Simulation Modelling Practice and Theory 137 (2024) 103017

Contents lists available at ScienceDirect

Simulation Modelling Practice and Theory

journal homepage: www.elsevier.com/locate/simpat

Advancements in traffic simulation for enhanced road safety: A review

Aliyu Mustapha [a,b,*], Ahmad Majdi Abdul-Rani [a], Noorhayati Saad [c], Mazli Mustapha [a]

[a] *Mechanical Engineering Department, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, Perak, Malaysia*
[b] *Industrial and Technology Education Department, Federal University of Technology Minna, Nigeria*
[c] *Faculty of Innovation and Technology, Taylor's University Subang Jaya, Selangor, Darul Ehsan, Malaysia*

A R T I C L E I N F O

Keywords:
Microsimulation
Microsimulation modelling
Risk assessment
Road safety
Surrogate safety
Traffic simulation

A B S T R A C T

Traffic simulation techniques play a crucial role in transportation engineering, offering a sophisticated framework for analysing the intricate dynamics within transportation systems. This paper thoroughly reviews the latest developments in traffic simulation techniques and their applications in improving road safety. Drawing from a comprehensive analysis of recent literature from the Scopus database spanning 2014 to 2024, this review highlights the various analytic methods employed in traffic simulation and their practical applications. Focusing mainly on microsimulation techniques, the study underscores their ability to provide proactive and reactive surrogate safety measures, offering stakeholders valuable insights into traffic safety dynamics. Leveraging methodologies such as microsimulation modelling, surrogate safety measures, statistical model creation, simulation-based conflict prediction, and sensitivity analysis, contemporary research aims to address safety concerns comprehensively. However, the absence of comprehensive crash simulation models presents a significant challenge, raising doubts about the efficacy of traffic simulation in road safety assessment. To overcome this challenge, interdisciplinary research is essential to develop practical solutions that harness technological advancements and foster collaboration across domains. By overcoming existing limitations and refining methodologies, researchers can pave the way for more robust and comprehensive approaches to traffic safety evaluation, contributing significantly to the global goal of enhancing road safety.

1. Introduction

Traffic simulation analysis in transportation engineering provides insights into complex network dynamics, with microscopic simulation focusing on individual car behaviour within traffic systems, accounting for lane shifts, acceleration, and interactions [1]. Transportation engineers use microscopic simulation to analyse road network dynamics and risks, assessing safety without crash data. Surrogate safety metrics provide valuable indicators, such as time-to-collision and traffic conflicts [2]. By exploiting these measures, engineers can create tailored countermeasures and acquire insights into safety risks.

Microscopic simulation aids transportation engineers in efficiently evaluating various safety-related aspects of transportation systems by examining the impact of speed constraints, traffic signal timing, geometric design factors, and driver behaviour on safety

* Corresponding author.
E-mail addresses: aliyu_22000469@utp.edu.my, al.mustapha@futminna.edu.ng (A. Mustapha).

https://doi.org/10.1016/j.simpat.2024.103017
Received 10 March 2024; Received in revised form 5 September 2024; Accepted 8 September 2024
Available online 10 September 2024
1569-190X/

performance [3,4]. Existing research highlights the importance of traffic simulation in road safety assessment. However, there is a need to consolidate findings and identify practical areas for road safety evaluation through simulation [5]. This study addresses this gap by reviewing traffic simulation applications for road safety evaluation, focusing on emerging technologies and methodologies. Furthermore, the study highlights the role of traffic simulation in road safety assessment, allowing engineers to simulate high-risk areas and complex traffic situations without relying on actual crash data.

This review consolidates previous research, underscores the importance of traffic simulation in road safety assessment, and pinpoints effective areas for simulation systems. Bridging the gap between driving behaviour and traffic simulation offers a detailed understanding of safety dynamics and valuable insights for transportation planners. The study emphasises the importance of traffic simulation approaches in road safety evaluation, aiming to enhance their use by transportation planners. The paper explores research selection and safety evaluation systems in traffic simulation, addressing infrastructure-related risks, road type-specific hazards, automated transportation, urban contexts, and road geometry design. It highlights emerging topics, such as integrating automated video image processing and real-time traffic data, emphasising their role in road safety evaluation. The study thus provides a comprehensive overview of current advancements. It identifies critical areas for ongoing research in traffic simulation and road safety evaluation.

1.1. Aim

This study aims to consolidate previous research and identify areas for road safety evaluation where traffic simulation systems are effective through a thorough literature review.

1.2. Scope of literature review

This study, supported by the Cochrane Collaboration, uses the population, intervention, comparison, and outcomes (PICO) to investigate the impact of simulation training on reducing road traffic accidents in drivers over ten years.

1. Population: The populations under study range from simulated to actual traffic scenarios, such as managed toll lane access zones, motorways, roundabouts, highway work zones, and signalised intersections. This diversity, which includes various road infrastructure types and traffic circumstances, reflects the scope's breadth.
2. Intervention: The study examines traffic safety interventions like signal timing plans, left turn phasing schemes, active vehicle safety systems, and lane merging control strategies to reduce traffic problems and improve road safety.
3. Comparison: The study employs statistical analysis, field studies, microsimulation, and machine learning classifiers to investigate traffic safety issues. Despite limitations like simulated data, it contributes significantly to traffic safety research by developing new methodologies and optimising road design.
4. Outcome: The studies' findings include the creation of statistical models to estimate crash risk, the identification of traffic situations that are likely to cause conflicts, the assessment of safety performance metrics like average delay and traffic conflict intensity, and the construction of safety evaluation models using surrogate safety measures. This illustrates a thorough method for evaluating and calculating the results of traffic safety.

2. Methods

The study involved identifying keywords, conducting a literature search, assessing studies, and interpreting and synthesising the findings. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) was used as the framework for our research to ensure a strict and organised approach [6]. We conducted our literature search in the Scopus database from 2014 to 2024, utilising search phrases such as ("road safety assessments" OR "road assessments" OR "safety assessments" AND "surrogate safety" AND "traffic simulation" OR "microsimulation modelling"). The study flow diagram in Fig. 1 depicts our search process.

This systematic review encompasses studies that investigate "road safety assessments," "road assessments," or "safety assessments" using "traffic simulation." Only studies with more than 10 citations, published in peer-reviewed journals, conferences, and lecture

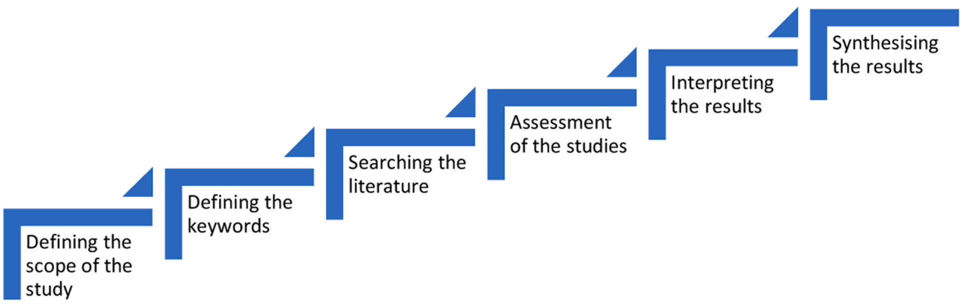

Fig. 1. Methodology.

notes, and accessible in English were considered. This review excludes studies focusing on off-road safety assessments, off-road traffic simulation, and grey literature sources, including reports, books, book chapters, theses, dissertations, protocols, and studies not written in English.

The quality assessment of the literature in traffic safety studies was conducted using clearly defined criteria, including the presence of defined objectives/hypotheses, described study scope, robust study designs, and detailed statistical/ modelling methods (Table 1). These criteria, fundamental to rigorous scientific research, were evaluated using an objective binary system (present = 1, absent = 0), reducing subjectivity. The studies were then classified into quality categories based on their total scores, with most studies receiving high-quality qualifications, demonstrating a solid foundation in methodology and rigour. The process of data exploration started with creating a data-gathering form in a Microsoft Excel spreadsheet. This systematic and objective assessment underscores the robustness and comprehensive nature of traffic safety research across various publications, emphasising the multidisciplinary integration of knowledge Fig. 2 summarises the study's selection procedure using PRISMA.

Table 1 assesses the quality of articles in traffic safety assessment primarily through a methodical approach. Most studies achieved a high-quality rating of 100 %, exemplifying excellence in defining objectives, presenting study scopes, designing methodologies, and describing statistical methods. Studies by Appiah et al. [11], Essa & Sayed [12], Ghanim et al. [13], Giuffrè et al. [17], Katrakazas et al. [18], Saad et al. [19], Cafiso et al. [20], Lee et al. [21], Qi & Zhao [22], Jeong & Oh [23], So et al. [27], Essa & Sayed [28], So et al. [27], Azevedo et al. [32], and Habtemichael & De Picado Santos [31] consistently excelled. However, Li et al. [24] received a medium-quality rating of 75 %. While this study effectively defined objectives and hypotheses and used appropriate study designs and statistical methods, it lacked a precise presentation of the study population. This discrepancy suggests slightly lower quality compared to most reviewed studies. Therefore, these findings highlight the methodological robustness and rigorous approach observed across most studies in traffic safety assessment. This is a multidisciplinary study, and Table 2 lists the various publications in which the included articles have appeared.

Table 2 presents a diverse array of journals that have contributed significantly to the multidisciplinary analysis discussed in the study. The table highlights "Accident Analysis and Prevention" as the most influential journal with five publications, underscoring its pivotal role in shaping research on road safety. Other notable journals include "IEEE Transactions on Intelligent Transportation Systems," which focuses on advancements in intelligent transportation, and "International Journal of Environmental Research and Public Health," indicating a linkage between public health, environmental research, and multidisciplinary studies. Journals like "Journal of Computing in Civil Engineering," "Journal of Advanced Transportation," and "Transportation Research Record" reflect the study's exploration into computing technology, advanced transportation topics, and comprehensive transportation research, respectively. Each journal selected in the table contributes uniquely to the broader understanding of how various disciplines intersect to enhance traffic simulation methodologies to improve road safety.

Table 1
Quality assessment of included articles.

Author(s), (Year)	Quality factors				
	Quality Qualification (%)	Defined objectives/ hypothesis	Presented study scope	Study design	Described statistical/ modelling methods
Shahdah & Azam, [7]	H = 100%	1	1	1	1
Guo et al. [8]	H = 100 %	1	1	1	1
Khashayarfard & Nassiri, [9]	H = 100 %	1	1	1	1
Sinha et al., [10]	H = 100 %	1	1	1	1
Appiah et al., [11]	H = 100 %	1	1	1	1
Essa & Sayed, [12]	H = 100 %	1	1	1	1
Ghanim et al. [13]	H = 100 %	1	1	1	1
Gruden et al. [14]	H = 100 %	1	1	1	1
Giuffrè et al. [15]	H = 100 %	1	1	1	1
Ghanim & Shaaban, [16]	H = 100 %	1	1	1	1
Giuffrè et al. [17]	H = 100 %	1	1	1	1
Katrakazas et al. [18]	H = 100 %	1	1	1	1
Saad et al. [19]	H = 100 %	1	1	1	1
Cafiso et al. [20]	H = 100 %	1	1	1	1
Lee et al. [21]	H = 100 %	1	1	1	1
Qi & Zhao, [22]	H = 100 %	1	1	1	1
Jeong & Oh, [23]	H = 100 %	1	1	1	1
Li et al. [24]	M = 75 %	1	0	1	1
Essa & Sayed, [25]	H = 100 %	1	1	1	1
Behbahani et al. [26]	H = 100 %	1	1	1	1
So et al. [27]	H = 100 %	1	1	1	1
Essa & Sayed, [28]	H = 100 %	1	1	1	1
So et al. [29]	H = 100 %	1	1	1	1
Vedagiri & Killi, [30]	H = 100 %	1	1	1	1
Habtemichael & De Picado Santos, [31]	H = 100 %	1	1	1	1

Keys: Present (1); Absence (0); H= High quality (80-100 %); M= Medium quality (60-79 %); L= Low quality (0-59 %).

