Simulation framework for connected vehicles: a scoping review [version 2; peer review: 2 approved]

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Abstract

Background: V2V (Vehicle-to-Vehicle) is a booming research field with a diverse set of services and applications. Most researchers rely on vehicular simulation tools to model traffic and road conditions and evaluate the performance of network protocols. We conducted a scoping review to consider simulators that have been reported in the literature based on successful implementation of V2V systems, tutorials, documentation, examples, and/or discussion groups.

Methods: Simulators that have limited information were not included. The selected simulators are described individually and compared based on their requirements and features, i.e., origin, traffic model, scalability, and traffic features. This scoping review was reported according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR). The review considered only research published in English (in journals and conference papers) completed after 2015. Further, three reviewers initiated the data extraction phase to retrieve information from the published papers.

Results: Most simulators can simulate system behaviour by modelling the events according to pre-defined scenarios. However, the main challenge faced is integrating the three components to simulate a road environment in either microscopic, macroscopic or mesoscopic models. These components include mobility generators, VANET simulators and network simulators. These simulators require the integration and synchronisation of the transportation domain and the communication domain. Simulation modelling can be run using a different types of simulators that are cost-effective and scalable for evaluating the performance of V2V systems in urban environments. In addition, we also considered the ability of the vehicular simulation tools to support wireless sensors.

Conclusions: The outcome of this study may reduce the time required
for other researchers to work on other applications involving V2V systems and as a reference for the study and development of new traffic simulators.

**Keywords**
V2V, network simulator, mobility generator, simulations, connected vehicles, microscopic models

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**Author roles:** Abdul Razak SF: Conceptualization, Data Curation, Investigation, Methodology, Writing – Original Draft Preparation, Writing – Review & Editing; Yogarayan S: Conceptualization, Data Curation, Investigation, Validation, Writing – Review & Editing; Azman A: Investigation, Project Administration, Validation; Abdullah MFA: Investigation, Visualization, Writing – Review & Editing; Muhamad Amin AH: Methodology, Validation; Salleh M: Validation, Visualization, Writing – Review & Editing

**Competing interests:** No competing interests were disclosed.

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Traffic simulations are categorised by level of detail into three separate categories. First, the most precise information on each vehicle in the system is microscopic simulations. Second, mesoscopic simulations exploit aggregate velocity-density functions to represent their behaviour and view traffic as a continuous stream of vehicles. Finally, macroscopic simulation is the large-scale traffic model, which focuses on combined traffic status. Microscopic simulations provide the highest degree of detail for modelling, although they are the slowest to execute.

In addition, mobility generators are a possible option for modelling vehicle elements such as traffic, temporal and spatial mobility, and generating mobility traces. These traces are then uploaded to a network simulator, which mimics vehicle-to-vehicle communication. Furthermore, these traces can be generated by observing real-world vehicles on the road and then used in network simulations. The effect of network parameter modifications on traffic mobility is a strategic objective simulation. It is also restricted to the use of the trace controlled by the mobility model. Another option is to use a simulator that directly integrates the mobility framework.

This study focuses on the Vehicular Adhoc Networks (VANET) which rely on network protocols to assess their performance, given that actual experiments are not possible. Over the last decade, efforts have been made to produce a full transport simulator for VANET solutions, including a wireless network simulator for modelling and evaluation. A wide range of simulators can be used for VANET simulation modelling, both commercial and open source. Older simulators provide a network simulator to communicate with stationary mobility models. Many researchers have examined various mobility models with simulation tools for several contexts. Such simulator tools are not yet well explored since many researchers base their simulations depending on their use case settings. Thus, this motivates the identification of different simulators do not yet exist. Therefore, this study conducted a systematic scoping review to identify the applicability and availability of existing mobility generators, network simulators, and combination simulators.

The rest of the paper is organised as follows. The following section explains the methods used for analysing existing mobility generators and network simulators. Further, the outcome of the review scoping is depicted with several discussions. The final section concludes by considering future directions.

### Methods

A This work involves identifying the research question, identifying relevant studies, selecting the studies, charting the data, collating, summarising, and reporting results. The review was carried out in compliance with the PRISMA Extension for Scoping Review.

### Inclusion criteria

Under standard procedures for performing scoping reviews, published primary studies on VANET were considered for inclusion. Although research may be conducted in any country without focusing on language restrictions, we only obtained data from studies published in English-language journals. Studies had to include mobility generators, network simulators, and vehicle network simulators. We included studies related to vehicular communications that investigated V2V safety.
applications, vehicle network performance, driver behaviour, and vehicle simulation tools. We excluded studies prior to the year 2015.

