAB (11.8%). Network simulators like Veins [Sommer *et al*., 2010] are often used for their open-source capabilities and realistic enhancement of V2X network simulations.

Mobility simulators, designed for environments with dynamic movement traits, are integrated into these network simulators, as depicted in Figure 10. The most frequently used mobility simulators are SUMO (42.8%) and VanetMobiSim (6.2%), with a notable 37.8% of simulation-based articles not specifying the mobility tool used.

The past five years have seen an increase in the use of real maps compared to synthetic ones in mobility simulations, as

Table 4. Comprehensive Comparison of Survey Data Across Different Conferences and Journals

Survey Item	Our Survey's Results	Vanet's Survey	MobiHoc's Survey
Used simulation in research	205 of 317 (64.66%)	210 of 283 (74.20%)	114 of 151 (75.5%)
Stated code availability	0 of 205 (0%)	1 of 210 (0.47%)	0 of 114 (0%)
Stated which simulator was used	107 of 205 (52.12%)	180 of 210 (85.71%)	80 of 114 (70.2%)
Used self-developed or custom simulators	6 of 205 (2.93%)	16 of 210 (7.62%)	22 of 114 (19.3%)
Version of the public simulator was used	73 of 205 (35.63%)	43 of 210 (20.48%)	7 of 114 (6.14%)
Stated which operating system was used.	40 of 205 (20.48%)	17 of 210 (8.09%)	3 of 114 (2.6%)
Addressed initialization bias.	37 of 205 (18.04%)	20 of 210 (9.52%)	8 of 114 (7%)
Addressed the type of simulation.	49 of 205 (23.90%)	52 of 210 (24.76%)	48 of 114 (42.1%)
Addressed the PRNG used.	2 of 205 (0.97%)	6 of 210 (2.86%)	0 of 114 (0%)
Stated the simulation area size	173 of 205 (84.39%)	122 of 210 (58.10%)	62 of 151 (41.05%)
Stated the transmission range	138 of 205 (67.31%)	137 of 210 (64.79%)	62 of 151 (41.05%)
Stated the simulation duration	187 of 205 (91.21%)	88 of 210 (41.90%)	49 of 151 (32.45%)
Stated the traffic send rate	89 of 205 (43.41%)	83 of 210 (39.52%)	41 of 151 (27.15%)
Stated the traffic type	15 of 205 (7.32%)	33 of 210 (15.73%)	31 of 151 (20.53%)
Stated the number of simulation runs.	57 of 205 (27.80%)	73 of 210 (34.76%)	39 of 109 (35.8%)
Used plots to illustrate results	143 of 205 (69.76%)	206 of 210 (98.10%)	112 of 114 (98.25%)
Used confidence intervals on plots	28 of 205 (13.66%)	73 of 210 (34.76%)	14 of 112 (12.5%)
Missed labels or units on data	65 of 205 (31.71%)	88 of 210 (41.90%)	28 of 112 (25%)