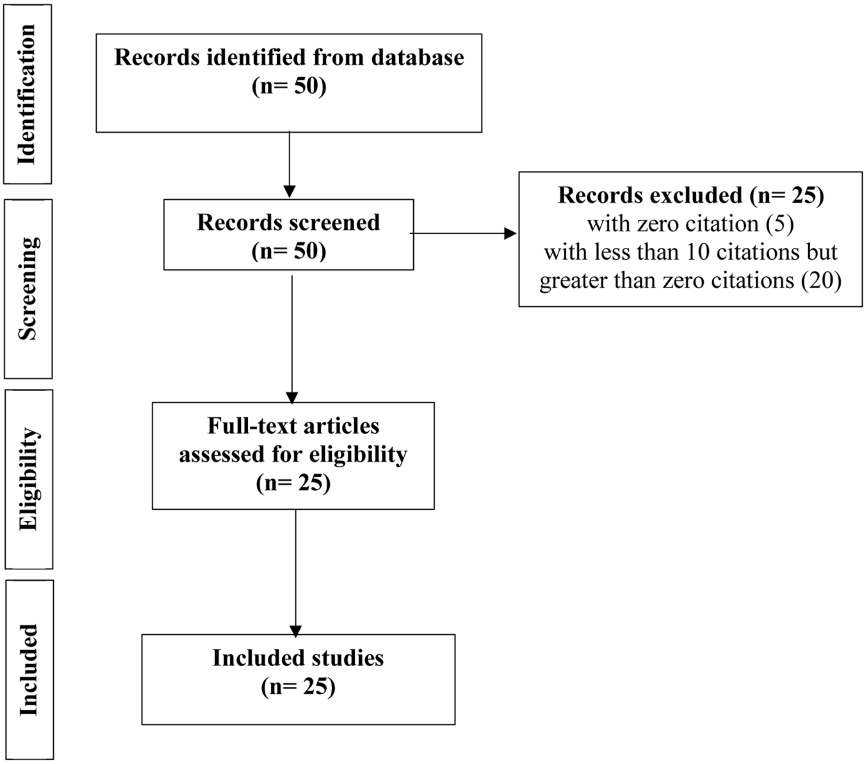

Fig. 2. PRISMA flow diagram.

3. Studies reviewed

This literature review explores recent advancements in traffic simulation models, which are crucial in enhancing road safety by providing comprehensive insights into traffic dynamics and potential conflict scenarios. It highlights studies that employ micro-simulation, machine learning, and real-time safety models, demonstrating their use in various traffic settings such as signalised junctions, roundabouts, highway interchanges, and managed toll lanes. The review underscores the limitations of traditional crash-based methods and stresses the importance of innovative, proactive safety measures. Consolidating findings from multiple studies identifies common themes and research gaps, offering a thorough understanding of how advanced simulation techniques improve road safety and inform future traffic management strategies. A data-gathering form was created using a Microsoft Excel spreadsheet before commencing the data exploration.

Shahdah & Azam [7] investigated the effects of installing speed humps on the safety and mobility of unconventional median U-turn, three-leg intersections using the VISSIM microscopic traffic simulation model. They measured mobility by average delay and assessed safety using the time-to-collision (TTC) surrogate safety measure. Their findings indicated that 5.0 km/h speed humps significantly increased the average intersection delay by 109–448 % and significantly escalated traffic conflicts, regardless of hump location. In contrast, 20.0 km/h speed humps raised the average delay by 2–36 % based on traffic conditions and potentially reduced severe conflicts by 11–20 %. This study underscores the importance of balancing mobility and safety in traffic management.

Guo et al. [8] propose an innovative calibration method for microsimulation models to enhance crash prediction accuracy by linking non-crash events to crashes using extreme value theory (EVT). The goal is to align the extreme value distribution of simulated conflicts with field-measured conflicts, achieved through a genetic algorithm to fine-tune VISSIM model parameters. Their study utilised traffic video data from two approaches at a signalised intersection in Surrey, Canada, as case studies. Field-measured conflicts were extracted with automated traffic conflict analysis techniques. In contrast, simulated conflicts were derived from vehicle trajectories using the SSAM tool. EVT models estimated the generalised Pareto (GP) distributions for field-measured and simulated conflicts, showing significant alignment. This calibration method is recommended for simulation-based safety evaluations of signalised intersections.

Khashayarfard & Nassiri [9] examine the combined impact of autonomous vehicles (AVs) and distracted driving on safety at unsignalized intersections through simulations in PTV VISSIM software, mainly focusing on driver distraction caused by texting. Five scenarios reflecting different AV market penetration rates were simulated. Safety assessments were conducted using the Surrogate Safety Assessment Model (SSAM), employing Time to Collision (TTC) and Deceleration Rate to Avoid Crashes (DRAC) as indicators of potential accidents. The findings revealed that a 100 % presence of AVs could reduce potential accidents by up to 93 %.

Sinha et al. [10] analyse the effects of connected and automated vehicles (CAVs) on traffic safety and network performance during

Table 2
Diversity in multidisciplinary analysis journal.

No	Journal/Conference/Lecture Note	No. of publications	Justification
1	Accident Analysis and Prevention	5	The study appears to be significantly influenced by this journal, which has the most publications.
2	IEEE Transactions Intelligent on Transportation Systems	1	This journal focuses on the advancement of intelligent transportation systems.
3	International Journal of Environmental Research and Public Health	1	The journal focuses on public health and environmental research, indicating a potential link between these subjects and multidisciplinary studies.
4	Journal of Computing in Civil Engineering	1	The study explores the potential connection between computing technology and civil engineering.
5	Journal of Advanced Transportation	2	This journal focuses on advanced transportation topics.
6	Journal of Transportation Engineering Part A: Systems	1	This journal publishes research-related articles on transportation engineering systems.
7	Arabian Journal of Science and Engineering	1	This journal primarily focuses on science and engineering subjects.
8	Transportation Research Record	4	The journal, a reputable source, has two papers in its study, highlighting its significance in transportation research.
9	Transportation Research Part F	1	This journal focuses on the study of traffic psychology and behaviour.
10	Procedia Computer Science	1	The journal is potentially connected to computer science, possibly related to transportation or another aspect of the multidisciplinary methodology.
11	Transportation Planning and Technology	1	This journal focuses on the intersection of transportation planning and technology.
12	Traffic Injury and Prevention	1	The journal's focus on road injury prevention indicates a specific area of interest in the study.
13	Transportation Letters	1	This publication presents innovative transportation technology and methods.
14	Ain Shams Engineering Journal	1	The journal's focus on integrating diverse engineering disciplines and practical applications aligns well with the review's exploration of traffic simulation for enhancing road safety through innovative engineering solutions.
15	Simulation Modelling Practice and Theory	1	This journal was chosen for its comprehensive coverage of both theoretical aspects and practical applications of simulation in various domains, including transportation systems, which is critical for evaluating advancements in traffic simulation for road safety.
16	Lecture Notes in Networks and System	1	It was selected for its rapid dissemination of research in systems and networks, including areas like Cyber-Physical Systems and Autonomous Vehicles, which are directly relevant to the technological advancements in traffic simulation explored in the review.
17	IOP Conference Series: Material Science and Engineering	1	This journal provides a suitable platform for publishing proceedings related to computational simulation, materials science, and engineering applications, which are pivotal for understanding how simulation methodologies can enhance road safety through innovative materials and technologies.

the transition period when both CAVs and conventional vehicles are present in fleets. The VISSIM microsimulation platform assessed crash severity and frequency at different CAV penetration rates on the M1 Geelong Ring Road network in Victoria, Australia. Surrogate safety measures and network performance metrics were examined, revealing that CAVs do not significantly reduce crash severity and rates involving manual vehicles. The study finds that the full benefits of CAVs are realised only at 100 % penetration. A Pareto frontier for varying CAV operational behaviours was also developed, offering valuable insights for insurance companies and industry stakeholders.

Appiah et al. [11] used complex statistical models in microsimulation to evaluate the probability of left-turn collisions at signalised junctions. The study aimed to explore the intricate connections between intervention strategies and traffic conditions at critical junctures. Simulated data was utilised to evaluate the efficacy of various left-turn phasing strategies. The outcomes were determined by sophisticated statistical algorithms that precisely assessed various traffic factors to assess the risk of left-turn collisions. Nevertheless, the study acknowledged many limitations, including the need for further validation, the modelling's underlying assumptions, and its intrinsic reliance on simulated data. Nevertheless, the outcomes demonstrated how microsimulation modelling might support the development of an intricate, time-varying, safety-based left-turn phasing system.

In 2020, Essa and Sayed conducted a study comparing the Surrogate Safety Assessment Model (SSAM) and real-time safety models for predicting conflicts at signalised crossings. They used traffic data from Surrey, British Columbia, and found that SSAM can accurately predict conflicts but requires strict calibration. However, this study highlights SSAM's drawbacks, such as the requirement for exacting calibration. The alternate technique that has been suggested uses real-time safety models in conjunction with simulated vehicle trajectories to forecast rear-end collisions by considering dynamic traffic characteristics. When the process was tested with actual video data, it outperformed SSAM regarding conflict prediction accuracy. Their research exposed the flaws in SSAM and offered alternatives for improving conflict prediction accuracy. The study provided innovative solutions by integrating simulated trajectories with real-time safety models. It highlighted potential directions for advancing conflict prediction techniques.

Using SSAM and simulation techniques, Ghanim et al. [13] assessed a signalised roundabout's operational and safety performance. The population consisted of vehicles navigating the signalised roundabout during peak hours. The intervention involved analysing different signal timing plans. The article discusses the safety and operational effectiveness of signalised roundabouts in Doha, focusing on traffic conflicts and phasing schemes. Results show that signal timings and phasing are related to roundabout safety, and high traffic volume does not always lead to conflicts. Despite its reliance on simulated data, the study offered a compelling case study in Doha, highlighting the significance of signal timings in shaping roundabout safety. The findings underscored the nuanced relationship between traffic flow management and safety outcomes at signalised roundabouts.

Gruden et al. [14] compare video data gathering and microsimulation techniques to estimate pedestrian safety in a confined space. The focus is on pedestrian-pedestrian interactions, less studied than vehicle-pedestrian accidents. A real case was evaluated using cameras and a microsimulation model. The results showed how the environment influenced pedestrian behaviour and validated the reliability of the microsimulation tool in replicating pedestrian movement and providing comparable surrogate safety values.