Databases
IEEE Xplore and Science Direct were used to perform in-depth searches of the information included in these databases.

Literature Search Strategy
The search method included controlled vocabulary and free-text word phrases generally linked to (1) network simulation, mobility generators, or network simulators, and (2) VANET, vehicle, or nodes. All searches were initiated in November 2019 and December 2020, when the database was updated. Endnote was used to import the search results.

Citation Screening
After removing duplicate studies, search results were exported for screening. This was done to filter references based on the above-mentioned inclusion criteria. To minimise the possibility of bias, each reference was checked twice by two team members, and the team addressed any inconsistencies. The first screening process ended in April 2020, and the outcomes were updated in January 2021.

Data Extraction
To extract data from each included research, a spreadsheet was created using Microsoft Excel. Several rounds of piloting the data extraction spreadsheet was performed, during which all team members collected data from the same research, and the results were reviewed during team meetings to ascertain content consistency. The piloting extraction process guaranteed that all relevant data fields were collected and that the content was uniform across the research team. After familiarising all team members with the data extraction method, studies were allocated to each member, and the relevant data were extracted separately. Year, country, mobility generators, network simulators, active development, release date, licence, predefined map, traffic model, architecture language, and simulation language were collected from each included research where accessible. In March 2021, data extraction was finalised.

Data Analysis
The objective outcomes of all included studies were retrieved in the order in which they were reported. The research team then classified these findings according to their similarity to the measured concepts: routing protocol, scenario, mobility generator, and network simulator. Subjective outcomes were similarly retrieved in the way described in the publications and then classified according to their similarity to the assessed concepts: contribution. The subjective outcome criteria for each study were extracted and operationalised by consensus among our research team.

Results
The initial search turned up 269 matches. After removing duplicates, a total of 184 titles and abstracts were screened, from which 72 publications were subjected to full-text review. 10 studies fulfilled the criteria for inclusion and were included in the analysis (see Figure 1 for the PRISMA Flow Diagram).
We found that open-source mobility and network simulators were popular among researchers. Microscopic models were preferable for research related to vehicular communications since the simulations provide the most precise information of each vehicle or mobile node and the highest degree of detail for modelling compared to macroscopic and mesoscopic models. Common network simulators were NS-2, NS-3, and OMNeT++. However, not all mobility simulators supported active development, which is important in current active research domains such as vehicular communications. The mobility generators and simulators available after 2015 are further shown in Table 1 and Table 2, respectively. Besides, summarised previous studies are shown in Table 3 of using mobility generators or simulators.

**Discussion**

Since this area of study is considered as a relatively new but rapidly growing field, this scoping review process only considers relevant papers published from 2015 onwards, which shows that extensive research has been conducted to create security standards for communication technologies, particularly the vehicular network. Although various simulators can be enhanced with library extensions, none of the simulators is related to security and privacy. Ultimately, researchers and professionals cannot compare their security measures to a given circumstance. For instance, ensuring the privacy of a vehicular user in a fast-moving network and disseminating messages in a secure vehicular environment. However, there is no simple practice of extending existing simulators to the desired security standard, which implies that future development research will need to be done.

In addition, the quality of a simulation depends largely on the precision of the models. The range of precision has increased dramatically recently, where several modules contain signal attenuation components, multiple antenna models, and environmental interferences. However, one continuous barrier to producing accurate simulations is the evolution of rapid prototyping and its increasing use in-vehicle networks. For example, vehicle nodes would depend on three-dimensional scenarios to communicate with other nodes. It would be crucial for current and future simulators to extend the current simulators to these new conditions.

| Reference(s) | Name of mobility generator | Active development | Release | License | Map | Traffic model | Network simulator |
|--------------|----------------------------|--------------------|---------|---------|-----|---------------|------------------|
| 28–30        | SUMO                       | Y                  | 2021    | Open Source | Real and User Defined | Microscopic | NS-2, NS-3, OMNeT++ |
| 31–33        | MATSim                     | Y                  | 2021    | Open Source | Real and User Defined | Microscopic | N/A |
| 34           | DTALite                    | Y                  | 2021    | Open Source | Real | Mesoscopic | N/A |
| 35,36        | SMARTS                     | Y                  | 2020    | Open Source | Real and User Defined | Microscopic | N/A |
| 21,37,38     | PARAMICS                   | Y                  | 2020    | Commercial | Real and User Defined | Microscopic | NS-2, OMNeT++ |
| 32,38        | MovSim                     | Y                  | 2018    | Open Source | Built-In | Microscopic | N/A |
| 21,27,39     | VISSIM                     | Y                  | 2016    | Commercial | Real and User Defined | Microscopic | NS-2, QualNet |
| 40           | VNEtIntSim                 | N                  | 2015    | Open Source | Real and User Defined | Microscopic | Integration OPNET |
| 38           | Traffisim                  | N                  | 2014    | Open Source | Real and User Defined | Microscopic | N/A |
| 41           | CityMob                    | N                  | 2009    | Open Source | Built-In | Microscopic | NS-2 |
| 41           | FreeSim                    | N                  | 2008    | Open Source | Real | Microscopic | N/A |
| 41           | STRAW                      | N                  | 2007    | Open Source | Built-In | Microscopic | NS-2, SWANS |
| 41           | Vanet-MobiSim              | N                  | 2007    | Open Source | Real and User Defined | Microscopic | NS-2, QualNET, OMNeT++, GloMoSim |

