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Review Article

Evolution of Traffic Microsimulation and Its Use for Modeling Connected and Automated Vehicles

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Traffic microsimulation has a functional role in understanding the traffic performance on the road network. This study originated with intent to understand traffic microsimulation and its use in modeling connected and automated vehicles (CAVs). Initially, the paper focuses on understanding the evolution of traffic microsimulation and on examining the various commercial and open-source simulation platforms available and their importance in traffic microsimulation studies. Following this, current autonomous vehicle (AV) microsimulation strategies are reviewed. From the review analysis, it is observed that AVs are modeled in traffic microsimulation with two sets of strategies. In the first set, the inbuilt models are used to replicate the driving behavior of AVs by adapting the models' parameters. In the second strategy, AV behavior is programmed with the help of externalities (e.g., Application Programming Interface (API)). Studies simulating AVs with inbuilt models used mostly VISSIM compared to other microsimulation platforms. In addition, the studies are heavily focused on AVs' penetration rate impact on traffic flow characteristics and traffic safety. On the other hand, studies which simulated AVs with externalities focused on the communication aspects for traffic management. Finally, the cosimulation strategies for simulating the CAVs are explored, and the ongoing research attempts are discussed. The present study identifies the limitations of present CAV microsimulation studies and proposes prospects and improvements in modeling AVs in traffic microsimulation.

1. Introduction

Automated vehicles (AVs) are closer than ever to making their mark over the road network. Given that AVs will ultimately not require the involvement of humans, which is known to be a contributing factor in most accidents [1], both researchers and practitioners have great hopes that AVs will improve the performance characteristics of traffic and enhance its safety standards [2, 3]. However, verifying the assertions about AVs' added benefits to traffic efficiency and safety is quite challenging. Traffic microsimulation (i.e., soft computing platform for modeling the detailed intervehicular interactions in a traffic stream) can help to understand the implications of AVs' performance and communication aspects on traffic and support developing better traffic management strategies. Considering this, traffic microsimulation and its application to understanding the implications of AVs

is vital. Therefore, this paper first describes the evolution of traffic microsimulation tools and then reviews the state-of-the-art in using traffic microsimulation for modeling the implications of Connected and Automated Vehicles (CAVs) on traffic efficiency and safety.

The following sections include an introduction to traffic microsimulation (Section 1.1), followed by an introduction to CAVs (Section 1.2) and finally identifying the research aim and method (Section 1.3).

1.1. Traffic Microsimulation. For setting the traffic signals, Webster [4] attempted a computer simulation technique to support the framework in developing optimum signal time for the intersections. This can be marked as one of the initial attempts in traffic microsimulation. To account for the randomness in traffic modeling, researchers have relied on

Monte Carlo simulation techniques [5–7] and cellular automata models [8, 9]. Simultaneously, researchers have developed and integrated mathematical models, such as different car following models [10] and lane changing models [11], into different simulation tools [12, 13]. The basic functionality of the simulation is time and space, along with the system state. Both time and space can be categorized as discrete or continuous with a system state. In this direction, a series of simulation approaches have been developed over time. In microsimulation, models exhibit discrete-time and continuous space phenomenon.

Advancements in computing and developments of new mathematical frameworks have led to major upgrades to microsimulation packages. Supported by advanced processing in computations, traffic microsimulation models are gradually found to be meticulous and realistic. Relying on empirical traffic data for analysis may not be feasible at all times, and implementation of proposed solutions to the traffic network without any checks can put human life at risk and cause unnecessary damage to the infrastructure. Traffic microsimulation offers numerous customization options for testing a variety of scenarios. Sensing the importance of microsimulation in understanding traffic characteristics, researchers have conducted numerous studies and developed various traffic microsimulation frameworks over the last few decades. These studies relate to various aspects of traffic, including among others car following [14], lane changing [15], signal control [16], traffic safety [17], traffic emissions [18], pedestrian flow [19], ramp metering [20, 21], roundabouts [22], toll operations [23], and truck parking operations [24]. To visualize this, the literature related to traffic microsimulation was identified by Scopus [25] search engine using the keyword “traffic microsimulation” and was then segregated into subareas resulting in the network plot shown in Figure 1. The size of the nodes and thickness of the links in Figure 1 depict the scale of the publications in that area, and the color depicts the clusters.

Figure 1 shows that traffic microsimulation was utilized in all kinds of traffic studies, and numerous traffic flow modeling concepts were evolved in connection with microsimulation. Given the ease and effectiveness, both researchers and industry partners have extensively used microsimulation approaches in supporting their decision making. Furthermore, numerous researchers [26–30] strongly advocated the importance of calibration for the reliability of the microsimulation outcomes. It is observed that researchers of various backgrounds widely use microsimulation in their studies. New microsimulation platforms were also developed and upgraded over time with the purpose of commercialization. Traffic microsimulation platforms have found a place across various domains for searching for optimized solutions.

1.2. Connected and Automated Vehicles. Researchers from both academic and industrial backgrounds, over the last five decades, believed that automobiles will achieve the self-driving functionality and evolve as autonomous vehicles [31–33]. Given the advancements in computing and the

availability of superior complex modeling, research on AVs has progressed. Currently, most of the automobile industries focus on developing their own AVs. Considering the potential market for AVs, multinational conglomerates showed a great interest in developing AVs [34]. To harmonize the definition of the level of automation, the Society of Automotive Engineers (SAE) has proposed six levels of autonomy, ranging from level 0 (no driving automation) to level 5 (full automation). The SAE levels of automation primarily differ in their Dynamic Driving Tasks (DDTs), Object and Event Detection and Response (OEDR), and Operational Design Domain (ODD). The ODD is the conditions under which Automated Driving Systems (ADSs) are designed to work. At level 0, drivers will perform all the DDTs and OEDR. At level 1, drivers will still perform some of the DDTs and be responsible for the OEDR. At level 2, the system will perform the lateral and longitudinal DDTs while the drivers will be still responsible for the OEDR. At higher levels, the system will be responsible for the DDTs and the OEDR. The ODD of levels 1 to 4 is limited. At level 5 automation, unconditional DDTs will be carried by the ADS and unlimited ODD.

Past and ongoing research attempts have resulted in developing AVs with initial SAE level functionalities. Simultaneously, to assess AVs driving performance, AVs are being tested at various testbed conditions. Several researchers [35–37] strongly advocate that AVs can significantly impact the traffic characteristics of the road network. Unlike regular traffic, empirical data on AVs in traffic are still relatively scarce, and field experiments are limited given the risk for human life and potential damage to the infrastructure. Considering this, traffic microsimulation can play a huge role in assessing AVs impacts on the road network.

1.3. Research Aim and Method. The main aim of this paper is to understand the development of the research on traffic microsimulation in connection with modeling AVs. To achieve this aim, this study was carried out in two stages:

- (i) Firstly, considering the significance of traffic microsimulation platforms in simulation studies, the progression of traffic microsimulation and microsimulation platforms were reviewed.
- (ii) Secondly, the modeling aspects of AVs in traffic microsimulation and cosimulation with AV simulation tools were reviewed.

In the present study, literature was mined in three different parts: traffic microsimulation, C/AV microsimulation, and cosimulation studies. To understand the trend of traffic microsimulation, literature related to traffic microsimulation was first identified and then segregated using the keywords reported in Table 1 and the Scopus [25] search engine. Scopus database contains only the publications with Scopus indexing. The Scopus search engine provides advanced search options like authors, keywords, title, affiliation, journal title, avoid references, along with different conditional options for sorting the search. The keywords that were used for identifying relevant traffic

The rest of the paper is structured as follows: Section 2 presents the sources of traffic microsimulation studies, followed by the review of different microsimulation platforms in Section 3. Section 4 synthesizes the AVs traffic microsimulation studies, and Sections 5 and 6 summarize the paper and introduces the prospects and future research directions for AVs traffic microsimulation.

2. Sources of Traffic Microsimulation Studies

Researchers across the world have used traffic microsimulation to understand the traffic characteristics, such as driving behavior, traffic management, and traffic safety. Traffic characteristics are varying in nature with different geographical, cultural, and economic conditions. For example, vehicles have proper lane discipline under homogeneous traffic conditions. In the case of cold climatic conditions, cars have dominant proportion in comparison to motorized two-wheelers. On the other hand, in Southeast Asia and South Asian countries, given the favorable conditions with added fuel mileage, the proportion of motorized two-wheelers is higher. Along similar lines, the physical characteristics of vehicles are varying in nature across the world. Furthermore, economic status of countries affects their advancements in transportation infrastructure. Differences in cultures and norms affect road users' behavior. Road user behavior, which is the root source of understanding traffic performance, is highly diverse with different circumstances. As a result, solutions to traffic problems are never taking a unique form.

To understand the geographical distribution of traffic microsimulation studies, the identified literature was mapped considering author's affiliations and nationality. This would help in understanding the quantum of microsimulation studies sources. For visualization purposes, a radial plot is presented in Figure 2. The rectangular bars represent the number of publications for each affiliation. It can be observed that traffic microsimulation studies were conducted all over the world, with a significant share by the United States of America (27%), China (26%), Germany (7%), and Netherlands (7%). Some of the major universities in these countries have contributed heavily to this research domain: in Netherlands, Delft University of Technology (211); in China, Tongji University (96), Beijing Jiaotong University (96), Southeast University Nanjing (80), and Tsinghua University (63); in the United States of America, Virginia Polytechnic Institute and State University (79) and University of California, Berkeley (57); in Germany, Technical University of Munich (56); and in Singapore, the National University of Singapore (51). In recent years, in addition to developed nations, microsimulation studies are slowly picking up as well in developing nations.

In the present context, around 1250 traffic microsimulation studies have been published in more than 50 scientific journals. The analysis was carried forward to understand the articles' share in journals as shown in Figure 3. Note that in Figure 3, only journals with a minimum of 15 published articles were considered. The Transportation Research Record (28%) has the largest share,

followed by Transportation Research Part C: Emerging Technologies (10%), IEEE Transactions on Intelligent Transportation Systems (7%), and the Journal of Transportation Engineering (6%). Publications in other journals with smaller share are also presented in Figure 3. With respect to conference proceedings, IEEE International Conference on Intelligent Transportation Systems (ITSC) proceedings (177) and Transportation Research Procedia (80) have accumulated most studies in this domain.

3. Traffic Microsimulation Platforms

With the increase in computational efficiency and availability, researchers and industry partners used programming scripts and input parameters to integrate the traffic modeling concepts into simulation packages. Initially, simulation packages were limited to case-specific ones with a small set of programming scripts. Most of the simulation platforms in their early versions were basic, including the car following functionality on a straight midblock road section. Given the opportunities with the evolution in programming over the last three decades, developers and researchers have updated different microsimulation platforms. In addition, the evolution of new research concepts, such as car following and lane changing models and traffic signal optimization techniques, led to various inbuilt customization options in traffic simulation over time. To understand these better, present traffic microsimulation platforms were reviewed, and their details and characteristics are summarized in Table 2.