Giuffrè et al. [15] use microscopic traffic simulation models to analyse road safety. The Surrogate Safety Assessment Model (SSAM) was used to calculate surrogate safety measures to analyse vehicle trajectory files from two micro-simulators, AIMSUN and VISSIM. The study compared the safety performance of three roundabout layouts, offering insights on how to set SSAM filters to achieve comparable conflict frequencies across different simulation software. This approach facilitates software-independent safety analyses.

Ghanim and Shaaban [16] investigated the possibility of utilising the SSAM to forecast conflicts at a significant signalised intersection. The population included vehicles and pedestrians at the intersection in Doha, Qatar. The intervention utilised SSAM to identify and classify traffic conflicts. The outcome aimed to assess SSAM's feasibility in predicting conflicts. Limitations include challenges in replicating the actual behaviour of road users and accurately identifying conflicts within the simulation model. The outcomes show that the simulation can detect disputes involving unique intersecting manoeuvres. However, it overestimates collision risks, especially for pedestrians. It emphasised the importance of refining simulation methodologies for more accurate safety assessments.

In Katrakazas et al.'s [18] work, machine-learning and micro-simulation techniques were used to identify conflict-prone highway situations with previously unheard-of accuracy. The study used machine learning classifiers to analyse traffic data from the M62 motorway and predict real-time conflict probability. However, issues with calibration and identifying conflict-prone conditions arose. The study used traffic micro-simulation and SSAM to estimate conflicts as surrogate traffic safety measures. Although successful, comparing pre-collision traffic with typical situations was not always realistic.

Giuffrè et al. [17] investigated the assessment of roundabout safety using state-of-the-art traffic simulation models. The study utilised AIMSUN and VISSIM traffic simulation models to estimate traffic conflicts and create a crash prediction model for Slovenian roundabouts. The population consisted of roundabouts in Slovenia with crash data. The intervention utilised microsimulation to evaluate roundabout safety, resulting in a crash prediction model that relied heavily on the microscopic traffic simulation model. Limitations include reliance on simulation models and the need for further validation. Despite reliance on simulation models and the need for further validation, the study emphasised the importance of leveraging advanced simulation techniques for robust safety assessments.

Saad et al. [19] thoroughly analysed the safety complexities of managed toll lane access zones. Based on evaluations of conflict frequency, they employed microsimulation scenarios to determine the optimal access designs. Traffic, particularly South Florida I-95 corridors, was part of the population. The article conducts a safety analysis of controlled highway toll lanes' access zone design, utilising microsimulation scenarios to determine the safest level and weaving length. The best access design was found as a result. A small sample size and restricted data availability are among the limitations. The study found that managed lanes reduced conflict rates compared to general-purpose lanes. The most secure solutions were one accessibility level and a 305-meter weaving length for lane changes.

Cafiso et al. [20] used microsimulation-based conflict analysis to examine merging area lengths and passing lane sections. The population included traffic on roads with passing lanes. The lengths of the merging area and passing lanes were evaluated as part of the intervention. The impact of lengths on safety performance was the focus of the outcome. Reliance on simulated data and the requirement for more study with comprehensive crash data are among the limitations. This study examines the geometric design of passing lanes, explicitly focusing on merging area lengths and passing lane portions. The best duration for these portions and their effect on safety performance are assessed by the study using conflict analysis based on microsimulation. The study highlights the importance of conflicts as a safety measure and the significant impact of additional lane length on the $2 + 1$ short passing lane's safety performance.

By carefully combining SSAM with microscopic traffic simulation, Lee et al. [21] assessed countermeasures for red lights running at signalised intersections. They offered workable strategies for lowering RLR frequency and conflicts. The population included vehicles and drivers at selected intersections in Virginia. Interventions studied included various countermeasures. The outcome aimed to reduce RLR frequency and conflicts. Limitations included differences between surrogate safety measures and actual crashes. The method is applied to a genuine signalised intersection in Virginia, USA, considering several conditions, such as utilising an RLR camera, adding a warning sign, and lengthening the yellow signal interval. The study concludes that the effectiveness of each countermeasure varies depending on the type of RLR-related conflict, and the evaluated countermeasures can be applied to specific intersections based on their RLR crash issues.

Jeong and Oh [23] conducted a study on the effectiveness of AVSS using microscopic traffic simulation techniques. The population included simulated vehicles in different traffic conditions. The intervention was implementing active vehicle safety systems. Outcomes showed a reduction in conflicts and delays. Limitations include the need for further analysis and economic assessment of safety systems. The findings demonstrate the effectiveness of AVSSs in lowering average delay in non-event traffic situations and rear-end and lane-change conflicts. However, under some traffic situations, the effectiveness is reduced. Rear-end collisions and vehicle delays during incident traffic situations are decreased when AVSSs have a high market penetration rate. The study's extensive testing showed that putting these creative mechanisms into place significantly decreased disputes and the delays they caused. Nonetheless, to fully evaluate the effectiveness of these safety devices, the researchers stressed the necessity for additional investigation and cost analyses.

Qi and Zhao [22] evaluated the safety benefits of signalised lane merge control strategy in highway work zones, focusing on reducing lane-change conflicts. The study combined field studies and simulation-based analyses. The population included drivers and vehicles encountering highway work zones. The intervention involved the implementation of a signalised lane merge control strategy. The outcome focused on safety benefits, particularly in reducing lane-change conflicts. Limitations include challenges in generalising findings and variations in driver behaviour. The study highlights the effectiveness of a signal control device in reducing lane-change conflicts at work zone merge locations, emphasising the need for proactive safety measures.

Li et al. [24] used microscopic simulation and the traffic conflict technique to conduct a thorough safety assessment at freeway interchanges. The study aimed to define risk indices and severity criteria to create a reliable safety evaluation model. Population not explicitly mentioned. The intervention included defining risk indexes and severity thresholds. The outcome aimed to establish a safety evaluation model based on risk indexes. The authors established severity limits for time to collision and created hourly composite risk indices. The study utilised a microsimulation simulator and a multivariate linear regression model to analyse the safety dynamics of freeway interchanges despite the complexity of the simulation. The study highlights the importance of accurate risk assessment methodologies in proactive safety management within complex traffic infrastructures, with the HCRI model showing higher fitting than hourly conflicts.

Essa & Sayed [25] explore the correlation between field-measured and simulated conflicts at an urban signalised intersection using the VISSIM microsimulation model and the Surrogate Safety Assessment Model (SSAM). The study collected and analysed sixty hours of traffic data through automated video-based computer vision techniques. A two-step calibration procedure was proposed to improve the correlation between simulated and field-measured conflicts. Conflict heat maps were used to compare the locations of field-measured and simulated conflicts, emphasising the critical role of model calibration and identifying limitations within the SSAM.

Behbahani et al. [26] present a new time-based surrogate safety measure for assessing crash risk in car-following scenarios. This measure combines the variation rate of time-to-collision (TTC) and the associated hazard level to serve as a safety indicator. A microsimulation model was used to validate this measure on Interstate 80, demonstrating its effectiveness in improving the detection of hazardous collisions and providing a more accurate risk assessment. The proposed technique enhances the precision of in-vehicle collision avoidance warning systems (IVCAWS).

The integration of a vehicle dynamics model with microscopic traffic simulation was pioneered by So et al. [27], which marked a paradigm shift in the approaches used for surrogate safety assessments. The population included vehicle trajectories generated by the integrated model. The intervention was developing a more realistic simulation environment. The outcome demonstrated a reduction in conflicts compared to the standalone simulation model. The study found that an integrated approach to traffic safety reduced conflicts and correlated with actual crashes, demonstrating its effectiveness in assessing surrogate safety despite limitations in vehicle trajectories and modelling lateral movements.

Essa & Sayed [28] studied the transferability of simulation model parameters across multiple sites in Surrey, BC, comparing results from calibrated parameters to estimate traffic conflicts. The population included vehicles and traffic conditions at two intersections. The intervention used calibrated parameters from one intersection to estimate conflicts at another. The result sought to ascertain whether disputes measured in the field and simulated were correlated. Limitations include the challenge of representing unsafe interactions in simulation models. Despite challenges in representing unsafe interactions, the study provided valuable insights into calibrating simulation models for accurate conflict prediction. It emphasised the importance of data-driven approaches in enhancing simulation model reliability for safety assessments.

To analyse highway infrastructure safety, So et al. [27] investigated the creative use of a traffic conflict-based surrogate technique population, including segments and signalised intersections in Virginia's Tysons Corner neighbourhood. The intervention compared conflict-based and crash-based methods, showing a high correlation with the benchmark method. However, limitations include multiple sites evaluated and challenges in reflecting on driving situations. The findings demonstrate that the conflict-based approach outperforms the crash frequency method in identifying hot regions and strongly correlates with the benchmark method. According to the study, the conflict-based approach helps identify hot spots and evaluate safety performance, mainly when there is insufficient crash data.

In evaluating traffic safety at uncontrolled intersections under mixed traffic conditions, Vedagiri and Killi [30] address the increasing vehicle numbers in developing countries like India and the challenges of relying solely on accident data for safety assessments. They emphasise the ethical issues of waiting for accidents to gather data, advocating instead for developing accurate models using surrogate safety measures (SSMs). These models offer a more frequent and reliable prediction of crashes. Focusing on a three-arm uncontrolled intersection, the study employs microsimulation modelling to evaluate traffic safety, introducing a unique methodology for measuring Post Encroachment Time (PET) and demonstrating enhanced accuracy in crash predictions with this approach.

Using microscopic traffic modelling techniques, Habtemichael and De Picado [31] assessed the safety effects of aggressive driving on motorways. The population consisted of simulated vehicles on motorways. The intervention was modelling different types of road aggression. Outcome quantified crash risk associated with aggressive driving. Limitations included using historical crash data and underestimation of risk. Using a microscopic traffic simulation approach, this article quantitatively evaluates the safety implications of aggressive driving on motorways. The SSAM and VISSIM are combined in the study to model motorways and evaluate the safety of simulated automobiles. Through correlation with past crashes, the researchers verify the application of vehicle conflicts. Based on historical crash data, the study reveals that aggressive driving poses a significant risk with minimal benefits despite its high crash risk. The final model calibration confirms the accuracy of microscopic traffic models in replicating precise traffic and safety metrics, revealing a multi-step sensitivity analysis framework to identify uncertainty sources.

4. Results and discussion

4.1. Search outcomes

The search strategy used for this investigation produced fifty articles in total. This analysis could not find duplicate entries using a single database (Scopus). Twenty-five full-text papers were selected for further review after these articles were assessed for eligibility. Ultimately, this study comprised twenty-five eligible articles that passed the screening process. This approach ensured that the literature on traffic simulation applications in road safety evaluation was thoroughly reviewed.

4.2. Study features

The included articles were carried out in 10 countries: United States of America - six studies; Canada - four studies; Italy - four studies; Qatar - two studies; Australia - two studies; one study was conducted each in the United Kingdom, Korea, Slovenia, Poland, and China. Two studies did not indicate the country where the study was conducted, as shown in Fig. 3.