Table 5. Detailed Comparison of Model Preferences in VANET Research

Details	Our Survey's	Vanet's Survey
Mobility Models (MM)		
Used MM in the research.	210 of 317 (66.24%)	221 of 283 (78.10%)
Stated which model/tool was used.	102 of 210 (48.57%)	96 of 221 (43.44%)
Only stated the mobility trace generator tool	2 of 102 (1.96%)	34 of 96 (35.42%)
Used Manhattan model.	14 of 102 (13.72%)	16 of 96 (16.67%)
Used own (or proposed) model.	13 of 102 (12.74%)	14 of 96 (14.58%)
Used IDM model.	2 of 102 (1.96%)	13 of 96 (13.54%)
Used Freeway model.	3 of 102 (2.94%)	7 of 96 (7.29%)
Used other models.	15 of 102 (14.70%)	7 of 96 (7.29%)
Used only real traces.	46 of 102 (45.09%)	4 of 96 (4.17%)
Used random waypoint model.	7 of 102 (6.86%)	3 of 96 (3.13%)
Propagation Models (PM)		
Used PM in the research.	159 of 317 (50.15%)	214 of 283 (75.62%)
Stated which model was used.	59 of 159 (37.10%)	83 of 214 (38.78%)
Used Nakagami model. (40.96%)	20 of 59 (33.89%)	34 of 83
Used Two-Ray Ground model.	23 of 59 (38.98%)	26 of 83 (31.32%)
Used Free Space (Friis) model.	2 of 59 (3.38%)	8 of 83 (9.64%)
Used Rayleigh model.	4 of 59 (6.77%)	8 of 83 (9.64%)
Other models.	10 of 59 (16.94%)	7 of 83 (8.43%)
Used own model.	4 of 59 (6.77%)	6 of 83 (7.23%)
Routing Protocols (RP)		
Used RP in the research	211 of 317 (66.56%)	97 of 283 (34.28%)
Stated which protocol was used.	60 of 211 (28.43%)	64 of 97 (65.98%)
Used own (or proposed) protocol.	37 of 60 (61.66%)	33 of 64 (51.56%)
Used the GPSR protocol.	8 of 60 (13.33%)	12 of 64 (18.75%)
Used the AODV protocol.	17 of 60 (28.33%)	9 of 64 (14.06%)
Used the OLSR protocol.	8 of 60 (13.33%)	6 of 64 (9.38%)
Other protocols.	16 of 60 (26.66%)	4 of 64 (6.25%)
Used the DSR protocol.	1 of 60 (1.66%)	3 of 64 (4.69%)
Used the DYMO protocol.	1 of 60 (1.66%)	3 of 64 (4.69%)

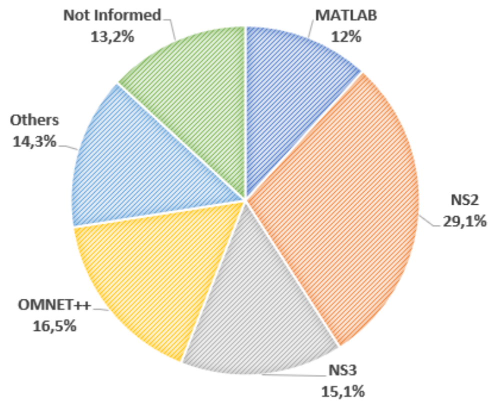

Figure 9. Preferences in network simulators.

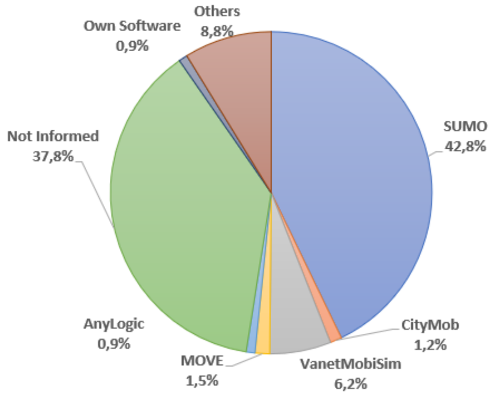

Figure 10. The mobility simulation environment.

shown in Figure 11. This trend may be attributed to the demand for more realistic models, facilitated by free tools like SUMO and Openstreemap [Haklay and Weber, 2008].

In terms of propagation models, the Two-Ray Ground model was most used (38.98%), closely followed by the Nakagami model (33.89%). These percentages are not mutually exclusive, as studies sometimes employ multiple models. A shift in preference between these two models has been observed compared to earlier research.

Approximately two-thirds (66.56%) of all reviewed articles utilized some form of routing protocol, indicating an increase of about 30% compared to the findings in Cavalcanti *et al.* [2018]. Notably, one-third of these studies proposed new protocols, with AODV, GPRS, and OLSR being the most commonly used, accounting for 28.33%, 13.33%, and 13.33%, respectively.

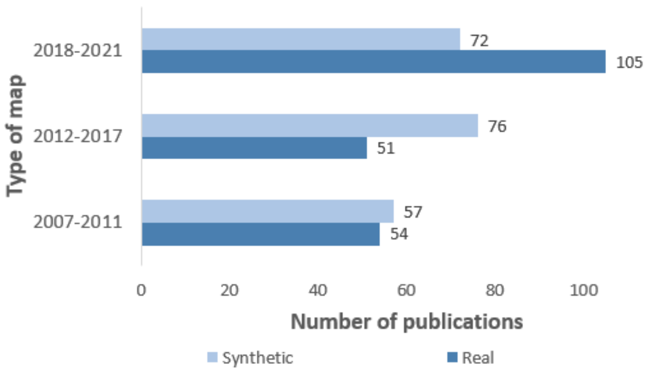

Figure 11. Comparison of map styles employed in VANET.