Paramics [38] project was supported by the UK Department of Transportation and developed by the researchers of the University of Edinburgh, Scotland. The initial platform was purely based on the Hans-Thomas Fritzsche car following model [39]. Later, research inputs from the University of California, Irvine, helped in embedding numerous packages, which include traffic signals, ramp metering, and bottleneck in freeway scenarios. Finally, in the year 2005, the Quadstone Paramics acquired the Paramics simulation platform. On the other hand, another variant of Paramics, S-Paramics, was distributed by the SIAS Group [40]. Presently, both Quadstone Paramics and S-Paramics are identified as old and new Paramics, respectively. Like Paramics, VISSIM was developed by researchers of Karlsruhe University, Germany, with a psychophysical car following model [41] and other input packages which were added over time. Later, PTV group acquired VISSIM from Karlsruhe University and developed it further as PTV VISSIM. Under MIT's Intelligent Transportation Systems (ITS) program in collaboration with Caliper Corporation, researchers of the Massachusetts Institute of Technology, USA, developed MITSIM [42, 43] with the idea of an open-source traffic microsimulation.

There are many other platforms including AIMSUN [44], MIXIC [45], CORSIM [46, 47], SUMO [48, 49], TransModeler [50, 51], MOTUS [52, 53], TRITONE [28], and OpenTrafficSim [54]. Among these platforms, AIMSUN, CORSIM, and TransModeler are commercial, whereas SUMO, MOTUS, TRITONE, and OpenTrafficSim are open-

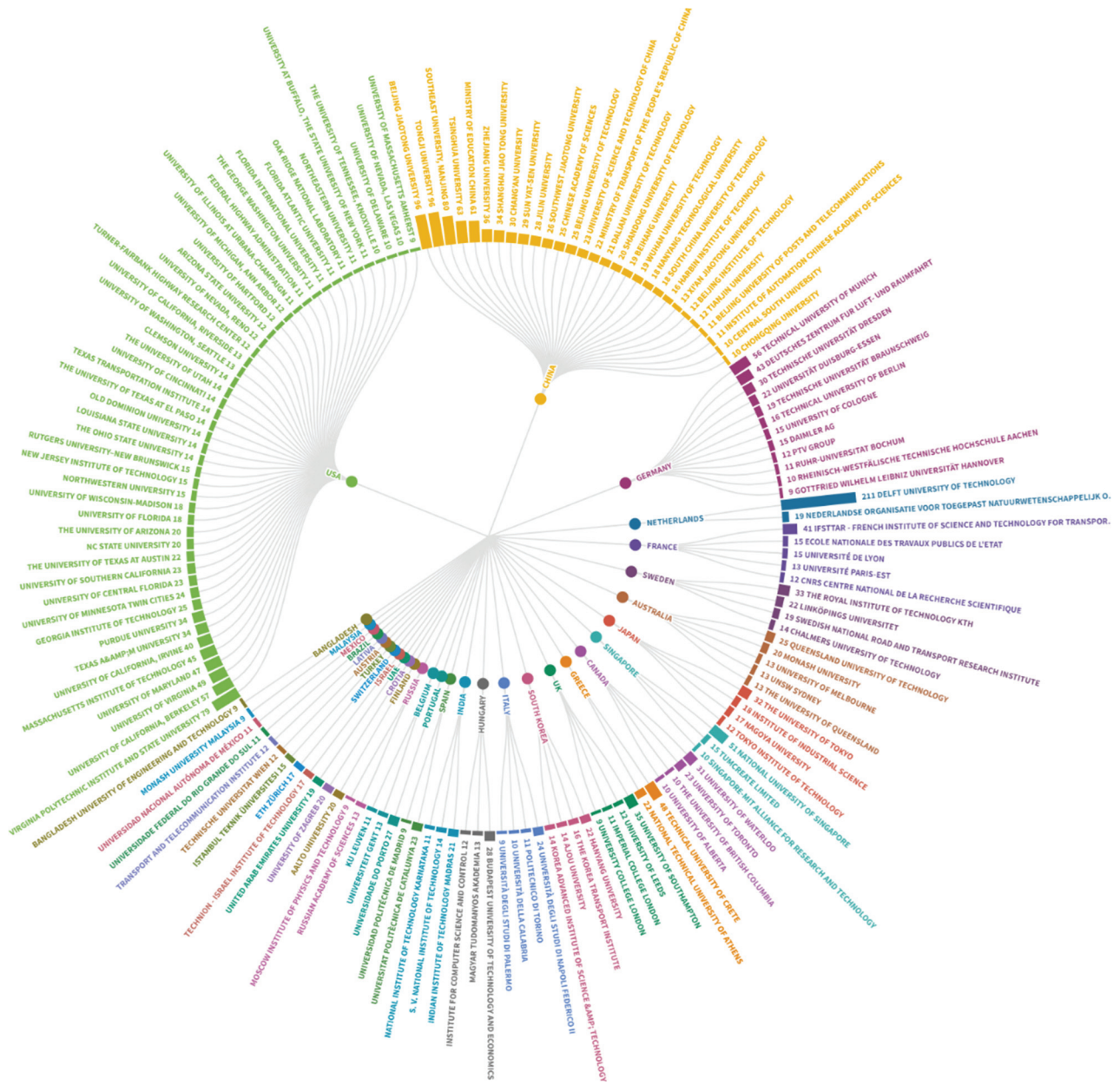


FIGURE 2: Radial plot depicting the involved institutes across the nations.

source platforms. Other microsimulation platforms, such as Integration [55], SimTraffic [56], HUTSIM [57], THOREAU [58], FAUSIM [59], FOSIM [60], RuTSIM [61], and GLD traffic simulator [62], evolved from certain project ideas. It can be noted that most of the established microsimulation platforms were instigated in the 90s and were developed with the idea of simulating homogeneous lane-based traffic conditions.

From the review of the different simulation packages, it is observed that most of traffic microsimulation platforms were initiated and developed by transportation researchers at their institutes within frameworks of specific projects. Later, in collaboration with industrial partners, these simulation platforms have further evolved, which led to the development of commercial traffic microsimulation

platforms. On the other hand, some traffic microsimulation platforms were kept open in carrying the research. Most commercial variants provide free time-limited licenses for academics. Microsimulation platforms with explicitly available details are summarized in Table 2.

Further, based on the specific functionality (core behavioral models, optimizing computation, user groups), microsimulation platforms were developed over various programming interfaces. Most of the inbuilt models in simulation platforms are sufficient to test basic scenarios. On the other hand, in some cases, inbuilt models must be replaced by external behavioral logic/algorithms for the research analysis. Keeping this in mind, presently, external modules are offered in coding behavioral logic/algorithms. Those external modules give opportunities for researchers



FIGURE 3: Traffic microsimulation work share of the journals with at least 15 papers.

to bypass the inbuilt logic. Various programming interfaces are used in different microsimulation platforms as detailed in Table 2. However, unlike microsimulation platforms with inbuilt models, the processing speed with external modules is lower; this again depends on the coded script's logical flow.

3.1. Publication Share of Microsimulation Platforms. To better understand the existing research using different microsimulation platforms, literature on traffic microsimulation platforms was mined. The identified studies were later segregated by the year of publication. A Mekko chart was prepared, as shown in Figure 4, to illustrate the results. The x -axis in Figure 4 represents the timeline in years, and the y -axis demonstrates the percentage share. The width of the rectangles depicts the scale of publications in that year. From the database, it is shown that initially the research work was limited to its developers. Later in early 2000s, those microsimulation platforms were open to researchers outside the development teams.

The number of publications was low initially, with a minimum of 17 publications in 2001, but gradually increased over the years to a record of a maximum of 376 publications in the year 2019. Unlike the increase in total publications, the share of the different microsimulation packages in these publications has varied over the years. Starting from 2001, CORSIM and Paramics have a fair share of the scientific

publications whereas VISSIM and AIMSUN have a minor share. However, over time the shares of VISSIM and SUMO have increased, and in 2020 both had the biggest shares among other simulation platforms.

On the other hand, AIMSUN has a relatively uniform number of publications over the years. Publications using TransModeler have been relatively stable with a relatively minor share. Publications from MITSIM, MOTUS, MIXIC, TRITONE, HUTSIM, Integration, DRACULA, SimTraffic, and OpenTrafficSim have been identified over time, with most of the publications being from developers' backgrounds.

This analysis signifies that microsimulation in traffic engineering research has picked up the pace in the previous two decades. Numerous researchers and industry partners are testing different logic and scenarios using microsimulation platforms for decision making in the present driving context. Simultaneously the variation in the platforms' share can be attributed to various factors, including commercialization, user interface, supported traffic conditions, and user support.

Based on the number of publications in traffic microsimulation, the top twenty-five publishers were identified. Later, the publications were labeled based on the utilized microsimulation platform. To express this better, a Sankey plot was generated considering the microsimulation platforms and the journals, as shown in Figure 5. The width of the connection demonstrates the number of publications

TABLE 2: Details of the microsimulation platforms.

Platform	Developer	Country	Car following (CF) models	Lane changing models (LC)	Programming interface	External module	External module interface	Nature of distribution	Release
Params (two versions)	Initial: University of Edinburgh Present: Quadstone Params, S-Params	UK	Fritzsche CF	Gap acceptance-based LC	C++, Java, Python	External DLLs	C++, MATLAB	Commercial	Initial: 1990 Stable: Params Discovery (2020), S-Params (SLAS group)
VISSIM	Initial: Karlsruhe University Present: PTV Planung Transport Verkehr AG	DE	Wiedemann 74, Wiedemann 99	Sparmann model	C++, Java, Python	COM interface, External DLLs	C++, MATLAB, Python	Commercial	Initial: 1992 Stable: PTV VISSIM 2021 (2020)
MIXIC	TU Delft and Transport Research Center (AW) of Rijkswaterstaat	NL	Autonomous Intelligent Cruise Control (AICC) and rule-based MIXIC CF	Rule-based MIXIC LC	C	Source code can be scripted	—	Open-source	Initial: 1995 Stable: MIXIC 1.3 (2006)
MITSIM	ITS Lab, Massachusetts Institute of Technology	USA	Gazis-Herman-Rothery (GHR) CF	Utility based LC	C++ (runs in Linux)	Source code can be scripted	—	Open-source	Initial: 1996 Stable: 2010
AIMSUN	Initial: TSS-Transport Simulation Present: acquired by Siemens Mobility	ES	Gipps CF	Rule-based Gipps LC	C++, Java, Python	AIMSUN MicroApi	C++, Python, Delphi, C#	Commercial	Initial: 1997 Stable: AIMSUN Next 20 (2020)
CORSIM	McTrans Center, University of Florida	USA	Pitt CF	Intralink LC	C	Run-Time Extension (RTE)	Visual basic script	Commercial	Initial: 1998 Stable: TSJS-CORSIM 6.3 (2012)
SUMO	German Aerospace Center	DE	Krauss, Daniel, IDM, IDMM, P. Wagner, B. Kerner, Wiedemann, ACC, CACC	DK2008, LC2013, SL2015	C++, Java, Python	Traci	Python, MATLAB	Open-source	Initial: 2001 Stable: SUMO 1.9.2 (2021)
TransModeler	Caliper Corporation	USA	General Motors, Gipps, longitudinal control, constant time gap, IDM, Wiedemann 74, Wiedemann 99	Gap acceptance LC with discrete behavior	C++, Java, Python	Caliper Script	GISDK, C#, .Net	Commercial	Initial: 2005 Stable: TransModeler (2020)
MOTUS	TU Delft	NL	IDM+	LMRS	Java, MATLAB	Source code can be scripted	—	Open-source	Initial: 2010 Stable: 2015
TRITONE	UNICAL (TIS Group)	IT	General Motors, Gipps, Van Aerde, GHR, Fritzsche, Wiedemann, Krauss Pitt, Giofrè models, etc.	Mobil, Gipps, Giofrè	Not identified	Source code can be scripted	—	Open-source	Initial: 2012 Stable: TRITONE (2018)
OpenTrafficSim	DiTTab, TU Delft	NL	IDM+	LMRS	Java	Source code can be scripted	—	Open-source	Initial: 2016 Stable: 2016