4.2.1. Co-authorship of countries

The co-authorship analysis evaluates authors' collaboration from varied geographic regions, which required at least two countries to be involved in each publication. Only eight of the seventeen countries met this criterion. Table 3 presents an overview of these eight countries, detailing their association strength, total citations, and number of documents.

The co-authorship analysis highlights that the United States leads with six documents, showing moderate international collaboration (total link strength of 2) and a substantial citation count of 84, indicating a significant impact. With four documents, Canada stands out for its high citation count (205) but lower collaboration (link strength of 1). Italy, with four documents, and China, with three, show moderate international collaboration (link strength of 2) and strong impact (81 and 90 citations, respectively). Slovenia, South Korea, Iran, and Qatar have fewer publications and varying degrees of collaboration and impact, with Slovenia and South Korea showing moderate collaboration. At the same time, Iran and Qatar have no recorded international collaborations.

4.2.2. Publications analysis

In analysing the publication trends across the selected studies, it was observed that 2015 recorded the highest number of articles, totalling 6 publications. The trend in article publications exhibited fluctuations over the years, with notable peaks in 2015, 2018 (5 articles), and 2020 (4 articles). Conversely, no publications or data were available for 2022 to 2024. Fig. 4 shows the analysis features data labels for each point, providing clear visibility into the number of articles published annually. This graphical representation facilitates the easy identification of peaks and troughs in publication frequency, offering valuable insights into the temporal distribution of research output in the field.

The analysis of publication distribution across 17 venues in the field reveals a total of 25 publications, averaging 1.47 per venue. "Accident Analysis and Prevention" leads with 5 publications, followed by "Transportation Research Record" with 4, and "Journal of Advanced Transportation" with 2, while other venues contributed 1 publication each. The top two venues account for 36 % of all publications, emphasising concentration in select outlets amidst various interdisciplinary topics covering transportation, environmental research, civil engineering, and computer science. This diversity underscores the field's broad dissemination through various academic platforms, including journals and conference proceedings, highlighting both dominant publishers and the breadth of research dissemination avenues. Fig. 5 accurately reflects the distribution of publication types: journal articles dominate 88 % of the total, comprising 22 publications. Conference papers have increased slightly to 8 %, totalling 2 publications, while lecture notes remain 4 % with 1 publication. This visualisation underscores the predominance of journal articles in disseminating research findings while acknowledging the contributions from conference papers and lecture notes within the reviewed publications.

4.2.3. Co-authorship (Authors)

Co-authorship analysis identifies key researchers and collaboration networks within this field. This tool maps the strength of co-authorship ties, with Total Link Strength (TLS) reflecting the overall strength of these connections. The analysis required a minimum of two authors and ten citations per author. Of the 72 authors examined, 8 met these criteria. Among them, five formed a well-connected cluster, indicating their significant collaborative contributions to the field (Table 4).

The table above provides an overview of the authors, total link strength, citations, and documents associated with their publications. It encompasses data from eight authors, each with varying numbers of documents, citations, and link strength. The co-authorship analysis of authors reveals two distinct clusters of collaboration and impact. Giuffre, O., Giuffre, T., Grana, A., Trubia, S., and Tumminello, M. L., each with two documents and a total link strength of 8, indicate a tightly knit group with significant collaboration and a moderate citation count of 39. On the other hand, Essa, M. and Sayed, T., with four documents each and a citation count of 205, show strong individual impact but moderate collaboration (total link strength of 4). So, J. has two documents and a citation count of 34 but no recorded co-authorship links, suggesting independent or isolated work within the research network.

4.2.4. Co-occurrence author keywords

Analysing author keywords is crucial for understanding their relevance and frequency in scientific articles. Co-occurrence measures the relationship between keywords, while total link strength reflects their frequency. Node size represents keyword frequency, and thicker lines indicate closer proximity. Using Scopus and VOS viewer with a minimum of five occurrences per keyword, 25 out of 323

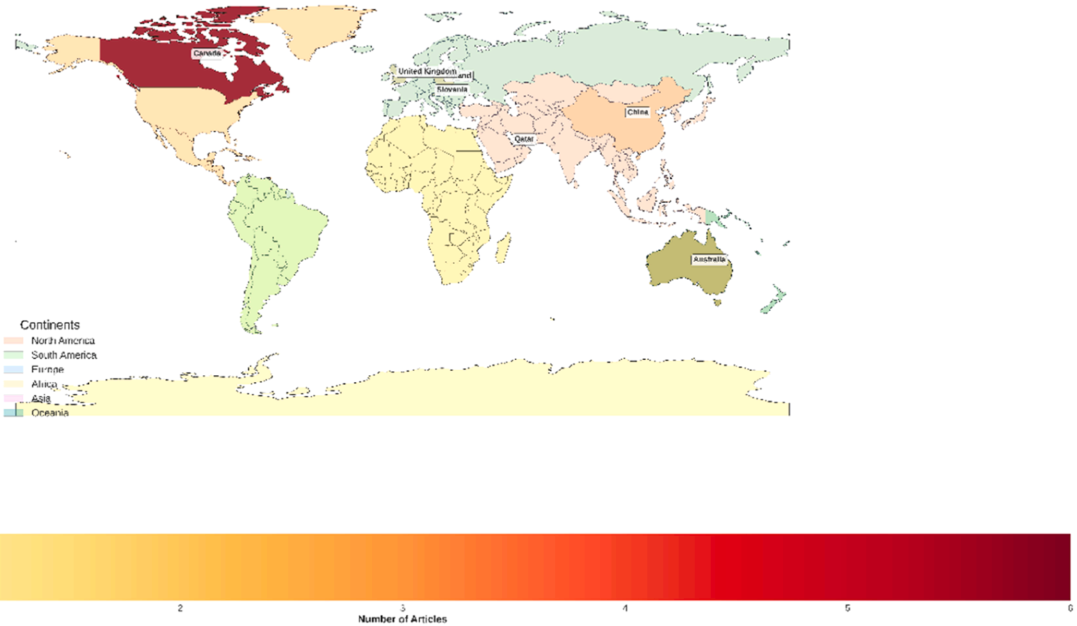

Fig. 3. Global Distribution of Studies.

Table 3
Co-authorship analysis of countries.

Country	Documents	Citations	Total Link Strength
China	3	90	2
Italy	4	81	2
Slovenia	2	39	2
United States	6	84	2
Canada	4	205	1
South Korea	2	66	1
Iran	2	48	0
Qatar	2	36	0

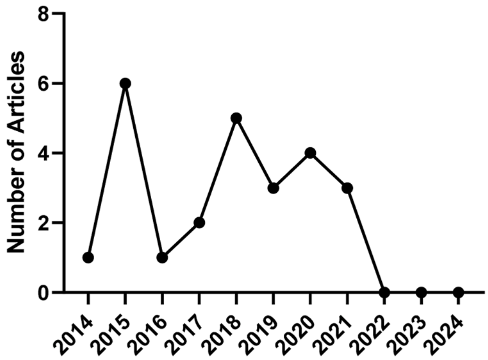

Fig. 4. Temporal Distribution of Eligible Studies.

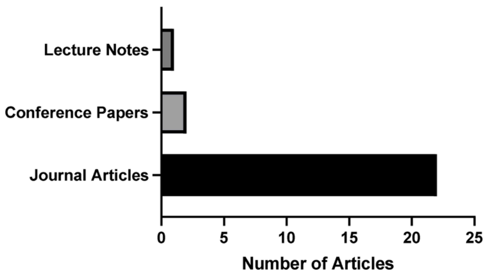

Fig. 5. Publication Distribution.

Table 4
Co-authorship analysis of authors.

Authors	Documents	Citations	Total Link Strength
Giuffre, O	2	39	8
Giuffre, T	2	39	8
Grana, A	2	39	8
Trubia, S	2	39	8
Tumminello, M. L	2	39	8
Essa, M	4	205	4
Sayed, T	4	205	4
So, J	2	34	0

keywords were identified, forming three clusters. Fig. 6 and Table 5 indicate the occurrences and total link strength of the author's keywords.

The keyword analysis reveals the primary focus areas within the research. "Traffic Accident" emerges as the most central keyword with the highest occurrences (14) and link strength (159), underscoring its critical role in the studies. This suggests that traffic accidents are a primary focus, reflecting their importance in both theoretical and practical aspects of road safety. Keywords such as "Human," "Safety Engineering," "Automobile Driving," and "Car Driving" are also prominently featured, indicating that the interaction between human factors, safety engineering, and driving behaviours are crucial areas of study. While keywords like "Traffic Control,"

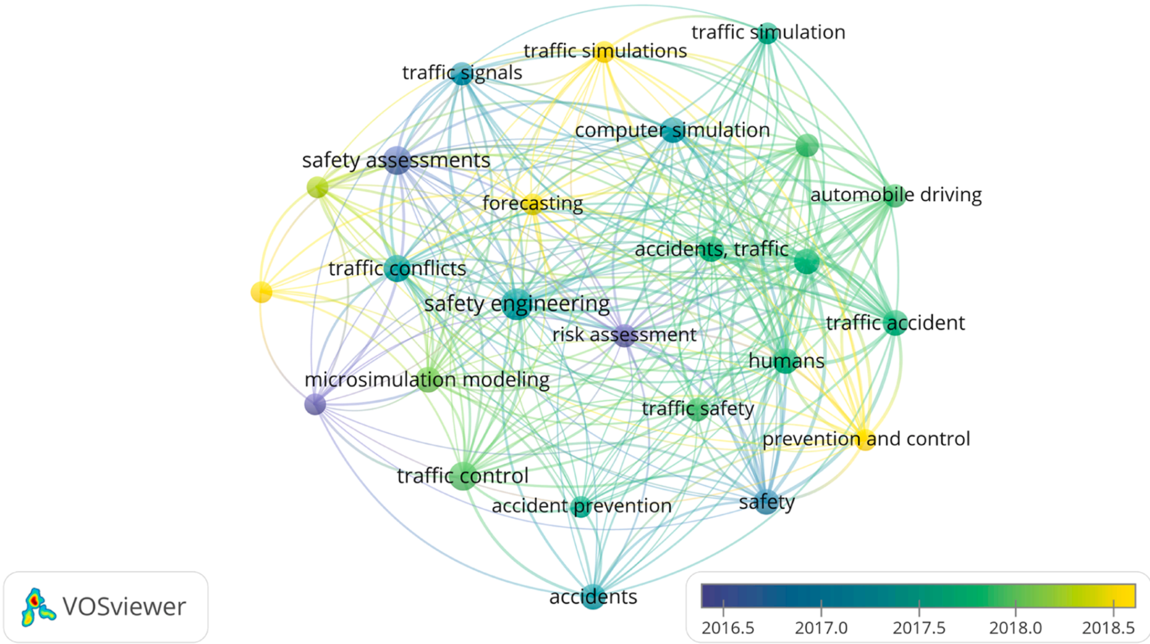

Fig. 6. Occurrences and Total Link Strength of the Top 20 Author Keywords.

Table 5
Occurrences and Total Link Strength of the Top 20 Author Keywords.