5.4 Which research themes have garnered more or less interest within the scientific community?

The categorization of research topics in VANETs adheres to the classification system proposed by Cavalcanti *et al.* [2018], comprising MAC and Physical layers issues (MAC-PHY), Performance comparison analysis (PERF), Application layer protocols and services (APP), Data management (DATA), Complementary services (SERV), Routing protocol (ROUT), Mobility issues (MOB), and Tools (TOOL).

In the initial five-year span, nearly 20% of the studies concentrated on developing new standards, techniques, or protocols for the lower layers, namely, the physical and MAC layers, as illustrated in Figure 12. Conversely, the APP class, encompassing articles proposing new applications, saw an increase from 9% to 26% in the last period. This growth indicates a maturing field with expanding standardizations and protocols for upper layers, thus facilitating application development.

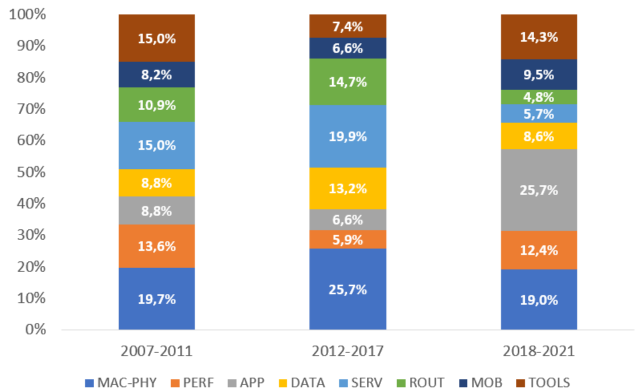

Figure 12. Top-level research categories in VANETs research between 2007 to 2021.

The SERV class, encompassing articles on complementary services such as QoS, security, and location, mirrored the trend of the MAC-PHY class, experiencing a decline in popularity from 17.5% to 6%. The ROUT, PERF, and TOOLS classes each garnered around 10%, with slight variations. ROUT class studies often focused on network topologies (proactive, reactive, or hybrid), with geographical and delay-tolerant approaches showing promise. PERF class studies involved performance or protocol comparison analyses, including design, testing, and verification of protocols. The TOOLS class, representing studies on development tools, witnessed a decrease in publications from 273 to 27 in the respective periods.

The MOB and DATA classes each accounted for about 8% of the research, with a notable decline in papers related to dissemination strategies, transmission algorithms (DATA), and mobility issues like modeling and clustering algorithms (MOB). Figure 13 showcases the trends in these categories over recent years.

Section 3.5 delves into the four application categories for VANETs: safety, efficiency, urban sensing, and entertainment. Studies sponsored by vehicle manufacturers typically emphasize safety and urban sensing, while public or governmental initiatives often develop traffic solutions for en-

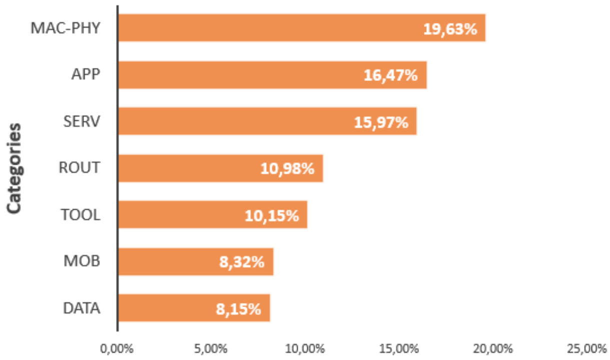

Figure 13. Research categories in VANETs.

hanced efficiency. Entertainment applications, primarily developed by major software companies, have also gained traction [Cavalcanti *et al.*, 2018].

Initially, VANET research predominantly targeted safety and transportation system efficiency, with about 90% of articles between 2007 and 2011 focusing on these areas (Figure 14). Over time, there has been a discernible shift toward entertainment and urban sensing, propelled by advancements in IoT and 5G technologies. Only 9% of articles addressed these topics in the earliest period (2007 to 2011), compared to over 40% in the latest period (2017 to 2021).