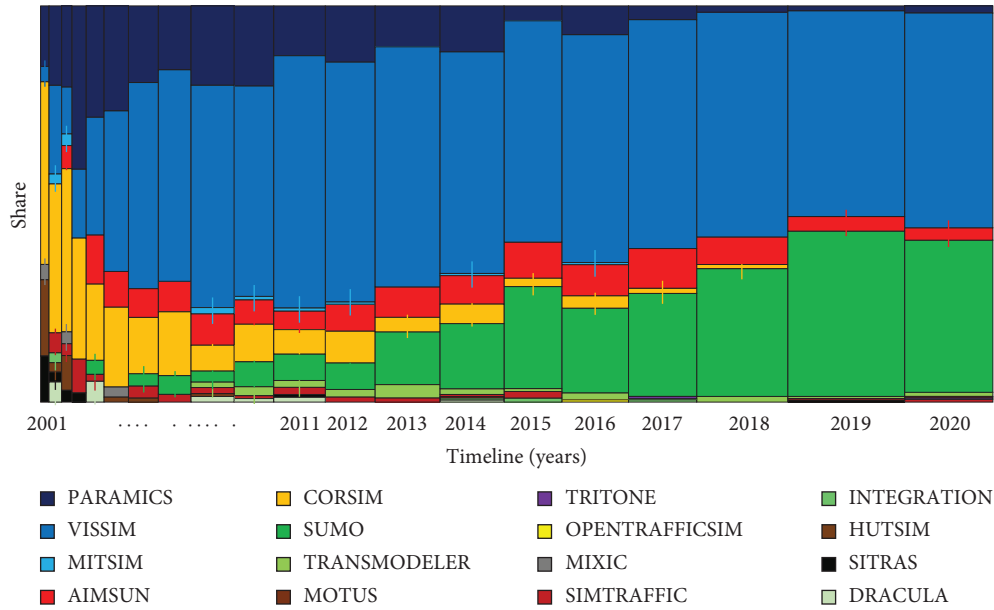


FIGURE 4: Publication share of microsimulation platforms over the years.

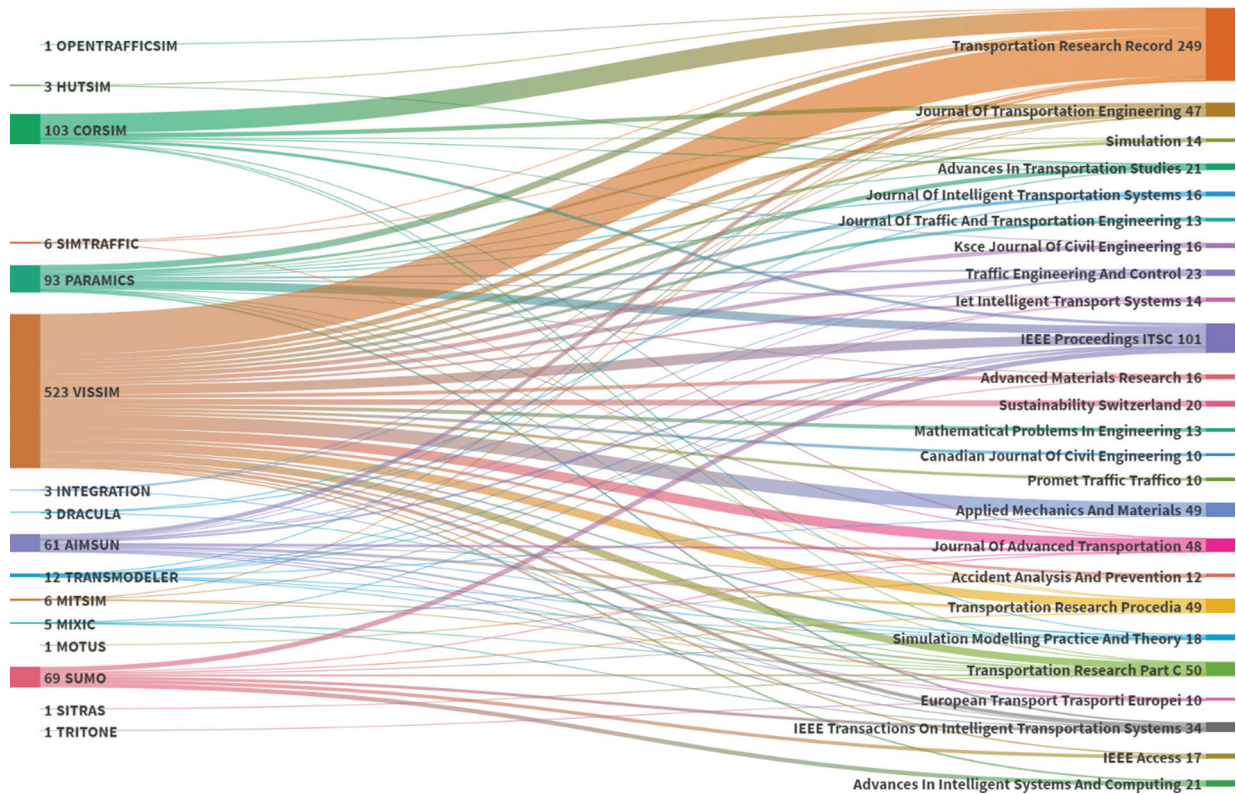


FIGURE 5: Publication shares of microsimulation platforms over top 25 publishers.

concerning the microsimulation package in that journal. The sizes of the head (microsimulation platform) and tail (publisher) nodes show the scale of publications. The analysis shows that Transportation Research Record, Transportation Research Part C, Journal of Transportation Engineering Part A, IEEE ITSC proceedings, Transport

Research Procedia, and Applied Mechanics and Materials have a significant share of microsimulation publications. It is noticed that, with 523 publications, VISSIM has a major share in all journals. CORSIM (103), Paramics (93), SUMO (69), and AIMSUN (58) had also a relatively significant share in publications.

4. Automated Vehicle Microsimulation

Over the years, traffic microsimulation platforms have proven their mantle and their extensive use for various research and industrial activities across different domains. Presently traffic microsimulation platforms have reached a level that can support decision making of practitioners. At the same time, researchers and industrial partners are foreseeing the deployment of AVs on the exiting road network in the near future. Researchers of various backgrounds are predicting the use of AVs for private transport [63], public transport [64], and freight transport such as autonomous trucks [65], as well as for ridesharing [66] such as autonomous shuttles [67]. An increasing number of research studies [68, 69] support the claims that AVs improve traffic safety and efficiency. However, currently quantifying the impacts of AVs in real life from a traffic engineering point of view is highly challenging. This is because of several reasons, such as exposing road users to potential risks, uncertainty regarding the suitability of current traffic management plans, and road authorities being uncertain yet regarding the minimal infrastructure requirements for safe operation of AVs in mixed traffic. Simultaneously, developing strategies and frameworks from only an empirical, experimental point of view is challenging from a cost-benefit point of view. Therefore, the impact of AVs on traffic flow operation must be first studied extensively using traffic microsimulation. With proper utilization of technology and AVs' communication, a good quantum of benefits can be achieved from a traffic engineering point of view.

Given this potential of microscopic simulation platforms in carrying the research in this domain, researchers across the world have already performed various AV studies using different microscopic simulation platforms. Particularly, in the second half of the previous decade, these kinds of studies have picked up. To understand the research flow in this domain, keyword analysis was performed on the literature database, and the visualization plot in Figure 6 presents the findings. The size of the node and the thickness of the links in Figure 6 depict the scale of the work, and the colors depict different clusters. Similar to the regular traffic studies, AV microsimulation studies were also conducted in connection with many traffic related topics including ramp metering [3, 70], car following [71, 72], traffic signals [73], emissions [74], road safety [75], and mixed traffic [76].

Most of the microscopic simulation studies have differentiated AVs and human-driven vehicles by their driving behavior and inferred that the driving behavior is the crux in modeling AVs. In the present context, most researchers (e.g., [77, 78]) unilaterally assumed that, in comparison to human-driven vehicles, the behavior of AVs is less stochastic. In addition, it is believed that AVs have good lane discipline and consistent behavior.

To investigate this in more detail, the literature was reviewed. From the initial assessment, it is observed that researchers used two main types of strategies to model AVs in simulation platforms. The first strategy is about bringing consistency in AVs driving behavior with the inbuilt car following and lane changing models. Following this

direction, AV's behavior was regulated by adapting the model parameters. The second strategy is about coding AVs' behavior and connecting it to a simulation software using Application Programming Interface (API). In the following sections, these two approaches and the related studies are further described and discussed.

4.1. AV Modeling by Inbuilt Models. In giving due weightage to inbuilt behavioral models, researchers modeled AVs by adapting the parameters of the inbuilt car following models in microsimulation platforms. For example, to understand the safety at intersections and roundabouts due to AVs, [79, 80] adapted the Wiedemann model's behavior in VISSIM. It was found that AVs improve traffic safety and throughput of the study sections. With a similar framework, [81] modeled AVs at roundabouts. At a higher penetration rate of AVs, a 75% decrease in crash probability was observed compared to a base scenario with no AVs. Along similar lines, by adapting the psychophysical Wiedemann 74 and 99 car following models in VISSIM, various other studies were carried out for different test scenarios to understand the impacts of AVs. These studies included congested networks [82], traffic signals [83], roadway capacity [84], traffic stream characteristics [85], free speeds [86], operational performance [87], emission impacts [88], safety performance [89], unsignalized intersections [90, 91], and transitional impacts [92]. Other studies have adapted the inbuilt Krauss model in SUMO [93, 94] to model AVs. Zeidler et al. [95] tested the compatibility of inbuilt Wiedemann models for inducing the communication between AVs and compared it to field driven AVs. The focus of these mentioned studies, the behavioral models used, and the studies' key findings are summarized in Table 3.