Keyword	Occurrences	Total Link Strength
Traffic Accident	14	159
Human	7	80
Safety Engineering	11	70
Automobile Driving	6	70
Car Driving	7	70
Safety	7	68
Traffic Control	9	58
Prevention and Control	5	55
Traffic Conflicts	8	54
Risk Assessments	6	49
Safety Assessments	9	48
Microsimulation Modelling	7	47
Traffic Signals	6	47
Signalized Intersection	5	44
Forecasting	5	37
Traffic Simulations	5	36
Traffic Safety	6	31
Vehicles	5	30
Accident Prevention	5	24
Vehicle Trajectories	5	20

"Prevention and Control," and "Traffic Conflicts" hold moderate link strength, they are essential for understanding the broader context of traffic management and risk mitigation. Keywords with lower link strength, such as "Microsimulation Modelling," "Traffic Signals," and "Vehicle Trajectories," still contribute valuable insights into specific methodologies and interventions related to traffic safety. Therefore, the distribution of keyword occurrences and link strength highlights the multifaceted nature of traffic safety research, with a clear emphasis on accident prevention and safety engineering, while also acknowledging the importance of detailed traffic management strategies and innovative modelling approaches.

4.2.5. Modelling methods

All articles investigate traffic dynamics and evaluate safety actions using simulation models, such as microsimulation, VISSIM, SSAM, and microsimulation models without specifying either VISSIM or SSAM. Twelve studies used the VISSIM: three used SSAM, two utilised both VISSIM and SSAM and eight used microsimulation models without specifying either VISSIM or SSAM, as shown in Fig. 7.

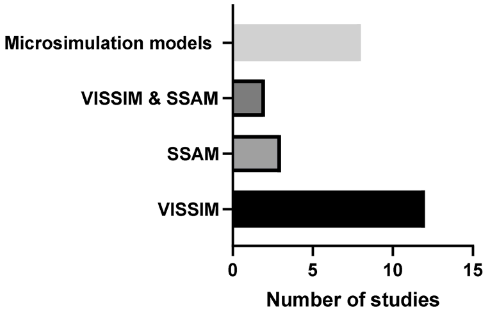

Fig. 7. Utilisation of Simulation Models in Traffic Dynamics and Safety Evaluation.

4.2.6. Study context/scope

Some studies have safety and mobility assessments, while others combine safety and mobility assessments. 23 studies utilised safety assessment, one utilised mobility assessment, and one combined safety and mobility assessment, as shown in Fig. 8.

4.2.7. Intervention

Across the 25 studies analysed, interventions were varied and strategic in addressing traffic safety and operational efficiency. AVs were the subject of 2 studies, focusing on their impact at unsignalized intersections and within mixed fleets. Signal timing adjustments were explored in 4 studies to reduce conflicts and enhance operational efficiency. At the same time, speed humps were specifically implemented in 1 study to mitigate severe conflicts at unconventional median U-turn intersections. Real-time safety algorithms were investigated in 2 studies to predict and prevent conflicts at signalised crossings. Calibration of microsimulation models was a significant focus, with 4 studies utilising methods like Extreme Value Theory (EVT) to enhance crash probability estimations. A broad category encompassing 12 studies explored various other interventions, including machine learning classifiers to identify conflict-prone situations, passing lane design analyses, surrogate safety measures (SSMs) in microsimulation models, and traffic conflict-based surrogate approaches for highway safety assessments. These interventions collectively underscore a diverse approach to traffic management strategies, emphasising technological advancements and methodological innovations in enhancing traffic safety outcomes and operational efficiencies, as shown in Fig. 9.

Although some research concentrates on interventions, such as signalised lane merge control and left turn phasing schemes, others investigate more general safety evaluation techniques, such as traffic conflict analysis and calibration of simulation models.

4.2.8. Population and scope

The population varies in terms of what can be done regarding interventions and outcomes; examples of specific locations include signalised intersections and roundabouts; broader contexts include motorways and highway work zones; these factors impact the choices made regarding interventions and outcomes. Nine studies focused on interventions and outcomes in specific locations (for example, signalised intersections and roundabouts). Sixteen studies focused on interventions and outcomes in broader contexts (for example, motorways and highway work zones), as shown in Fig. 10.

4.2.9. Methodology

The research uses a variety of approaches, including machine learning classifiers, statistical analysis, and sensitivity analysis, which reflects the variety of approaches in traffic safety research. Seven studies used machine learning classifiers appeared seven times in the selected studies. Statistical analysis appeared twenty-two, and sensitivity analysis appeared nine times, as shown in Fig. 11.

4.2.10. Outcome measures

All studies aim to enhance safety outcomes; however, the methods used to measure this vary. These methods include traffic conflict crash prediction models. Fourteen Studies used traffic conflict models. Six studies used crash prediction models, and five used traffic

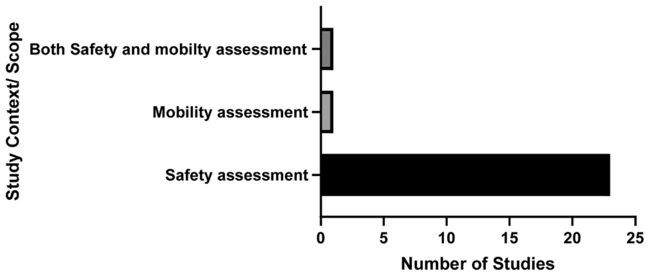

Fig. 8. Characterizing Study Context/ Scope.

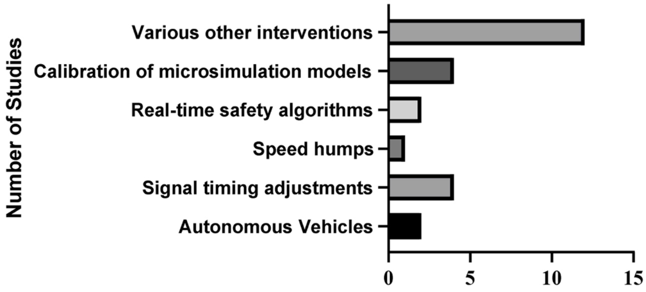

Fig. 9. Intervention Type.

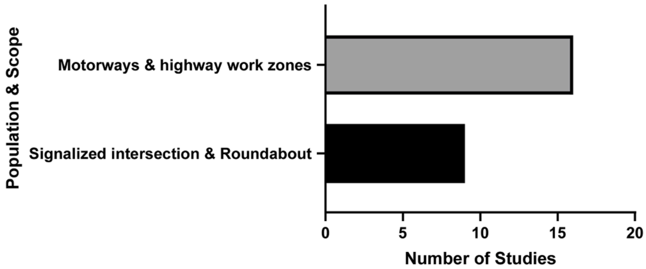

Fig. 10. Population and Scope in Safety Intervention Studies.

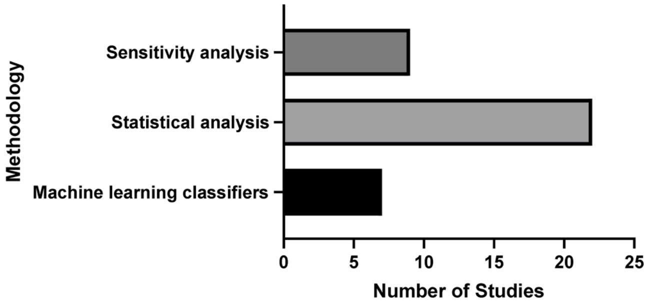

Fig. 11. Methodological Approaches in Traffic Safety Research.

conflicts and crash prediction models, as shown in Fig. 12.

Simulation-based studies on traffic safety offer valuable insights into statistical model development, conflict-prone condition prediction, safety intervention evaluation, and simulation model calibration. However, limitations include dependence on simulated data and validation requirements. Consequently, these research's significant parallels are as follows:

4.2.11. Utilisation of microsimulation modelling

Microsimulation modelling is essential for understanding the complexities of traffic dynamics and assessing safety solutions. This was demonstrated by Appiah et al. [11], who used microsimulation modelling to examine the possibility of left-turn collisions at

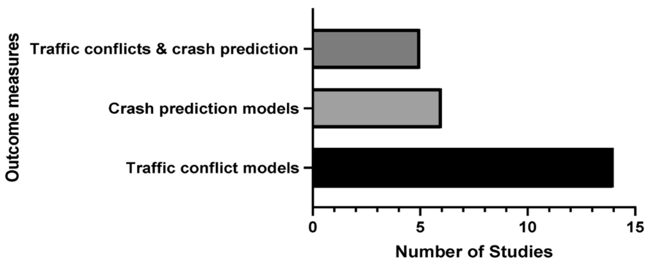

Fig. 12. Outcome Measures in Traffic Safety Research.

signalised junctions and to analyse the effects of various phasing methods on safety parameters. Like this, Katrakazas et al. [18] demonstrated the real-time predictive capabilities of microsimulation in enhancing safety by combining the capacity of microsimulation with machine learning approaches to forecast locations prone to motorway conflicts.

4.2.12. Surrogate safety measures

Traffic disputes and near misses are examples of surrogate safety measures essential in predicting crashes and providing important information about potential safety dangers. The effectiveness of surrogate measures in examining safety initiatives and predicting conflict scenarios was highlighted in studies by So et al. [27]. Ghanim and Shaaban [16] highlight their critical role in advancing traffic safety research.

4.2.13. Development of statistical models

Statistical models based on microsimulation data provide a solid foundation for measuring the efficacy of treatments and estimating safety risks. Li et al. [24] proved the potential advantage of combining statistical methods and microsimulation in safety evaluations by skilfully applying statistical models to assess safety at freeway interchanges.

4.2.14. Simulation-based conflict prediction

Conflict prediction based on simulation provides an anticipatory approach to spotting possible safety risks and evaluating traffic situations. In order to highlight the critical role that simulation-based techniques play in safety assessments, Jeong and Oh [23] used a microscopic traffic simulator to evaluate the effectiveness of active vehicle safety systems.

4.2.15. Evaluation of safety interventions

Improving the results of traffic safety is dependent on the evaluation of safety actions. In order to clarify this, Saad et al. [19] examined safety in controlled toll lane access zones, highlighting the critical function that microsimulation plays in assessing the efficacy of interventions and optimising access designs.

4.2.16. Calibration and sensitivity analysis

Calibration and sensitivity analysis are essential to ensure that microsimulation models are reliable and accurate. The importance of calibration and sensitivity analysis in improving simulation models and enhancing their dependability for safety evaluations was highlighted by Essa & Sayed [12] and Azevedo et al. [32].

4.2.17. Limitations based on simulation data

Studies that use simulated data have inherent limitations, such as relying on simulated data and having difficulty accurately replicating real-world user behaviour, despite their usefulness. These limitations were persuasively discussed by Ghanim et al. [13], who also emphasised the importance of validating using real-world observations.

4.2.18. Intervention effectiveness

Evaluating the efficacy of safety measures is crucial for informing policy choices and improving safety results. The usefulness of countermeasures for red light running was persuasively assessed by Lee et al. [21], highlighting the need for simulation-based surrogate metrics in determining the success of interventions.

4.2.19. Study design and population

Careful thought must go into study design and population selection for research findings to be relevant and valuable. Essa and Sayed [12] persuasively discussed the significance of carefully calibrating simulation models and accounting for variances in driving behaviour when choosing study populations, highlighting the relevance of careful study design in furthering the field of traffic safety research.