Y = Supported, N = Not Supported
Table 3. Previous studies.

| Reference | Contribution | Scenario | Protocol Used | Mobility Simulator | Network Simulator | Simulator and Framework |
|-----------|--------------|----------|---------------|--------------------|--------------------|-------------------------|
| 46        | This paper provides a comparison of three routing protocols in the VANET scenario. The result focuses on determining the effectiveness of routing protocols for several performance measures of which the vehicle is an essential aspect of the evaluation. | Urban | DSDV AODV DSR | SUMO MOVE | NS-2 | N/A |
| 47        | The paper provides a simulation in the VANET scenario at a vast scale. The result is focused on the performance of four routing protocols under different checks in terms of delay, packet delivery, overhead, and transmission power. | Urban | OLSR DSDV AODV DSR | SUMO | NS-3 | N/A |
| 48        | This paper uncovers an automatic routing protocol for the VANET scenario. The idea is to disseminate the information provided by several roadside units. There are three routing protocols evaluated using several performance metrics in terms of delay, number of hops, total service time, and number of fragments. | Urban | ARP GSR A-STAR | SUMO | OMNeT++ | N/A |
| 49        | The paper focuses on two routing protocols within the VANET scenario. The idea is to ensure an optimal path from source to destination under a few performance measures in terms of throughput and packet delivery ratio. | Generic | DYM0 OLSR | N/A | QualNet | N/A |
| 50        | This paper investigates DSRC 5.9 GHz for the V2V scenario in restricted areas. The findings were reviewed using three routing protocols using different performance parameters in terms of delay and number of forwarding nodes. | Generic | EMDV >MHVB EDB | N/A | NetSim | N/A |
| 30        | The paper provides an analysis of four routing protocols within the VANET scenario. The outcome was assessed based on a different mobility model and speed and performance parameters such as goodput, throughput, packet receive performance and receive rate. | Urban | OLSR AODV DSDV DSR | SUMO | NS-3 | N/A |

Table 2. Network simulators.

| Reference(s) | Name of network simulators | Active development | Release | License | 802.11p Support | Architecture Language | Simulation Language |
|--------------|----------------------------|--------------------|---------|---------|-----------------|-----------------------|---------------------|
| 42,43        | OPNET                      | Y                  | 2021    | Commercial | Y | C++ | C++ OTCL |
| 33,42,44     | NS-3                       | Y                  | 2021    | Open Source | Y | C++ Python | C++ Python |
| 42           | OMNeT++                    | Y                  | 2020    | Open Source | Y | C++ | C++ |
| 33,42        | QualNet                    | Y                  | 2019    | Commercial | Y | C++ | C++ |
| 42,45        | NS-2                       | N                  | 2011    | Open Source | Y | C++ | C++ OTCL |
| 33,42        | JIST/SWANS                 | N                  | 2005    | Open Source | N | JAVA | JAVA |
| 40,45        | GloMoSim                   | N                  | 2000    | Open Source | N | C | C |

Y = Supported, N = Not Supported
Apart from that, integration with real-time system modelling based on non-real-time events creates additional challenges. Due to resource limitations, current simulators do not correspond with the physical properties of the hardware prototype while simulating a comprehensive network with multiple vehicles. Several alternatives have been put forward to reduce the complexity that could speed the simulation. However, this approach usually does not include indirect outcomes, which could seriously impact the behavior of real-world network components. It is, therefore, necessary to examine the interconnection between simulators and hardware devices with the security standards concerned.