It is observed that there is inconsistency in the findings of the studies regarding the penetration rates of CAVs at which there is an improvement in safety and traffic efficiency, with reported penetration rates ranging from 20 to 70%. Some studies demonstrated a deterioration in safety and drop in capacity standards at penetration rates below 30%; this is observed in all kinds of modeled road sections. In addition, the transition point of the penetration rate of AVs at which an improvement is observed is not consistent across the studies.

The strategy of modeling AVs with inbuilt models has its advantages and disadvantages. When the inbuilt model parameters are tweaked for AVs, the microsimulation models typically run with fewer externalities; as a result, a consistent traffic movement will be observed at less computational capacity.

Many AV simulation studies with inbuilt models used VISSIM and relied on its psychophysical car following models. The influential critical parameters to mimic AVs vary among the studies and depend on the specific circumstances being studied as summarized in Table 3. It is inferred that very few studies considered the lane changing parameters for AV modeling. Furthermore, the modeled behavior of the AVs is highly oriented towards the inbuilt models; as a result, the simulated AVs can be less realistic in

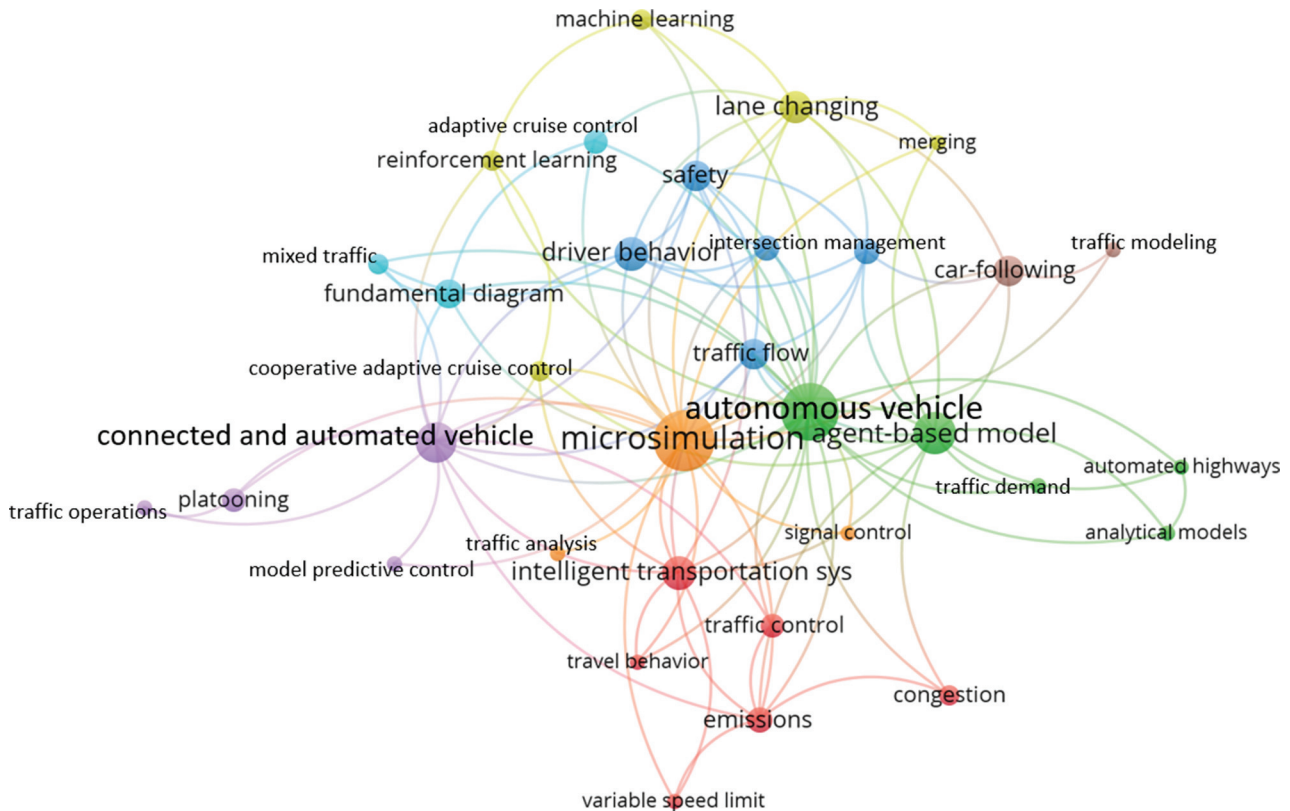


FIGURE 6: Keyword network of AV microsimulation studies.

comparison to field behavior. Furthermore, there seems to be less weightage to modeling the communication of AVs. Connectivity which is the key in CAVs was simulated by means of adapting the parameters that determine the headway and the number of observed vehicles, with any predefined logic/algorithms. Considering the importance of communication aspects of AVs, this is a huge limitation in this direction.

4.2. AV Modeling by Externalities. The externalities of microsimulation platforms give prospects in scripting the external logic. During the run-time of the simulation process and with the help of Application Programming Interface (API), the inbuilt models can be overridden, and as a result the vehicle motion can be dictated by the data feeds. This gives researchers a considerable advantage in testing their models/frameworks. Considering the potential of applying external models, researchers applied predefined behavior logic of AVs. Given the flexibility in controlling the characteristics of the simulation objects during the run-time, communication logic was also induced among the vehicles. The basic idea of this kind of studies is that AVs have the added functionality of communication as CAVs and are controlled by the externalities, while the human-driven vehicles are operated by the inbuilt models. Based on this framework, researchers modeled CAVs on different road segments and modeled various AV maneuvers. To understand this better, the literature related to AV simulation

studies in connection with externalities has been reviewed and is summarized in Table 4 with details regarding the study focus, logic modeled, CAV behavior, and key findings.

It is observed that researchers applied numerous logic systems/algorithms, including adaptive dynamic programming [97], optimization-based ramp control strategy [70], Virdi CAV Control Protocol [99], decision-making CAV control algorithm [75], Model Predictive Control [100], Autonomous intersection management [107], Platooning Extension Plexe [108], cooperative scheduling mechanism for CAVs [110], discrete-time occupancies trajectory-based intersection traffic coordination algorithm [113], lane sorting [114], matrix-based intersection management logic [116], and Cooperative Controller and Distributed Algorithm [72].

The main aim of the algorithms mentioned above was to induce CAVs' behavior and instigate communication among the vehicles for better traffic movement over the traffic network. Researchers tested the CAVs across various traffic facilities, including midblock sections, signalized intersections, unsignalized intersections, on- and off-ramps, etc. The behavior of the AVs was governed by various models including the Gipps model [119], Intelligent Driver Model (IDM) [120], Optimum Velocity Model (OVM) [121], Adaptive Cruise Control (ACC) [45], Cooperative Adaptive Cruise Control CACC [71], Theoretical model, and cooperative longitudinal following behavior.

The focus of the researchers varied following the type of study segments. In midblock sections, researchers were

TABLE 3: Details of AV microsimulation studies with inbuilt models.