4.3. Road safety assessment techniques

4.3.1. Conflict-based road safety assessment via traffic microscopic simulation

Traffic simulation approaches have grown prevalent within transportation engineering due to their ability to examine various facets of transportation networks. Particularly in the safety field, microscopic simulation, also known as microsimulation, has gained popularity, attaining real-world accuracy through numerous approaches and methodological frameworks for surrogate safety evaluation. Notably, the conflict-based approach is extensively applied, enabling transportation engineers to evaluate high-risk zones without relying on actual collision data [33]. The Federal Highway Administration's SSAM software is a crucial tool for simulated confrontations, detecting conflicts based on established parameters like time-to-collision and post-encroachment time [34]. These conflicts are further divided into rear-end, lane change, and crossing conflicts based on the angle of conflict, providing a complete examination of safety implications [35].

The dependability of surrogate safety metrics produced from microscopic simulations has been widely tested, demonstrating significant connections with actual accident data [36]. Studies have confirmed the predicted accuracy of simulated conflicts by comparing them with real-world incidents, indicating the efficacy of conflict-based models in capturing real-world scenarios [37,38]. Innovative ways have also emerged to thoroughly handle the difficulty of simulating probable crashes. Rezapour et al. [39] presented a novel process based on potential crash occurrences within microscopic simulation models, accounting for collisions with barriers and roadside objects.

Similarly, Tarko [40] utilized simulated conflicts to analyse the chance ratio of crash involvement, while Paul and Ghosh [41] developed a method for determining Crash Modification Factors (CMF) based on simulated conflicts officially linked to reported crashes (CMFs). Recently, Guo et al. [8] suggested a methodological framework applying microsimulation conflict-based analysis to estimate crash rates, network properties, and traffic metrics. Their investigation found underestimations of accidents, underscoring the significance of extensive simulation network calibration for more exact and trustworthy crash estimates [42]

4.3.2. Infrastructure risk evaluations

Cui & Xue [43] presented an innovative safety prediction early warning system to equip authorities with sufficient time to respond effectively to risky circumstances. This pioneering study introduced the application of Bayesian Belief Networks (BBN) to enhance traditional agent-based modelling, thereby refining crash probability calculations. The methodology entailed combining real-time observations from a network simulator, enhancing them through a multi-agent model enabling real-time network status updates, and incorporating crash scenarios using Monte Carlo simulation. The outcome was mainly successful, culminating in a BBN model leveraging different data inputs such as traffic levels, road network attributes, weather conditions, and driving habits.

Building upon this foundation, Wang et al. [44] further expanded this research trajectory to validate the safety criteria of road safety measures within the network. Once again, BBN technology was integrated into agent-based simulations. A significant advantage of BBN rests in its capacity to exploit existing knowledge, whether empirical or extrapolated from earlier research estimates. The model's creation relies on elements identified as significant predictors based on their correlation with previous crash records. While the Road Safety Analyzer (RoSA) tool displayed satisfactory performance, the authors highlighted the need for additional modifications.

Microsimulation models can be modified to capture specific infrastructural characteristics, hence strengthening the portrayal of the researched element or environment. For instance, Ma et al. [45] created a microscopic simulation model to assess the security of signalized junctions. This entailed methodically adding critical road user behavioural elements such as pedestrian gap acceptance, turning lane utilization, turn speeds, and stop-go decisions at the commencement of the yellow light. These elements were designed as simulated sub-models and quickly merged into the overarching model. Limited validation was undertaken utilizing an actual intersection supplemented with image processing techniques.

Diverse approaches have also been explored concerning other infrastructural components. For instance, Marcheggiani et al.'s [46] study assessed structural loads from traffic to evaluate bridges. Leveraging pay-toll data, regional registration data, and assumptions about traffic behaviour, the authors applied microscopic simulation to generate origin-destination (OD) values, thereby examining the structural safety of bridges. Although not strictly focused on crash-based or typical road safety assessments, the traffic simulations done in this study effectively addressed this network-level difficulty.

4.3.3. Country- or Road-type-specific approaches

Numerous safety implications have been evaluated, particularly in highway settings, utilizing the traffic conflict technique with microscopic simulation. Islam & Mannering [47] and Park et al. [48] evaluated aggressive driving habits on motorways across various traffic circumstances. The study used travel time and post-encroachment time (PET) indicators to assess the severity of potential crashes, estimating crash risk through simulated conflicts. Similarly, Wu et al. [49] analysed highway junction merging zones, using hourly composite risk indices from simulated conflicts and employing a multivariate linear regression model to estimate crash probability. A recent study investigates the impact of individual characteristics on highway safety, precisely the effect of the left hard shoulder on multi-lane highways [50]. By evaluating conflict features across varied lane counts, this study provides insights into the safety consequences for automobiles negotiating multi-lane roadways.

In rural road conditions, Chen et al. [51], Choudhari et al. [52], and Fadhil & Al-Bayatti [53] conducted a microscopic traffic simulation study to investigate the potential implications of overtaking assistance for two-lane rural roads. Their findings revealed that boosting safety might be achieved without affecting traffic efficiency or driver comfort. This underlines the significance of integrating modern safety measures while retaining road networks' overall performance and comfort. These studies illustrate the versatility and efficiency of microscopic simulation paired with the traffic conflict technique in evaluating safety solutions across varied roadway situations. Researchers can discover potential safety hazards by simulating various scenarios, evaluating conflict data, and proposing targeted interventions to promote roadway safety.

4.3.4. Risk assessments for urban contexts

The microscopic simulation methodologies have been expanded to examine risk assessment in urban networks, addressing numerous safety problems intrinsic to urban environments. For instance, Mousavi et al. [54] did a microscopic simulation study on traffic congestion and safety factors at crossings, notably studying signal settings and various turning-lane assignments. Their analysis, which considered vehicle conflicts and pedestrian interference, shed insight on optimizing intersection design to promote traffic safety. In metropolitan environments, running red lights constitutes a substantial safety concern. Komol et al. [55] developed a traffic simulation-based approach to evaluate countermeasures for red light running, including increasing yellow signal duration and deploying warning signs and cameras. Their study gave valuable insights for controlling this harmful driving habit, especially without solid crash data for statistical analysis.

Furthermore, Deliali et al. [56] assessed the safety benefits of a protected intersection design for bikers, indicating its usefulness in increasing road safety within urban areas. Regarding public transit, Lazar [57] applied microscopic traffic simulation models to examine the road safety consequences of installing bus lanes. The analysis underlined the need to address road safety consequences when developing public transit infrastructure enhancements. In response to the frequent issue of speeding in urban areas, Raju and Farah [58] applied agent-based microsimulation modelling to study the association between speeding, traffic density, and collision rates. Their findings showed the potential of increasing traffic congestion to reduce speeding. They underlined the necessity of adhering to speed restrictions to lower collision risks.

In addition, Farouk et al. [59] and Petrov et al. [60] suggested a privacy-ensuring emergency vehicle approaching warning system (PEEV-WS) inside the framework of vehicular ad hoc networks (VANETs), tested using microscopic simulation to ensure adequate driver reaction times. Similarly, Antony and Whenish [61] evaluated the deployment of Advanced Driver Assistance Systems (ADAS) using microsimulation, emphasizing the significance of incorporating ADAS-induced behavioural changes in monitoring road safety levels. These studies demonstrate the versatility and efficacy of microscopic simulation in tackling a wide array of safety concerns in urban environments, from intersection design optimization to installing advanced safety systems. Using simulation modelling, researchers can efficiently evaluate interventions and initiatives to promote road safety within urban contexts.

4.3.4. Road safety assessment for automated mobility

Given the lack of historically generalizable crash data, particularly in scenarios with high market penetration rates of connected and automated vehicles (CAVs), the microscopic simulation method appears as a crucial approach for assessing the influence of automated mobility on safety. Consequently, significant scientific efforts have been focused on this undertaking. For instance, Ye and Yamamoto [62] conducted microsimulation research to assess the influence of CAVs on intersection traffic safety using SSAM across varied penetration rates of CAV conditions. Similarly, Yang et al. [63] developed a methodology to evaluate the performance of AVSSs equivalent to Level 2 vehicle automation, employing a microscopic traffic simulator and SSAM to generate indirect safety measures. Matin and Dia [64] also validated simulated conflicts and employed SSAM in a case study assessing a recently constructed CAV application. Integrating CAVs with conventional human-driven traffic and vulnerable road users (VRUs), such as pedestrians and cyclists, is a fundamental obstacle to transportation. [65] addressed this issue by studying an intelligent controller deployed at an urban crossroads within a microscopic simulation scenario. Reinforced with game theory applications, their model captured the intricate interactions between different road user groups while negotiating passage through the intersection, albeit with preliminary results revealing implementation hurdles and possible traffic efficiency margins.

In connected automobiles, the continual flood of location data creates privacy concerns. Guido et al. [66] built a microscopic traffic simulation framework for generating silence-based location privacy methods to minimize tracking threats. Furthermore, Astarita et al. [36] conducted microsimulation research to analyse the safety impacts of delayed information on intelligent vehicle control systems, emphasizing substantial repercussions on vehicle operation. Moreover, with the rise of CAVs in transit services, studies have analysed the safety implications of automated point-to-point shuttle bus services [67] and autonomous on-demand mobility services [68] based on simulated traffic conflicts.

Additionally, developments in connected mobility enable the computation of new indicators or the refinement of current ones. Ko et al. [69] computed the crash potential index (CPI), which is compatible with DRAC computation, showing the potential of linked mobility in increasing safety assessment. Tafidis and Pirdavani [70] established proactive fuzzy surrogate safety metrics (PFS and CFS) for assessing automated vehicles' safety. In contrast, Lin and Nguyen [71] leveraged these metrics to develop a fuzzy controller for adaptive cruise control (ACC), validated using real-world data and traffic simulation. Furthermore, it acknowledges the limits of existing models in projecting traffic flows with growing vehicle automation. Bi et al. [72] suggested an enhanced open-source simulation system entitled Open Traffic Sim. This system allows gradual extensions of microscopic models with explanatory mental models, adapting to the evolving needs of traffic simulation models in the foreseeable future.

4.3.5. Risk evaluation of route geometric configuration

Regarding road design, the scarcity of naturalistic driving data typically leads to issues establishing trustworthy road geometric designs and effectively analysing operational and safety performance. Identifying the ideal geometric design needs diligent observation and evaluation of many configurations. Microscopic simulation technologies have become essential in this regard, as they allow for complete testing of numerous configuration situations and evaluate safety and performance. Consequently, microscopic simulation has become a cornerstone in assessing the impacts of various traffic planning and control methods. For instance, multiple recent studies have delved into roundabout traffic operations, examining different configurations to maximize performance and safety [13,15,73]. Hu et al. [74] also conducted a microsimulation study analysing the impacts of passing lanes and merging area lengths, essential elements in passing lane geometric design, to optimize Traffic Flow Efficiency (TFE) and safety.