Conclusions
Studies have led to the discovery of comprehensive and realistic simulation tools due to the increasing popularity and interest for the future transportation system. This work has examined the current availability of simulators. While testing VANET with essential performance, it is necessary to deploy a mobility generator and mobility network that accurately represent real vehicle traffic. Based on our comparative identification, NS-3 and SUMO has been the optimal choice for real-time VANET modelling. Although several simulators have many features, it is worth exploring further the improvement of the simulators for specific scenarios. In addition, this work can be further be expanded in future by investigating relationships of appropriate simulator for a V2V or V2X application to different scenarios and protocols. We plan to study the used simulators in this context and the extent of benefit and development achieved using the simulators.

Data availability
Underlying data
All data underlying the results are available as part of the article and no additional source data are required.

Reporting guidelines
Zenodo: PRISMA-ScR checklist for ‘Simulation framework for connected vehicles: a systematic review’, https://doi.org/10.5281/zenodo.563780

Data are available under the terms of the Creative Commons Attribution 4.0 International license (CC-BY 4.0).
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Current Peer Review Status: ✔️ ✔️

Version 2

Reviewer Report 24 February 2023

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✔️ Lionel Nkenyereye
Department of Computer and Information Security, Sejong University, Seoul, South Korea

I have carefully reviewed the revised version of the article. Therefore, the authors addressed all my comments. The paper is well shaped to the acceptance decision.

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Vehicular technology, edge computing, and software-defined networks

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Reviewer Report 23 February 2023

https://doi.org/10.5256/f1000research.143645.r163703

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✔️ Mahmoud Zaki Iskandarani
Al-Ahliyya Amman University, Amman, Jordan

There seems to be major improvements in the submitted work.

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Intelligent Transportation Systems, Artificial Intelligence, Mobile and wireless Communication, Sensors and systems.
I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Version 1

Reviewer Report 04 January 2023

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Mahmoud Zaki Iskandarani
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The article attempts to produce a guidance into the most appropriate simulators for V2V, and in general V2X communications. This effort is a good effort and in the right direction in terms of what is witnessed of V2X developments under cooperative driving. However, the authors can benefit from the following comments:

1. Assigning the most appropriate simulator for a V2V or V2X application with in depth correlative analysis linked to different scenarios and protocols.

2. Comparative analysis of the used simulators per specific published article or group of articles sharing common objective, and the extent of benefit and development achieved using such simulator.

3. More detailed discussion and more comprehensive conclusion and recommendation will greatly improve the article.

Are the rationale for, and objectives of, the Systematic Review clearly stated?
Yes

Are sufficient details of the methods and analysis provided to allow replication by others?
Yes

Is the statistical analysis and its interpretation appropriate?
Partly

Are the conclusions drawn adequately supported by the results presented in the review?
Partly

Competing Interests: No competing interests were disclosed.
Reviewer Expertise: Intelligent Transportation Systems, Artificial Intelligence, Mobile and wireless Communication, Sensors and systems.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 26 Jan 2023
Siti Fatimah Abdul Razak

The applicability of V2V or V2I (V2X) has been added in Table 2 (page 7).

The comparative analysis has been highlighted in Table 3 (page 7).

The conclusion has been revised as suggested (page 9).

Competing Interests: No competing interests were disclosed.

Reviewer Report 19 July 2022
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Lionel Nkenyereye

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The study surveys the existing simulation framework for connected vehicles. The works proposed a method based on PRISMA Extension for a Scoping Review. The previous study table is short but relevant contributions are presented. These contributions summarize the routing concept, dissemination of the information, and performance measures in terms of throughput and packet delivery ratio.

The following comments could enhance the quality of this work:

1. In the conclusion, I request the authors to specify the type of mobility generator and mobility network that are efficient for real-time system modelling.

2. At the Screening section, authors focus much on VANET. How about other vehicular network that support V2V? For instance software-defined based VANET or vehicular Edge/Fog technology or Vehicular Cloud network in their Search string. Is the current work includes different type of vehicular technology in general? Therefore, rewrite in the introduction that this study focuses particularly on VANET.
Are the rationale for, and objectives of, the Systematic Review clearly stated?
Yes

Are sufficient details of the methods and analysis provided to allow replication by others?
Yes

Is the statistical analysis and its interpretation appropriate?
Yes

Are the conclusions drawn adequately supported by the results presented in the review?
Partly

**Competing Interests:** No competing interests were disclosed.

**Reviewer Expertise:** Vehicular technology, edge computing, and software-defined networks

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 26 Jan 2023

**Siti Fatimah Abdul Razak**

The paper is mainly focusing on VANET deployment. The introduction has been revised as suggested (page 2 and 3).

The conclusion has been revised to specify the type of mobility generator and mobility network that are efficient for real-time system modelling (page 9).

**Competing Interests:** No competing interests were disclosed.
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