Platform	Study	Focus	Connectivity in AVs	AV car following behavioral model	Key adjusted parameters to mimic AV	Key findings
VISSIM	Morando et al. [79, 80]	Impact on safety due to AV at intersections and roundabouts	No	Wiedemann 99	(i) Headway time (ii) Following distance variation (iii) Look ahead distance	(i) In case of intersection, AVs reduce the number of conflicts by 20% to 65% with AV penetration rates of between 50% and 100%. (ii) For roundabouts, the number of conflicts is reduced by 29% to 64% with 100% AV penetration rate (iii) AVs reduce the crash rate at roundabouts at higher penetration rates (penetration rate higher than 75%)
	Tbilja's et al. [81]	Safety impacts of AVs at roundabouts	No	Wiedemann 74, Wiedemann 99	(i) Standstill distance (ii) Safety distance (iii) Following time variation (iv) Standstill distance (v) Headway time (vi) Following distance variation (vii) Threshold for entering following	(i) AVs reduce the crash rate at roundabouts at higher penetration rates (penetration rate higher than 75%) (ii) Substantial delay reduction is observed at 30% AV penetration rate
	Stankovic et al. [82]	AV impacts on congested networks	No	Wiedemann 74, Wiedemann 99	(i) Headway time (ii) Standstill distance (iii) Negative following threshold (iv) Positive following threshold (v) Speed dependency of oscillation (vi) Desired speed and acceleration distribution (vii) Standstill distance (viii) Headway time (ix) Following distance variation	(i) Substantial delay reduction is observed at 30% AV penetration rate
	Wang and Wang [83]	Understanding AV's performance on single lane with traffic signal phase	No	Wiedemann 99 with change in acceleration distributions	(i) Headway time (ii) Standstill distance (iii) Negative following threshold (iv) Positive following threshold (v) Speed dependency of oscillation (vi) Desired speed and acceleration distribution (vii) Standstill distance (viii) Headway time (ix) Following distance variation	(i) AVs show a conservative driving style (ii) Total flow rate of AVs in a signal time is the same as that of human-driven vehicles (iii) AVs manage to increase the flow rate in the middle of the green phase
	Martin-Gasulla et al. [84]	Impact on throughput due to CAV	Yes (based on time headway)	Wiedemann 99	(i) Headway time (ii) Standstill distance (iii) Negative following threshold (iv) Positive following threshold (v) Speed dependency of oscillation (vi) Desired speed and acceleration distribution (vii) Standstill distance (viii) Headway time (ix) Following distance variation	(i) Throughput increases at a CAV penetration rate of 44%
	Zedler et al. [95]	Test the potentiality of psychophysical CF models in replicating AV behavior	Yes (based on time headway policy)	Wiedemann 74, Wiedemann 99	(i) Headway time (ii) Standstill distance (iii) Negative following threshold (iv) Positive following threshold (v) Speed dependency of oscillation (vi) Desired speed and acceleration distribution (vii) Standstill distance (viii) Headway time (ix) Following distance variation	(i) Behavior of AVs communicating with the leading vehicle is reproduced well in VISSIM (ii) Problems remain when simulating CAVs that do not communicate with their leader
	Asadi et al. [85]	Impacts of CAVs on traffic stream	Yes (connectivity is brought by changing the smooth behavior and number of observed vehicles)	Wiedemann 99	(i) Headway time (ii) Standstill distance (iii) Negative following threshold (iv) Positive following threshold (v) Speed dependency of oscillation (vi) Desired speed and acceleration distribution (vii) Standstill distance (viii) Headway time (ix) Following distance variation	(i) Congestion levels decrease with CAVs
	Tafidiz et al. [91]	AVs operation at intersections	No	Wiedemann 74	(i) Headway time (ii) Standstill distance (iii) Negative following threshold (iv) Positive following threshold (v) Speed dependency of oscillation (vi) Desired speed and acceleration distribution (vii) Standstill distance (viii) Headway time (ix) Following distance variation	(i) Greater improvement of performance at uncontrolled intersections is achieved
	He et al. [86]	Identifying the freeway speeds at low AV penetration rates	Yes (connectivity is brought by changing the smooth behavior and number of observed vehicles)	Wiedemann 99/along with lane change parameters	(i) Headway time (ii) Standstill distance (iii) Negative following threshold (iv) Positive following threshold (v) Speed dependency of oscillation (vi) Desired speed and acceleration distribution (vii) Standstill distance (viii) Headway time (ix) Following distance variation	(i) The link speeds can be estimated by means of AVs even at small proportions
	Mathew et al. [87]	Impact on operational performance	No	Wiedemann 74	(i) Headway time (ii) Standstill distance (iii) Negative following threshold (iv) Positive following threshold (v) Speed dependency of oscillation (vi) Desired speed and acceleration distribution (vii) Standstill distance (viii) Headway time (ix) Following distance variation	(i) Given the high penetration of AVs, the operational performance is improved
SUMO	Tomas et al. [88]	Emission impacts of AV on freeways	No	Wiedemann 99	(i) Headway time (ii) Standstill distance (iii) Negative following threshold (iv) Positive following threshold (v) Speed dependency of oscillation (vi) Desired speed and acceleration distribution (vii) Standstill distance (viii) Headway time (ix) Following distance variation	(i) The penetration rate of AVs at 10% and 20% demonstrates nominal impact on the emissions
	Yang et al. [89]	Understanding safety performance of Wyoming Connected vehicle Pilot Deployment Program	Yes (assumed normal headway distribution and number of observed vehicles)	Wiedemann 99	(i) Headway time (ii) Standstill distance (iii) Negative following threshold (iv) Positive following threshold (v) Speed dependency of oscillation (vi) Desired speed and acceleration distribution (vii) Standstill distance (viii) Headway time (ix) Following distance variation	(i) Improvement in safety is not significant at low penetration rates; in 85% of autonomous trucks, maximum safety benefits are achieved
	Maryam Mousavi et al. [90]	Understanding safety at unsignalized intersections	No	Wiedemann 74	(i) Headway time (ii) Standstill distance (iii) Negative following threshold (iv) Positive following threshold (v) Speed dependency of oscillation (vi) Desired speed and acceleration distribution (vii) Standstill distance (viii) Headway time (ix) Following distance variation	(i) With connectivity of AVs and reduction in headways, the safety and throughput over the intersections increase
	Rezaei and Caulfield, [92]	Examining the transition from human-driven vehicles to AVs	No	Wiedemann 99	(i) Headway time (ii) Standstill distance (iii) Negative following threshold (iv) Positive following threshold (v) Speed dependency of oscillation (vi) Desired speed and acceleration distribution (vii) Standstill distance (viii) Headway time (ix) Following distance variation	(i) With AV penetration rates of more than 60%, the traffic performance is enhanced
	Rao and Park, [96]	Managing CAVs on connected highways	Yes (parameters not explicitly mentioned)	Wiedemann 99/along with lane change parameters	(i) Headway time (ii) Standstill distance (iii) Negative following threshold (iv) Positive following threshold (v) Speed dependency of oscillation (vi) Desired speed and acceleration distribution (vii) Standstill distance (viii) Headway time (ix) Following distance variation	(i) From 10% penetration of CAVs, there is a reduction in travel times over the road section (ii) The study highlights the optimal behavioral patterns for CAVs over the penetration levels for coordinated movement with non-CAVs
	Qiong Lu et al. [93]	AVs impact on capacity	No	Krauss Model	(i) Headway time (ii) Standstill distance (iii) Negative following threshold (iv) Positive following threshold (v) Speed dependency of oscillation (vi) Desired speed and acceleration distribution (vii) Standstill distance (viii) Headway time (ix) Following distance variation	(i) Capacity improves at high AV penetration rate
	Jesús Mesa-Oreja et al. [94]	Platooning maneuvers in mixed traffic	No	Krauss model	(i) Headway time (ii) Standstill distance (iii) Negative following threshold (iv) Positive following threshold (v) Speed dependency of oscillation (vi) Desired speed and acceleration distribution (vii) Standstill distance (viii) Headway time (ix) Following distance variation	(i) The study reports that model parameter combination impacts the platooning

TABLE 4: Details of AV microsimulation studies with externalities.

Platform	Study	Focus	Introduced logic	Connectivity in AVs	Coded AV behavior	Key findings
Paramics	Gao et al. [97]	Developing data driven adaptive framework for CAVs	Adaptive dynamic programming	Yes	Adaptive dynamic logic and bringing intervehicle communication	(i) The optimal controller strategy can asymptotically stabilize the connected vehicles (ii) The framework can be used for solving connected vehicle control problems with unknown system dynamics
	Olia et al. [98]	Evaluating the impacts of CAVs on the capacities of highway systems	—	No	Gipps model	(i) Maximum lane capacity of 6,450 vph per lane (300% improvement) is achievable if all vehicles are driven in a cooperative automated manner
	Xie et al. [70]	Modeling a merging strategy for freeway operations under connected autonomous environment	An optimization-based ramp control strategy	Yes	Dictating the movement based on default models	(i) The optimal control strategy demonstrated effective coordination among the merging vehicles and will improve the safety and mobility at undersaturated traffic conditions (ii) At low penetration rates of CAV, the potential conflicts will increase
	Virdi et al. [99]	Understanding the safety improvements in mixed traffic stream across the network elements	Developing Virdi CAV Control Protocol (VCCP) algorithm for modeling CAV behavior	Yes	AV following model (Talebpour a Mahmassani, 2016)	(ii) Results demonstrated that CAV operation seems to show a significant overall improvement in safety at midblock road sections (iii) With increase in CAV penetration rates, the potential conflicts reduced. The greater the priority, the more the reduction in conflicts
VISSIM	Papadoulis et al. [75]	Understanding the safety impacts of CAV on motorways	Decision-making CAV control algorithm	Yes	Assuming CAVs longitudinal time gap as 0.6 s and modeling the instant speeds	(i) Results indicated that CAVs bring about compelling benefit to road safety as traffic conflicts significantly reduce even at relatively low market penetration rates
	Ard et al. [100]	Studying the Anticipative Cruise Controller mechanism in two main different scenarios, under disconnected mode with human-driven vehicles and connected mode with other CAVs	Formulated Model Predictive Control (MPC) framework to dictate the movement of the vehicles	Yes	Control-oriented longitudinal dynamics model	(i) Automated vehicles perform at a 10%–20% higher energy efficiency over human-driven vehicles (ii) Simulated human-driven vehicles were found to drive up to 10% more energy-efficiently than they did in the baseline
	Liu and Fan [101]	Impacts on freeway capacity due to CAVs	—	Yes	IDM	(i) With an increase in CAV penetration rate, freeway capacity increases, and further the capacity increases significantly with the increase in speed limits

TABLE 4: Continued.

Platform	Study	Focus	Introduced logic	Connectivity in AVs	Coded AV behavior	Key findings
AIMSUN	Shladover et al. [102]	Understanding the impacts of CACC on traffic flow	—	Yes	Nissan ACC and CACC car following behavior (Bu et al., 2010)	(i) Use of ACC was unlikely to change lane capacity significantly (ii) CACC was able to increase capacity greatly after its market penetration reached moderate to high percentages (iii) Capacity increase could be accelerated by equipping non-ACC vehicles with vehicle awareness
	Chou et al. [103]	Coordinated merge control with vehicle-to-vehicle communication	V2V highway merge control algorithm	Yes	—	(i) Merging performance is found to be proportional to the CAV penetration rates (ii) Merge assist features to human-driven vehicles, even at less AV penetration rate, merge performance is enhanced (i) Roadway capacity increases by 84% by providing AV lanes
AIMSUN	Yu et al. [104]	Impacts of AV lanes in mixed traffic	—	No	IDM	(ii) Deterioration in safety is reported when the market penetration of CAVs is less than 40
	Wang et al. [105]	Effects of CACC on traffic flow	—	Yes	Following: IDM, lane changing: Gipps + Heuristic	(i) CACC helped significantly attenuate traffic congestion and even remove congestion at AV penetration rate greater than 40 percent
	Makridis et al. [106]	CAV impact on traffic flow and CO ₂ emissions	—	Yes	AV: Nissan ACC [102] CAVs (Van Arem et al., 2006)	(i) CAVs can deteriorate the status of the network, and that connectivity is the key to improved traffic flow (ii) Emission-wise, the CAVs have the highest fuel consumption per km traveled among other types, while CAVs only marginally lower the overall consumption of human-driven vehicles
	Olsson and Levin [107]	Management of traffic intersection in the connected scenarios	Autonomous Intersection Management (AIM)	Yes	—	(i) AIM+ is able to reduce delay and increase average speed in comparison to conventional intersection management practices

TABLE 4: Continued.