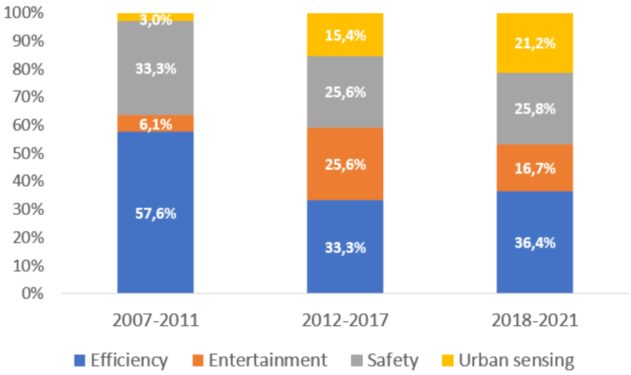

Figure 14. Research trends for VANETs' applications.

It is noteworthy that some applications may serve multiple purposes. For instance, an autonomous traffic light control system optimizing real-time traffic flow would primarily be an efficiency application but could also enhance safety by reducing risks like nighttime assaults at intersections.

6 Threats to Validity

This study provides a comprehensive overview of advancements in VANETs, focusing on contributions from selected journals and conferences between 2007 and 2021. However, due to the broad scope of VANET research, the inherent limitation of this study lies in the need to selectively include articles based on specific criteria such as thematic relevance, impact, and methodological rigor.

Journal and Conference Selection: Our analysis covers approximately 600 articles from highly regarded conferences and journals. While these sources represent significant trends and advancements in VANET research, they do not encompass the entire spectrum of knowledge within the field. Many other valuable studies published elsewhere could provide additional insights but were beyond the scope of this survey.

Ethical and Social Considerations: In conducting this research, we adhered to ethical guidelines to ensure the integrity and credibility of our analysis. This included fair and respectful citation of sources, objective evaluation of all selected articles, and avoidance of bias in data interpretation. Furthermore, we considered the social implications of VANET technologies, particularly their impact on privacy, security, and data protection, which remain paramount concerns as these technologies integrate more deeply into societal functions.

Methodological Limitations: The selection of articles was also guided by the availability of sufficient data to support robust analyses. However, this approach may overlook seminal works that could offer different methodological insights or innovative perspectives. Additionally, the rapid evolution of technology means that more recent developments may not be reflected in this analysis, potentially limiting the applicability of our findings to future advancements.

A detailed comparative analysis of key research parameters and practices in VANETs across three different historical phases: from 2005-2010, 2011-2016, and 2017-2022, is presented Table 6. This analysis is divided into various sections, each highlighting distinct aspects of VANET research such as methodology, simulation parameters, and key findings.

The methodology section illustrates the evolution of simulation tools from earlier applications like NS2 and OMNeT++ to more advanced and tailored solutions like SUMO and proprietary tools in the most recent period, reflecting a trend towards more sophisticated simulation capabilities. The Simulation Parameters section provides insights into the evolution of simulation environments, noting a significant expansion in the scale of simulations and an increase in the transmission ranges used in studies, pointing towards an effort to model more realistic and extensive network scenarios. Finally, the Research Findings section discusses the developments in network density and mobility models, marking a transition from simplistic and theoretical models to those that incorporate complex, real-world dynamics and data-driven scenarios.

7 Conclusion and Future Research Perspectives

VANET is a technology with a wide range of recurring applications that have been often used lately. In research, the choice of application in vehicular networks has different perspectives that can act in entertainment, efficiency, safety, and urban sensing. However, to implement a vehicular network, it is crucial to identify the main parameters for performing simulation, experimentation, or formal analysis. This article provides an intensive review report of various aspects for selecting/choosing parameters in vehicular network searches. It also presents the general architecture of vehicular network infrastructures, types of applications, resources that can be inserted in this area of study, problems, and future perspectives in VANETs.