Moreover, research concentrating on specific features of the road environment provides valuable insights. Guo et al. [75] emphasized probable conflicts with roadside items, providing an add-on to estimate new road safety indicators compatible with Tritone, VISUM, and AIMSUN software. Utilizing the 'Zombie Driver' methodology, the authors assessed road safety levels by considering the economic estimate of dangers posed by various roadside items or impediments. This technique exposes hazardous spots, such as areas with high crash energy values due to trees or steep curves, prone to run-off crash occurrences.

In addition, Appiah et al. [11] also did a study analysing the risk of left-turn crash occurrences at signalized intersections using a calibrated traffic microsimulation model. By simulating numerous situations, they may discover elements contributing to crash risks and suggest intersection design adjustments to boost safety. Collectively, these studies underline the crucial importance of microscopic simulation in analysing and optimizing road design features, from roundabouts to passing lanes, and in identifying potential safety issues linked to roadside objects. By employing simulation modelling, researchers may guide evidence-based decision-making to promote both operational efficiency and safety on roadways.

4.4. Road safety evaluation and new data sources

4.4.1. Automated video image analysis

Researchers have efficiently identified traffic conflicts in various studies by exploiting video data and employing matching video processing algorithms. These attempts serve dual purposes: confirming conflicts derived from traffic simulation and examining the transferability of model parameters. For instance, Rourke [76] applied video data and processing approaches to evaluate simulated conflicts, ensuring the correctness and reliability of simulation outcomes. Kustowski et al. [77] also applied similar approaches to study the transferability of model parameters, boosting the robustness and usefulness of simulation models across multiple contexts. These works have significantly contributed to refining and validating traffic simulation models by integrating video-based approaches into their research methodologies, enhancing our understanding of traffic dynamics and safety consequences.

4.4.2. Real-time traffic data

In a study by Katrakazas et al. [18], highly disaggregated vehicle-based traffic data and conflicts exported from traffic microsimulation were applied to assess real-time crash risk. Specifically, conflicts were derived utilizing SSAM. Three classifiers were used to identify real-time traffic conflict-prone situations: support vector machines, k-nearest neighbours, and random forests. The categorization results underlined the potential of traffic microsimulation and conflict identification from the SSAM for real-time safety evaluation. However, the study stressed the significance of rigorous calibration and validation of the simulation model to ensure the correctness and reliability of the evaluation. By exploiting highly detailed traffic data and advanced classification approaches, the study by Katrakazas et al. [18] and Li et al. [24] illustrates the viability of real-time collision risk estimation using microsimulation-based conflict identification. This approach offers vital insights into boosting road safety by enabling proactive identification and mitigating possible roadway dangers.

4.4.3. Incorporating behaviour into road evaluations

An earlier study by Meng et al. [78] intended to construct a 'nanoscopic' model of driver behaviour using macroscopic simulation, concentrating on traffic safety network assessment. In this technique, the authors augmented simulation models by including driver activities to validate better and resemble actual traffic circumstances. Notably, the models integrated driver intentions as inputs, permitting real-time modifications of the steering subsystem of automobiles. Using driver simulation, Cheng et al. (2019) studied the impact of adaptive cruise control (ACC) on vehicle acceleration and deceleration functions. The data suggested that ACC strongly influences acceleration and deceleration rates, suggesting possible safety benefits while contradicting past research. The study also underlined the dependency of ACC effects on underlying assumptions regarding driving behaviour.

Regarding aggregation methodologies, Bao et al. [79] underscored the importance of rigorous calibration and validation of the simulation model to guarantee the accuracy and reliability of the evaluation. Hoppe et al. [80] evaluated the behaviour of connected driving devices in extreme weather situations using agent-based simulation. Their work revealed insights into connected vehicles' driving and communication characteristics under severe weather using a comprehensive microscopic simulation model.

A recent study by Zhao et al. [50] focused on behavioural elements, presuming that specific driver profiles primarily cause crashes. Using the Next Generation Simulation (NGSIM) 101 dataset, they created aggressive, inattentive, and typical driver profiles. They tested simulated scenarios with varied profile percentages. The crash occurrence was connected to driver profiles. The Simulation of Urban Mobility (SUMO) Traffic Simulator was used to detect collisions and assess crash severity based on driver profiles. Similarly, Hussain et al. [81] deployed a traffic simulator to collect network speed data and recommend appropriate speeds based on traffic volume, weather, and surface conditions, arguing for adaptive local systems to promote road safety. However, their study assumed full compliance with enforced speed limits by simulated drivers. Collectively, these works show the need to integrate driver behaviour into simulation models, solve model calibration and validation issues, and evaluate varied elements influencing road safety, ultimately leading to breakthroughs in transportation safety research.

5. Applications, indicators and drawbacks of SSAM

SSAM is an effective tool for traffic safety analysis, offering a detailed evaluation of traffic interactions and potential conflicts. It enhances road safety through its comprehensive analysis capabilities, using specific indicators while highlighting associated drawbacks. Table 6 highlights the diverse applications of SSAM across various traffic safety studies from 2018 to 2023. For example, Nikolaou et al. [2] utilized SSAM for crash investigation, focusing on indicators such as Time-to-Collision (TTC), Post-Encroachment Time (PET), and Deceleration Rate (DR), emphasizing the necessity for precise and high-quality input data. Singh et al. [82] applied SSAM in intersection safety analysis using PET and Delta V, noting the potential oversight of human factors. Choudhari et al. [52] explored highway safety evaluation with indicators like TTC, PET, Crash Potential Index (CPI), and Maximum Deceleration Rate (MDR), highlighting the data-intensive and computational demands. Wu et al. [49] analysed work zone safety with TTC, PET, Crash Modification Factors (CMF), and Exposure Rate, pointing out the challenge of accurately simulating temporary changes. Komol et al. [55] evaluated safety countermeasures using TTC, PET, and Safety Performance Function (SPF), discussing the complexity of quantifying their effectiveness [83] investigated driver behaviour with TTC, PET, Speed Variation, and Reaction Time, mentioning limitations in behavioural modelling. Bucchiarone et al. [68] assessed public transport interactions using TTC, PET, Conflict Severity, and Bus Interaction Index (BII), with challenges in capturing specific public transport dynamics.

Raju & Farah [58] assessed the safety impact of traffic management with indicators like TTC, PET, Traffic Density, and Congestion Levels, emphasizing the complexity of integrating SSAM with dynamic traffic management systems. Martin-Gasulla & Elefteriadou

Table 6
Applications, Indicators and Drawbacks for SSAM.

Author(s)/Year	Application	Indicators	Drawbacks
Nikolaou et al., [2]	Crash Investigation	TTC, PET, Deceleration Rate	Requires accurate and high-quality input data
Singh et al. [82]	Intersection Safety Analysis	PET, Delta V	It may not account for all human factors
Choudhari et al., [52]	Highway Safety Evaluation	TTC, PET, CPI, MDR	Data-intensive and computationally demanding
Wu et al. [49]	Work Zone Safety	TTC, PET, CMF, Exposure Rate	Difficulties in simulating temporary changes accurately
Komol et al. [55]	Evaluation of Safety Countermeasures	TTC, PET, SPF	Complexity in quantifying the effectiveness of countermeasures
Zhao et al. [50]	Driver Behaviour Analysis	TTC, PET, Speed Variation, Reaction Time	Behavioural modelling limitations
Bucchiarone et al., [68]	Evaluation of Public Transport Interactions	TTC, PET, Conflict Severity, BII	Specifics of public transport dynamics may not be fully captured
Raju & Farah, [58]	Safety Impact of Traffic Management	TTC, PET, Traffic Density, Congestion Levels	Integration with dynamic traffic management systems is complex
Martin-Gasulla & Elefteriadou, [84]	Roundabout Safety Assessment	TTC, PET, IDR, MDR	Limited in capturing complex driver behaviours
Appiah et al., [11]	Pedestrian and Cyclist Safety	TTC, PET, PoC, Severity Index	Challenges in modelling pedestrian and cyclist behaviours
Appiah et al., [11]	Traffic Signal Timing Optimization	TTC, PET, Speed Differential, TFE	Real-time application can be challenging
Appiah et al., [11]; Deliali et al., [56]	Safety Impact of Traffic Calming Measures	TTC, PET, SRR	Limited scope in dynamic traffic environments
Kim et al. [3]	Roadway Design Improvement	TTC, PET, CPA	May overlook micro-level design details
Guo et al. [75]	Automated Vehicle Assessment	TTC, PET, TTR, ISI	Inadequate representation of autonomous vehicle algorithms
Guido et al. [66]	Urban Traffic Safety	TTC, PET, TCF	Insufficient granularity in dense urban settings
Meng et al. [78]	Real-Time Safety Monitoring	Real-time TTC, Real-time PET, DRI	Requires continuous, high-quality data feeds

[84] conducted a roundabout safety assessment using TTC, PET, Initial Deceleration Rate (IDR), and Maximum Deceleration Rate (MDR), noting limitations in capturing complex driver behaviours. [11] applied SSAM to pedestrian and cyclist safety with TTC, PET, Probability of Collision (PoC), and Severity Index, highlighting challenges in modelling pedestrian and cyclist behaviours. The same authors also explored traffic signal timing optimization using TTC, PET, Speed Differential, and Traffic Flow Efficiency (TFE), acknowledging the difficulty of real-time applications. Additionally, they examined the safety impact of traffic calming measures with TTC, PET, and Speed Reduction Rate (SRR), discussing the model's limited scope in dynamic traffic environments. [3] focused on roadway design improvement using TTC, PET, and Conflict Point Analysis (CPA), mentioning potential oversights in micro-level design details. [75] evaluated automated vehicle assessment with TTC, PET, Time-to-React (TTR), and Interaction Severity Index (ISI), noting inadequate representation of autonomous vehicle algorithms. Guido et al. [66] assessed urban traffic safety with TTC, PET, and Traffic Conflict Frequency (TCF), indicating insufficient granularity in dense urban settings. Lastly, [78] used SSAM for real-time safety monitoring with real-time TTC, real-time PET, and Dynamic Risk Index (DRI), stressing the need for continuous, high-quality data feeds.