Platform	Study	Focus	Introduced logic	Connectivity in AVs	Coded AV behavior	Key findings
	Jesús Mena-Oreja and Gozalvez [108]	Platooning maneuvers in mixed traffic	Platooning Extension Plexe, PERMIT	Yes	CACC model	(i) Identifying the importance of platooning in connected scenario
	Timmerman and Boon, [109]	Intersection management	Proposing platooning forming algorithms and providing equal predefined delay to the vehicles over the intersection	Yes	—	(i) Platoon forming algorithms with a low mean delay sometimes are relatively unfair, indicating a potential need for balancing mean delay and fairness
	Liu et al. [110]	Intersection management	Proposing a cooperative scheduling mechanism for CAVs passing through an intersection, called TP-AIM	Yes	—	(i) TP-AIM mechanism significantly reduces the average evacuation time and increases throughput by over 60s and over 20%, respectively. (ii) The maximum delay in TP-AIM can be reduced to less than 10% of Adaptive and Fixed Lights
	Domingues et al. [111]	Lane changing maneuvers and traffic congestion, fuel consumption, and CO ₂ emission	Proposing a negotiation method for the vehicular merging and lane changing scenarios	Yes	Negotiation logic for lane changing movement	(i) Platooning has an important impact on reducing fuel consumption and CO ₂ emissions (ii) Platooning combined with lane-merging shows a significant increase in performance
SUMO	Maske et al. [112]	Improving the mixed traffic performance by intervehicle communication	By means of deep reinforcement learning, intervehicle communication is carried	Yes	Optimum Velocity Model (OVM)	(i) Traffic stream performance is improved by the intervehicle communication
	Lu and Kim [113]	Intersection management with mixed traffic	Discrete-time occupancies trajectory-based intersection traffic coordination algorithm (DICA)	Yes	—	(i) Proposed DICA is found to be computationally efficient (ii) At uncongested traffic, DICA has better traffic throughput than the optimized traffic control mechanism
	Chouhan et al. [114]	Modeling the lane sorting strategies for CAVs	Proposing an algorithm that converts traffic composed of vehicles located randomly in a set of lanes into sorted traffic	Yes	—	(i) The lane sorting strategies were proven to improve the density of traffic streams
	Li et al. [115]	Modeling right of way (RoW) scenarios for mixed traffic	—	Yes	Theoretical model	(i) With proper RoW, the road capacities are improved at even a lower AV penetration rate
	Li and Liu [116]	Investigating intersection management strategy for CAVs	Proposing a matrix-based algorithm for allocating the vehicle movement	Yes	—	(i) The proposed algorithm performs better in comparison to both adaptive and fixed traffic signal systems
	Chamideh et al. [117]	Coordination of CAVs at intersections	An edge cloud controller is used to deliver services that provide traffic safety and efficiency	Yes	Intersection Coordination Unit (ICU) will allocate the vehicle speeds to move over the sections	(i) Delay is reduced over the intersection, along with improvement in safety and flow over the intersections (ii) High execution time was reported in processing the coded algorithms

TABLE 4: Continued.

Platform	Study	Focus	Introduced logic	Connectivity in AVs	Coded AV behavior	Key findings
	Wang et al. [72]	Cooperative car following control	Cooperative Controller and Distributed Algorithm	Yes	Developed CFC and C-CFC	(i) The developed algorithms improved the jam characteristics in traffic network
MOTUS	Xiao et al. [118]	Converting existing High Occupancy Vehicle (HOV) lanes into CACC lanes	—	Yes	CACC levels	(i) Converting to CACC lanes at low penetration less than 30 percent can decrease the congestion (ii) However, at medium CACC with penetration rates of 40 to 50 percent, the congestion is drastically alleviated due to a large share of traffic carried by CACC lanes

focused on CAVs following behavior and lane changing behavior with platooning logic to maximize the improvement in safety and throughput. On the other hand, at intersections and ramps, studies focused on communication among CAVs so that CAVs coordinate themselves and create necessary gaps for traffic movement, with the idea of limiting the stop and go conditions and eliminating traffic signals. Unlike the studies of CAVs with inbuilt models, the studies were focused on the efficacy of the behavioral logic rather than studying the penetration impacts of CAVs. To a certain extent, most of these studies demonstrated a good efficacy of their logic/algorithms. With some externalities, microsimulation platforms such as VISSIM, Paramics, and AIMSUN performed the simulation runs with a single core in the computer processor. As a result, the processing time with those externalities was high. Therefore, the application to a bigger network will be computationally inefficient. Furthermore, most of the logic/algorithms were tested at isolated study segments; therefore, their performance must be quantified in future studies for a traffic network level with greater stochasticity. Finally, to express the reviewed literature in a better manner, visualization analysis was carried out as shown in Figure 7.

4.3. Cosimulation. While in traffic microsimulation, interactions among vehicles are modeled and traffic characteristics are quantified, traffic microsimulation tools do not offer an opportunity to model the C/AV mechanism, and the behavior of the C/AVs is mainly governed by the behavioral models rather than the accurate perception of the infrastructure environment. On the other hand, from an individual C/AV perspective, the automobile industry programs the C/AV behavior in four planning stages: global route planning, behavior planning, motion planning, and local planning. To identify the state estimation and localization, C/AVs are reinforced with numerous sensors for the perception. To model the performance of these sensors and the perception of the infrastructure environment, nanoscopic AV simulation tools are available. Nanoscopic AV simulation tools offer numerous customization options, including detailed maps, 3D vehicle models, sensors, vehicular physics-based models, and external programming interfaces for controlling the actors during the run-time. To better understand the nanoscopic AV simulation tools, a review analysis was performed, and the results are summarized in Table 5.

From the analysis, it is observed that more than thirty AV simulation tools are available in the market. They are commercial and open source in nature and are built using game engines [122, 123]. In general, game engines give the flexibility to place the actors over the 3D space. Based on their character, the behavior will be exhibited. By connecting the actors and agents, the simulation environment is built. The open-source unreal game engine [124] was found to be a popular game engine for building the simulation environment. Most simulation tools offer all kinds of basic sensors for modeling the AV perception. To control the actors during the simulation run-time, application programming

interfaces are provided, mostly in python and MATLAB/Simulink.

Interestingly most of these tools offer a cosimulation environment, in which different AV simulation tools are coupled with traffic microsimulation tools. During the cosimulation, the C/AV behavior is completely governed by the AV simulation tool, where the behavior of C/AVs is modeled with perception from the system, and the entire traffic behavior is governed by the traffic microsimulation tool. These cosimulation strategies help in simulating the C/AVs more accurately and improve the simulation to achieve a more realistic estimation of the traffic operation. The review analysis observed that SUMO and VISSIM are used more often among other traffic microsimulation platforms as cosimulation tools. Given the open-source nature, SUMO is favored in the AV cosimulations.

The literature related to the C/AV cosimulation studies was reviewed and is summarized in Figure 8 and Table 6. The review analysis revealed that the studies are limited in nature. The cosimulation studies picked up recently, and a major proportion of these studies focused on developing methodologies for the C/AVs cosimulation. Interestingly, researchers favored VISSIM to couple it with CarMaker and SUMO with Carla to carry the cosimulation.

The cosimulation research studies highly concentrated at local and motion planning of the C/AVs, and less weightage was given to the global planning. It can be noted that AV simulation tools use the detailed network and simultaneously couple it to the microsimulation which demands good computational power. During the cosimulation, the microsimulation runs are carried out by the externalities, reducing the simulation processing speed and impacting the run-time. Most AV simulation platforms provide inbuilt maps/networks; however, generating such detailed maps for the study section requires additional tools. Given this, AV cosimulation studies are highly dependent on the inbuilt maps/networks in the present context. Finally, currently the cosimulation is restricted to traffic volume, simulation time, and network size.

5. Summary

Given the long research history and research activities, traffic microsimulation has evolved as a core area in traffic engineering. The research activities in the traffic microsimulation domain were found to be highly dynamic in nature with numerous traffic microsimulation studies emerging across the world. Therefore, understanding the flow of the research can help in carrying future research studies. Thus, this study attempted to understand the literature in the traffic microsimulation research domain. Initially, the literature was mined, and the analysis, in terms of the source of microsimulation studies, was performed. To realize this, the involved institutes and the scientific journals were reviewed. From the review analysis, it was observed that worldwide researchers addressed the traffic problems considering the unique traffic conditions in their own countries. Based on the analysis, it was found that few institutes from certain countries are heavily involved in this domain. Traffic

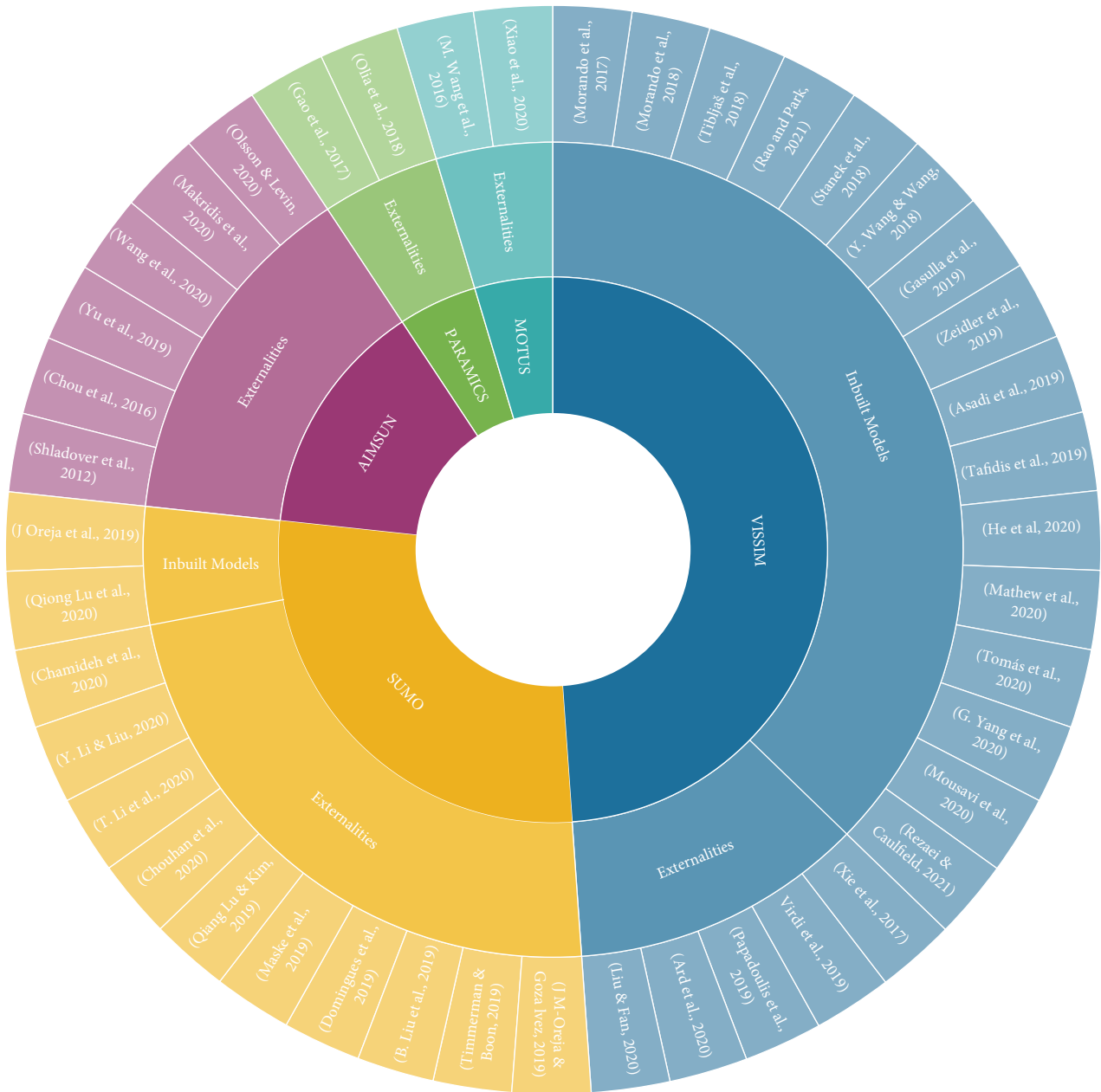


FIGURE 7: AV microsimulation studies over different platforms.

microsimulation studies have found a place in more than 50 journals and numerous conferences. Among them, some specific journals gathered a significant share of simulation studies.