Table 6. Comparative Review of Key Research Parameters and Practices in VANETs

Research Aspect	Findings from 2005-2010	Findings from 2011-2016	Current Study (2017-2022)
Methodology			
Simulation Tools	Predominantly NS2 and OMNeT++	Shift towards SUMO and Veins	Advanced use of Veins and custom tools
Research Artifacts	Limited sharing of code	Increased code availability	High availability and open-source emphasis
Simulation Parameters			
Area Size	Commonly small urban areas	Expanded to larger scenarios	Large-scale and dynamic urban environments
Transmission Range	Typically under 300 meters	Up to 500 meters	Over 700 meters for broader coverage
Research Findings			
Network Density	High density in simulations	More varied density	Realistic, variable density scenarios
Mobility Patterns	Basic random waypoint	Introduction of realistic patterns	Complex mobility models based on real data

Vehicular networks are a promising path for new research and strengthening of academic knowledge in the dissemination of possible solutions that can help in the day-to-day life of users and the general population. Among the main challenges and characteristics of VANETs, some future perspectives should be considered for the vehicular network interface, such as:

Security and privacy: The main security and privacy challenges in VANETs involve the application of infrastructure model management and delimitation techniques arising from compromises between authentication, non-repudiation, confidentiality, and privacy of information [Mahi *et al.*, 2022].

Intelligent processing techniques: Methods used to implement traffic accident prediction models from machine learning and artificial intelligence can be a promising area for new research solutions [Shendekar *et al.*, 2021].

Vehicle Edge Computing: Managing dynamic and heterogeneous resources in Vehicle Edge Computing is a challenging task. The vehicle workload can perform the unloading of incoming tasks to an ideal computing unit in order to improve system performance in the search for efficient solutions [Sonmez *et al.*, 2020].

Clustering in VANETs: There are different perspectives for optimizing the clustering technique, such as security applications, traffic congestion, and emergency event alerts. However, identifying the parameters of time constraints, signal fading, connectivity, and bandwidth are crucial factors and research subareas in development [Kaur *et al.*, 2021].

In this article, a comprehensive survey of recent studies was made available, which resulted from the adequacy of performance metrics and predilections made during the research, which may cause results sensitive to validation compared to related studies or even the non-reliability of the results of the research depending on the way the study was conducted. Finally, open challenges and research targeting that can be promising were indicated. This article is expected to become a guide for newcomers and professionals interested in vehicular networking.

In addition to the analysis presented, this study offers specific recommendations for future research in VANETs:

- **Standardization and Reproducibility:** We recommend the development of standardized protocols for simulation and experimentation in VANET research to enhance reproducibility and comparability of results.
- **Integration with Emerging Technologies:** Future studies should explore the integration of VANETs with emerging technologies such as 5G, IoT, and blockchain, to enhance communication efficiency and security.
- **Realistic Simulation Environments:** We encourage the use of more realistic simulation environments that closely mimic real-world conditions, including urban landscapes and traffic patterns.
- **Interdisciplinary Collaboration:** Collaborative efforts between technologists, urban planners, and policymakers are crucial to develop comprehensive solutions that address both technical and societal aspects of VANETs.

Furthermore, the significant contribution of this manuscript lies in:

- **Comprehensive Overview:** Providing an extensive review of VANET research, covering a wide range of topics, methodologies, and tools used in the field.
- **Identification of Trends:** Highlighting the evolving trends in VANET research, including the shift towards more application-oriented studies.
- **Gap Analysis:** Identifying gaps and persistent methodological flaws in existing research, which can guide future studies towards addressing these issues.
- **Resource for Future Research:** Serving as a valuable resource for researchers entering the field of VANETs, offering insights into past research and suggesting directions for future investigation.

However, it is important to recognize the limitations of this study. While our work provides a comprehensive overview of developments in the field of Vehicular Ad Hoc Networks

(VANETs), it is based on a sample of approximately 600 articles published between 2007 and 2021, selected from specific conferences and journals. Therefore, our analysis may not fully represent all the research and developments in the VANET area, as other journals and publications were not included. This limitation suggests the need for a broader scope in future research to include a wider variety of sources and publications, ensuring a more complete understanding of advances and trends in VANETs.

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Author's Contribution

JARS contributed to the conception of this study and performedthe experiments. ERC, and TSB contributed with the design of methodology. RCMG contributed with the Application of statistical. JARS is the main contributor and writer of this manuscript. All authors read and approved the final manuscript.

Competing Interests

The authors declare that they have no competing interests.

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