For supporting the research activities and industrial applications, numerous traffic microsimulation platforms have evolved. In this paper, commercial and open-source microsimulation platforms were reviewed; from the review analysis, it was found that some specific platforms kept on evolving, while some others lost their share. Particularly in the previous decade, microsimulation studies have picked up the pace. As a result, a great number of microsimulation studies were conducted. Microsimulation platforms were upgraded over time to match the realistic field conditions as closely as possible. In the present context, microsimulation

tools offer various customization options. To a certain extent, researchers can override the inbuilt models and test their frameworks, including advanced mathematical concepts, such as Artificial Intelligence logic.

Despite the many advantages, there are certain limitations associated with microsimulation platforms. The calibration of the simulation models plays a significant role in having confidence in the simulation outcomes. Given the sophisticated inbuilt models, microsimulation platforms demand detailed empirical data regarding the vehicle trajectories from field conditions. At the same time, generating such kind of microscopic data may not be viable all the time. Due to this, the simulations are calibrated with certain assumptions, and as a result, the same assumptions will be reflected in the simulation outcomes. While performing the

TABLE 5: Details of AVs nanoscopic simulation tools.

Nanoscopic simulation tool	Developer	Nature of distribution	Local planning	Global route planning	Available sensors for perception	Built environment	Application program interface	Latest release	Cosimulation with microsimulation tools
Carla	Computer Vision Center (CVC), Intel, Toyota Research institute, Futurewei	Open source	Yes	Yes	Camera, lidar, radar, safety, GNSS	Unreal Engine	Python (3.7)	Carla 0.9.12	VISSIM, SUMO
PreScan	TASS International (Siemens)	Commercial	Yes	Yes	Camera, lidar, radar, safety, GNSS	Unreal Engine	MATLAB and Simulink	Prescan 2020.4	VISSIM, SUMO, AIMSUN
VIRES virtual Test Drive	Hexagon Present: Mechanical Simulation Corporation Initial: University of Michigan Transportation Research Institute	Commercial	Yes	Yes	Camera, lidar, radar, safety, GNSS	Not identified	VTD API	VIRES VTD 2.2	VISSIM, SUMO
CarSim	National University of Singapore	Commercial	Yes	Yes	Camera, lidar, radar, safety	Unreal Engine	Python, MATLAB	CarSim 2021.1	VISSIM, SUMO
Summit	German Research Center for Artificial Intelligence	Open source	Yes	Yes	Camera, lidar, radar, safety, GNSS	Unreal Engine	Python (3.7)	Summit 1.0	SUMO
OpenDS	German Research Center for Artificial Intelligence	Open source	Yes	Yes	Camera, lidar, radar, safety, GNSS	jMonkeyEngine 3.2	Lightweight Java Game Library	OpenDS 5.0	VISSIM, SUMO
VI-WorldSim	VI-grade GmbH	Commercial	Yes	Yes	Camera, lidar, radar, ultrasonic, safety, GNSS	Unreal Engine	MATLAB	VI-WorldSim	Not identified
Automotive Simulation Models (ASM)	dSPACE GmbH	Commercial	Yes	Yes	Camera, lidar, radar, GNSS	Unreal Engine 4	MATLAB and Simulink	ASM 9.6	VISSIM, SUMO
Altair simulation	Altair	Commercial	Yes	Yes	radar, ultrasonic, and lidar	Not identified	MATLAB	Altair simulation	—
SCANeR studio	AVSimulation	Commercial	Yes	Yes	Camera, lidar, radar	Unreal Engine	Python	SCANeR 2021.2	Not identified
Driving Simulation	rFpro	Commercial	Yes	Yes	Camera, lidar	Not identified	MATLAB and Simulink	Driving Simulation rFpro	VISSIM, SUMO
Autonomous Vehicle Simulator	NI	Commercial	Yes	Yes	Camera, lidar, radar	Unreal Engine	Not identified	Autonomous Vehicle Simulator	Not identified
CarMaker	IPG Automotive	Open source	Yes	Yes	Camera, lidar, radar	Not identified	MATLAB and Simulink	CarMaker 10.0	VISSIM, SUMO
DriveSim	NVIDIA	Open source	Yes	Yes	Camera, lidar, radar, ultrasonic, safety, GNSS	NVIDIA RTX	Python	NVIDIA DriveSim 10.0	—
SVL Simulator	LG	Open source	Yes	Yes	Camera, lidar, radar, ultrasonic, safety, GNSS	Unity game engine	Python	LGSVL Simulator 2020.06	—

TABLE 5: Continued.

Nanoscope simulation tool	Developer	Nature of distribution	Local planning	Global route planning	Available sensors for perception	Built environment	Application program interface	Latest release	Cosimulation with microsimulation tools
veDYNA	TESIS GmbH	Commercial	Yes	No	Camera, lidar, radar, ultrasonic, safety, GNSS	—	MATLAB	veDYNA	—
Deepdrive	Voyage	Open source	Yes	Yes	Camera, lidar, radar	Unity game engine	Python	Deepdrive	—
Cognata	Cognata	Commercial	Yes	Yes	Camera, lidar, radar photorealistic sensor models	Cognata engine	Python	Cognata simulation	—
Metamoto	Initial: Metamoto Present: Foretellix Ltd.	Commercial	Yes	Yes	Laser radar, camera, millimeter wave radar, ultrasonic radar, GPS, and IMU	Unreal Engine	Python	Metamoto	—
RightHook	RightHook	Commercial	Yes	Yes	Camera, lidar, radar, ultrasonic, safety, GNSS	Unity, UE4, or CryEngine	Python	RightHook	—
Parallel Domain	Parallel Domain External Support: Toyota	Commercial	Yes	Yes	Camera, lidar, radar, ultrasonic, safety, GNSS	Unreal Engine 4, Houdini, Maya, 3DS Max, and Substance Suite	Python	Parallel Domain	—
51Sim-One	51World	Open source	Yes	Yes	Camera, lidar, radar, ultrasonic, safety, GNSS	Not specified explicitly	Python	51Sim-One	—
Pilot-D Gaia	Pilot-D Automotive	Commercial	Yes	Yes	Camera, lidar, radar, ultrasonic, safety, GNSS	Unreal Engine	Python	Pilot-D Gaia 3.0	—
ESI Pro-SIVIC	ESI	Commercial	Yes	Yes	Camera, lidar, radar, ultrasonic, safety, GNSS	Unreal Engine	Python	Pro-SIVIC 2020.0	—
PanoSim	PanoSim	Commercial	Yes	Yes	Camera, lidar, radar, ultrasonic, safety, GNSS	Not specified explicitly	Python, MATLAB	PanoSim 4.0	—
AAI	AAI GmbH	Commercial	Yes	Yes	Camera, lidar, radar, ultrasonic, safety, GNSS	Unity game engine	Python	AAI	—
Baidu Apollo	Baidu	Open source	Yes	Yes	Camera, lidar, radar, ultrasonic, safety, GNSS	Apollo Game Engine	Python, Baidu Cloud	Apollo 6.0	SUMO
Waymo Carcraft	Google Waymo	Open source	Yes	Yes	Camera, lidar, radar, ultrasonic, safety, GNSS	Unreal Engine	Python	Carcraft	—
TAD Sim	Tencent	Commercial	Yes	Yes	Camera, lidar, radar, ultrasonic, safety, GNSS	Tencent game engine	Python	TAD Sim 2.0	—
CruzWay	Univ. of California, Santa Cruz	Open source	Yes	Yes	Not specified explicitly	Unreal Engine	Python	CruzWay	SUMO
Gazebo	Univ. Grenoble Alpes, Inria	Open source	Yes	Yes	Camera, lidar, radar, ultrasonic, safety, GNSS	Not specified	Python	Gazebo 3D	SUMO
3DCoAutoSim	Universidad Carlos III de Madrid (UC3M)	Open source	Yes	Yes	Camera, lidar, radar, ultrasonic, safety, GNSS	Unity game engine	Python	3DCoAutoSim	SUMO

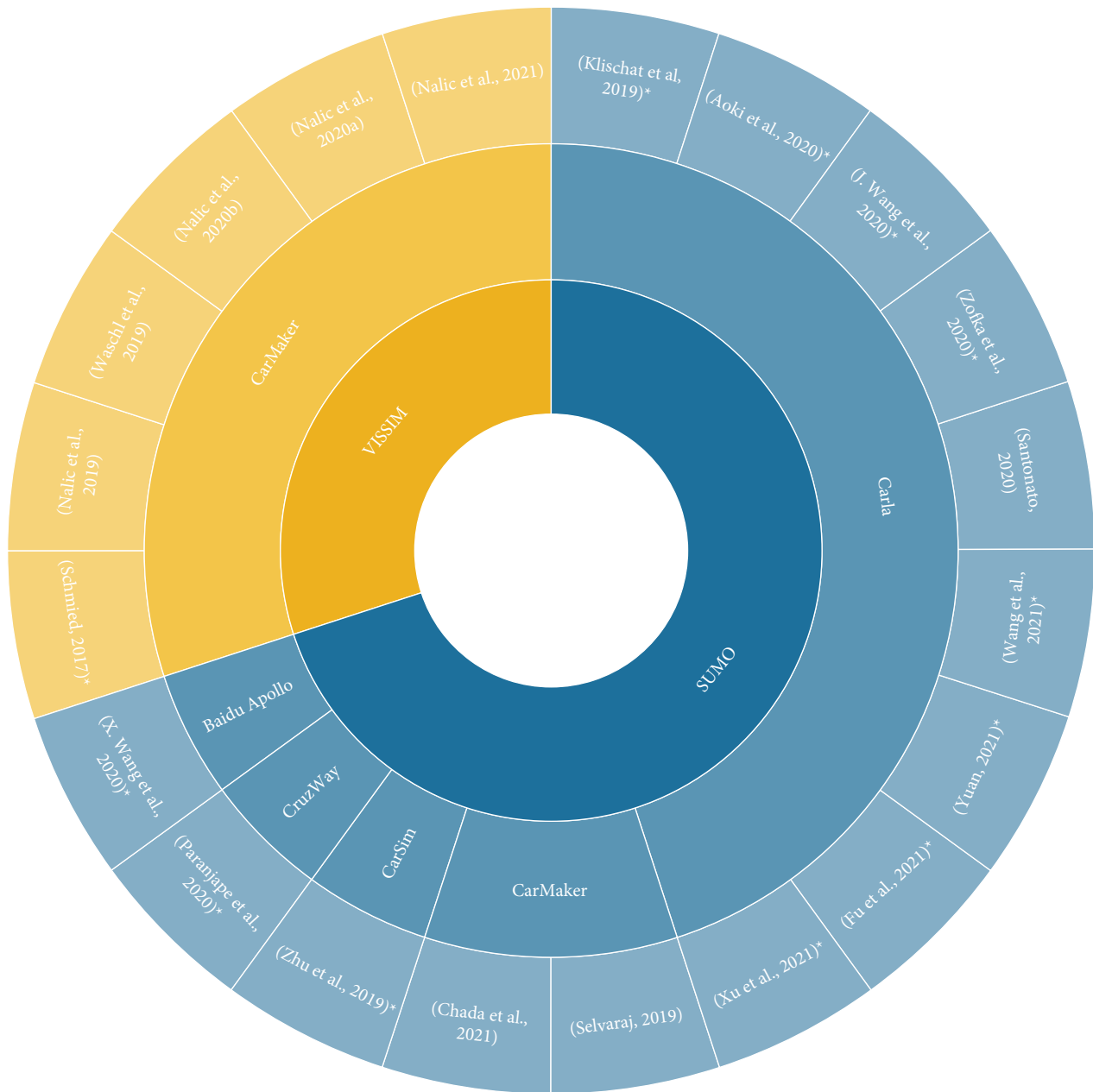


FIGURE 8: AV cosimulation studies over different platforms.

simulation runs with externalities, the processing falls to a single core in the computer processor in some microsimulation platforms. As a result, for medium-scale networks with heavy traffic flow conditions, the simulation run can overload a single processor's core, leading to simulation crashing. Presently, this is a limitation in expanding microsimulation studies with externalities for a more extensive network with heavy traffic.

6. Future Prospects for AVS

Given the considerable innovations in automobiles and top multinational conglomerates' involvement in research and innovation in this sector, anticipating AVs on our road

network is becoming a realistic scenario for the near future. Additionally, this has brought new challenges for the researchers in the transportation domain. Traffic microsimulation platforms can be one of the dependable resources in understanding AVs' impacts from a traffic engineering point of view. Particularly in the second half of the last decade, researchers focused heavily on understanding AVs' effects on traffic performance. The literature examination shows that the research attempts in this direction have taken two significant approaches. According to the first approach, the researchers have used the inbuilt models from the simulation platforms and have adapted the model's parameters to replicate the behavior of AVs. The second approach used by researchers is coding the CAVs' behavior

TABLE 6: Details of AV cosimulation studies.

Study	Study focus	Microsimulation tool	AV simulation tool	Scripted logic	AV behavior	AV perception sensors	Findings
Klischat et al. [125]*	Transferring the trajectories of vehicles controlled by a motion planner and the trajectories of other traffic participants between SUMO and Carla	SUMO	Carla	Lane change synchronization	Local	—	The proposed algorithm for synchronizing lane changes with SUMO yields a more realistic behavior in line with motion planning
Selvaraj, [126]	Focusing on developing a framework for sensor- and communication-assisted vehicle dynamic for AVs	SUMO	CarMaker	ACC and CACC controllers	Local, motion, global	—	Analyzing the importance of the connected vehicles in vehicular safety applications
Zhu et al. [127]*	Evaluating the performance of a proportional-derivative (PD) steering controller	SUMO	CarSim	—	Local	—	A new lateral control design procedure based on robust PD controller with parameter space design and add-on model regulator is introduced
Paranjape et al. [128]*	Generating town sized road networks and intersections for the modeling of AVs and pedestrians	SUMO	CruzWay	TownSim, IntGen, Netgenerate, Sumo2Unreal	Local, motion	—	With the help of CruzWay, the road network is modeled in the form of mesh and navmesh and imported to SUMO
Wang et al. [105]*	Introducing a Python API between the planning module of the Apollo platform and the CommonRoad framework	SUMO	Baidu Apollo	CommonRoad	Local, motion	—	Converting the road network and obstacle information from Apollo to CommonRoad and developing an interface with CommonRoad-SUMO for simulating the vehicles
Aoki et al. [129]*	Cooperative perception scheme with deep reinforcement learning to enhance the detection accuracy for the surrounding objects	SUMO	Carla	CIVS	Local, motion	Cameras	CIVS platform able to produce realistic 3D graphics, traffic model, vehicle model, sensor model, and communication among the vehicles
Wang et al. [130]*	Hierarchical behavior and motion planning (HBMP) to explicitly model the behavior in learning-based solution	SUMO	Carla	HBMP	Local, motion	Lidar, cameras	Giving a methodology to work on hierarchical behavior and motion planning using the reinforced learning
Zofka et al. [131]*	Robot Operating System (ROS) for a mixed reality environment	SUMO	Carla	ROS	Local, motion	—	Framework now enables the holistic simulation of traffic scenarios by coupling multiple domain expert models with real world entities
Santonato, [132]	Working on a framework for complete end to end simulation for AVs	SUMO	Carla	—	Local, global	Lidar, cameras	Identifying the importance of cosimulation for AV simulation

TABLE 6: Continued.

Study	Study focus	Microsimulation tool	AV simulation tool	Scripted logic	AV behavior	AV perception sensors	Findings
Wang et al. [133]*	CommonRoad-RL, an open-source toolbox to train and evaluate RL-based motion planners for autonomous vehicles	SUMO	Carla	CommonRoad-RL	Local, motion	—	Framework for an open-source toolbox to train and evaluate RL-based motion planning for autonomous vehicles
Chada et al. [134]	Cosimulation framework for testing predictive eco-driving assistance systems (EDAS) for commercial vehicles in urban environments	SUMO	CarMaker	Eco-driving assistance systems (EDAS)	Local, motion	—	Proposed cosimulation framework has been tested on the driving simulator in real time
Yuan, [135]*	Collective Multiagent Perception In combining SUMO and Carla for modeling the AVs	SUMO	Carla	COMAP	Modeling the cooperative behavior for AVs	Lidar, cameras	Collective perception proven to improve the localization accuracy for the AVs
Study	Study focus	Microsimulation tool	Nanosopic simulation tool	Scripted logic	AV behavior	AV perception sensors	Findings
Fu et al. [136]*	Working on network-level autonomous driving simulator framework based on the Cellular-Vehicle-to-Everything (C-V2X) protocol	SUMO	Carla	LTE-V2X	Connectivity at intersections	Cameras	Combining SUMO and Carla and working on cosimulation framework, demonstrating that framework is feasible for some advanced autonomous driving applications, such as multi-intersection vehicle scheduling and remote driving
Xu et al. [137]*	Working on cooperative driving automation logic for the AVs at merging section	SUMO	Carla	OpenCDA	Local, global	Lidar, external communication	Showing the importance of OpenCDA for modeling cooperative behavior logic among the AVs
Schmied, [138]*	Designing and comparing two different control concepts applied to Adaptive Cruise Control (ACC) and lane change assisted ACC (LC-ACC)	VISSIM	CarMaker	Model Predictive Control (MPC)	Local, motion	—	Mixed H2/H _∞ and predictive control concepts have been introduced to increase performance of the ACC and LC-ACC
Nalic et al. [139]	Cosimulation framework for systematic generation of scenarios for testing and validation of Automated Driving Systems	VISSIM	CarMaker	Dynamic Data Exchange interface	Local, motion	—	Demonstrating the importance of cosimulation for realistic behavioral analysis
Waschl et al. [140]	Framework for testing realistic traffic conditions	VISSIM	CarMaker	Predictive Adaptive Cruise Control (P-ACC)	Local	—	Considering the traffic control based on available V2X and I2V information or more sophisticated sensor models

TABLE 6: Continued.

Study	Study focus	Microsimulation tool	AV simulation tool	Scripted logic	AV behavior	AV perception sensors	Findings
Nalic et al. [141]	Implementation of a cosimulation framework	VISSIM	CarMaker	Model View Controller (MVC)	Local, motion	—	cosimulation framework for testing ADSs using MATLAB/Simulink, CarMaker, and VISSIM
Nalic et al. [142]	A novel stress testing method	VISSIM	CarMaker	External driver models	Local, motion	—	The developed stress testing method showed a significant increase of detected scenarios in the cosimulation environment
Nalic et al. [143]	Framework for testing AVs in traffic environment	VISSIM	CarMaker	Driver Model DLL interface (DMDI)	Local, motion	—	Driver model framework

*Literature from arXiv and conference proceedings.

with the help of externalities for the simulation runs. Presently, both strategies have their advantages and limitations. Most studies have focused on the impacts of AVs penetration rates on safety and efficiency, with the majority predicting that, at low AV penetration rates, both safety and efficiency will be degraded. At higher AV penetration rates, the studies forecast significant improvements in safety and efficiency standards. It is inferred that the results across the different studies are not consistent; the AV transition penetration rates are varying across the studies and range from 20% to 70%. The results of these studies are highly dependent on the inbuilt models of the simulation platforms. On the other hand, with externalities, researchers focused on the communication aspects among CAVs and worked on platooning models at midblock sections, cooperative merging models at merging sections, and cooperative gap formation models at intersections. The present ongoing studies adapt the behavioral model parameters in such a manner that C/AVs will have smooth behavior in comparison to human-driven vehicles. At the same time, the calibration of the parameters for C/AVs demands trajectory data of C/AVs from field conditions, which is limited in nature.

From the studies, it is concluded that most studies assume fully functional AVs in the simulation models. However, from a practical perspective, the functionality of AVs is discretized into five levels by the Society of Automotive Engineers (SAE). In supporting this, presently, AVs of initial levels find their place on our road networks. As a result, there can be a mixed proportion with different AV levels that can be observed. In existing studies, not much weight is given to these aspects. This forms a huge research gap in the present AV microsimulation studies. From recent investigations, it is observed that AVs' presence can influence the behavior of human-driven vehicles. However, present microsimulation studies assume that human-driven vehicles will have the same usual interaction standards even with AVs, ignoring human behavioral adaptation. This is once again one of the limitations of present AV microsimulation studies, which can be addressed by future studies.

Considering the importance of C/AV motion planning in microsimulation, cosimulation frameworks have evolved in recent years. Cosimulation strategies show a good promise to model the C/AV behavior in a much-detailed manner combined with sensor perception. In the present context, most of the cosimulation studies are at initial levels and are highly focused on developing cosimulation frameworks. Given the computational constraint in cosimulation APIs, the cosimulation studies focus on a single vehicle with limited traffic volume and network. Cosimulation studies are highly focused on C/AV motion planning with less weightage to traffic characteristics as in microsimulation. However, with the ongoing attempts and cosimulation APIs, it can be extended with a higher number of C/AVs guided based on the sensors in a traffic stream and the human-driven vehicles with the behavioral models. These developments will help develop new and improved strategies for better management of mixed traffic. At the same time, the

results can build enough confidence for practitioners in accepting the research outcomes.

Data Availability

The data that support the findings of this study can be made available upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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