Fig. 13 visualizes the frequency of various indicators used in traffic safety studies based on Table 6. The chart shows a clear dominance of PET and TTC, which were mentioned 15 and 14 times, respectively, highlighting their foundational role in SSAM applications and widespread acceptance in traffic safety analysis. There was a sharp drop in frequency after these metrics, with MDR

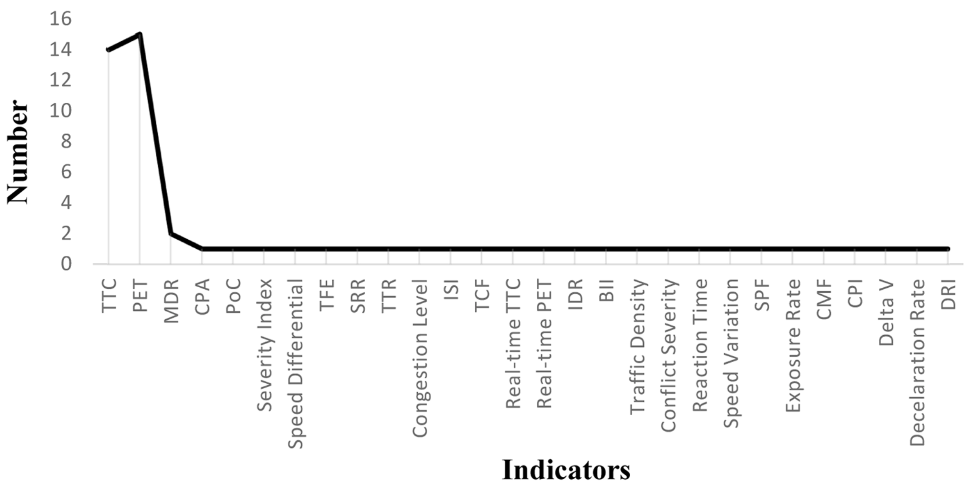

Fig. 13. Frequency of Indicators Used in Traffic Safety Studies.

appearing two times. Other indicators like CPA and PoC appear only once, underscoring the central importance of TTC and PET in capturing potential collision scenarios and near-miss events. The varied application of other metrics, though less frequent, reflects their specialized use or supplementary role in conjunction with TTC and PET, often tailored to specific types of analysis such as evaluating traffic management strategies, public transport interactions, or driver behaviours. This visualization emphasizes the need for consistent application of these critical metrics to ensure comprehensive traffic safety analysis while also suggesting potential areas for further research, particularly in exploring and expanding the use of less frequently applied indicators.

5.1. Principal findings

The studies show that various techniques can significantly improve road safety, such as optimizing left-turn phasing at signalized junctions, evaluating safety measures at roundabouts, and assessing lane merge control strategies. Road safety research encompasses various methodologies to mitigate the risks associated with transportation infrastructure and behaviours [85]. Studies consistently highlight effective techniques for improving road safety. For instance, optimizing left-turn phasing at signalized junctions has been shown to reduce conflicts and enhance traffic flow by minimizing the potential for collisions during turning manoeuvres [86]. Similarly, evaluations of safety measures at roundabouts emphasize the importance of proper signage, geometric design, and traffic calming elements in reducing accident severity and improving overall intersection safety [87]. Additionally, strategies such as effective lane merge control, informed by advanced techniques like microsimulation and machine learning, are crucial in minimizing congestion and enhancing safety during lane transitions [88].

Integrating advanced methodologies such as microsimulation, SSAM, and machine learning algorithms has significantly advanced safety assessments in recent years [89]. These tools enable researchers to simulate and predict potential traffic conflicts and safety hazards in a controlled virtual environment. By leveraging these predictive models, stakeholders can optimize traffic management strategies and proactively inform infrastructure design decisions to reduce road user risks. Practical implications derived from these studies include evidence-based interventions such as optimized traffic signal phasing and lane management strategies, which have shown measurable improvements in traffic safety metrics [90].

Despite technological advancements, road safety assessments face several challenges. One major limitation is the reliance on simulated data, which may not fully capture the complexities of real-world driving behaviours and environmental conditions [91]. Ensuring the accuracy and reliability of simulation models through rigorous calibration and validation processes remains critical to their effectiveness in predicting safety outcomes. Moreover, the complexity of these models poses challenges in balancing sophistication with practical usability, emphasizing the need for ongoing refinement and validation to enhance their applicability in real-world scenarios [2].

Looking ahead, future research directions in road safety emphasize the need for refining simulation models to reflect real-world dynamics better and integrating real-time data sources to improve predictive accuracy. Validating methodologies through comprehensive field studies and longitudinal evaluations will further strengthen the reliability of safety assessments. Addressing the interdisciplinary nature of road safety, from engineering solutions to understanding behavioural aspects, will facilitate holistic approaches in designing safer transportation systems. Researchers aim to significantly reduce road accidents and promote safer environments for all road users by tackling these challenges and advancing innovative solutions.

6. Conclusions

This study has explored a range of methodologies aimed at improving road safety. Key findings reveal that optimising left-turn phasing at signalised junctions, evaluating safety measures at roundabouts, and assessing lane merge control strategies are effective approaches. Advanced tools, such as microsimulation, SSAM, and machine learning algorithms, have proven valuable in predicting and mitigating traffic conflicts and hazards. These tools have significantly improved traffic safety metrics, including optimised signal phasing and more effective lane management.

Despite these advancements, several limitations remain. The reliance on simulated data may not fully capture the complexities of real-world driving behaviours and environmental conditions. Rigorous calibration and validation of these models are essential to ensure their accuracy and reliability. Additionally, balancing the complexity of these models with practical usability remains a challenge, necessitating ongoing refinement to enhance their real-world applicability.

Future research should focus on refining simulation models to better reflect real-world dynamics and integrating real-time data to enhance predictive accuracy. Field studies and longitudinal evaluations will be critical in validating these methodologies and ensuring their effectiveness. Furthermore, addressing the multidisciplinary nature of road safety, encompassing engineering solutions and human behaviour will support the development of more comprehensive and effective transportation systems. Emphasis should be placed on validating models across diverse traffic environments and incorporating dynamic behavioural factors to improve the accuracy of safety assessments and inform policy development in road design, traffic management, and automated vehicle integration.

Funding

The Petroleum Technology Development Fund (PTDF), Nigeria, funded this research, which sponsored the PhD for Aliyu Mustapha.

CRediT authorship contribution statement

Aliyu Mustapha: Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Ahmad Majdi Abdul-Rani:** Conceptualization, Writing – review & editing, Supervision. **Noorhayati Saad:** Resources, Writing – review & editing, Supervision. **Mazli Mustapha:** Visualization, Writing – review & editing, Supervision.

Data availability

No data was used for the research described in the article.

Acknowledgements

This study acknowledges all authors' contributions to the reviewed studies. Mechanical Engineering Department, Universiti Teknologi PETRONAS, Malaysia, Taylors University Malaysia and Industrial and Technology Education Department, Federal University of Technology Minna, Nigeria.

References

[1] F.A. Mullakkal-Babu, M. Wang, B. Van Arem, B. Shyrokau, R. Happee, A Hybrid Submicroscopic-Microscopic Traffic Flow Simulation Framework, IEEE Trans. Intell. Transp. Syst. 22 (6) (2021) 3430–3443, https://doi.org/10.1109/TITS.2020.2990376.
[2] D. Nikolaou, A. Dragomanovits, A. Ziakopoulos, A. Deliali, I. Handanos, C. Karadimas, G. Kostoulas, E.K. Frantzola, G. Yannis, Exploiting surrogate safety measures and road design characteristics towards crash investigations in motorway segments, Infrastructures. (Basel) 8 (3) (2023), https://doi.org/10.3390/infrastructures8030040.
[3] W. Kim, A.M. Svancara, T. Kelley-Baker, Understanding the impact of road design characteristic on teen driver's fatality, Traffic. Inj. Prev. 21 (5) (2020) 313–318, https://doi.org/10.1080/15389588.2020.1753038.
[4] S.M.S. Mahmud, L. Ferreira, M.S. Hoque, A. Tavassoli, Micro-simulation modelling for traffic safety: a review and potential application to heterogeneous traffic environment, IATSS Res. 43 (1) (2019) 27–36, https://doi.org/10.1016/j.iatssr.2018.07.002.
[5] A. Mustapha, A.M. Abdul-Rani, N.B. Saad, Assessment of road signs comprehension levels among oil and gas tanker drivers in North-central, Nigeria, in: R.D. S. Campilho, K. Thamizhmaran, R. Ramesh (Eds.), 9th International "Baskent" Congress on Physical, Engineering, and Applied Sciences Proceedings Book, BZT Academy Publishing House, 2023, pp. 386–398.
[6] A. Mustapha, A.M. Abdul-rani, N. Saad, M. Mustapha, Ergonomic principles of road signs comprehension: a literature review, Transp. Res. Part F: Psychol. Behav. 101 (2024) 279–305, https://doi.org/10.1016/j.trf.2023.12.020.
[7] U.E. Shahdah, A. Azam, Safety and mobility effects of installing speed-humps within unconventional median U-turn intersections, Ain Shams Eng. J. 12 (2) (2021) 1451–1462, https://doi.org/10.1016/j.asej.2020.08.033.
[8] Y. Guo, T. Sayed, L. Zheng, M. Essa, An extreme value theory based approach for calibration of microsimulation models for safety analysis, Simul. Model. Pract. Theory. 106 (2021), https://doi.org/10.1016/j.simpat.2020.102172.
[9] M. Khashayarfard, H. Nassiri, Studying the simultaneous effect of autonomous vehicles and distracted driving on safety at unsignalized intersections, J. Adv. Transp. 2021 (2021), https://doi.org/10.1155/2021/6677010.
[10] A. Sinha, S. Chand, K.P. Wijayaratna, N. Virdi, V. Dixit, Comprehensive safety assessment in mixed fleets with connected and automated vehicles: a crash severity and rate evaluation of conventional vehicles, Accid. Anal. Prevent. 142 (2020), https://doi.org/10.1016/j.aap.2020.105567.
[11] J. Appiah, F.A. King, M.D. Fontaine, B.H. Cottrell, Left turn crash risk analysis: development of a microsimulation modeling approach, Accid. Anal. Prevent. 144 (2020), https://doi.org/10.1016/j.aap.2020.105591.
[12] M. Essa, T. Sayed, Comparison between surrogate safety assessment model and real-time safety models in predicting field-measured conflicts at signalized intersections, Transp. Res. Rec. 2674 (3) (2020) 100–112, https://doi.org/10.1177/0361198120907874.
[13] M. Ghanim, M. Kharbeche, J. Hannun, J. Hannun, K. Shamiyeh, Safety and operational performance of signalized roundabouts: a case study in Doha, Procedia Comput. Sci. 170 (2020) 427–433, https://doi.org/10.1016/j.procs.2020.03.085.
[14] U. 8215/1 University of Zilina Zilina C. Gruden, T. Campisi, A. Canale, G. Tesoriere, M. Sraml, A cross-study on video data gathering and microsimulation techniques to estimate pedestrian safety level in a confined space, in: I. Y, M. M, M. D, A.M. D, D. T, D. N (Eds.), IOP Conference Series: Materials Science and Engineering 603, Institute of Physics Publishing, 2019, https://doi.org/10.1088/1757-899X/603/4/042008.
[15] O. Giuffrè, A. Granà, M.L. Tumminello, T. Giuffrè, S. Trubia, Surrogate measures of safety at roundabouts in AIMSUN and VISSIM environment, in: Lecture Notes in Networks and Systems, 52, Springer, 2019, pp. 53–64, https://doi.org/10.1007/978-3-319-98618-0_5.
[16] M.S. Ghanim, K. Shaaban, A case study for surrogate safety assessment model in predicting real-life conflicts, Arab. J. Sci. Eng. 44 (5) (2019) 4225–4231, https://doi.org/10.1007/s13369-018-3326-8.
[17] O. Giuffrè, A. Granà, M.L. Tumminello, T. Giuffrè, S. Trubia, A. Sferlazza, M. Rencelj, Evaluation of roundabout safety performance through surrogate safety measures from microsimulation, J. Adv. Transp. 2018 (2018), https://doi.org/10.1155/2018/4915970.
[18] C. Katrakazas, M. Quddus, W.H. Chen, A simulation study of predicting real-time conflict-prone traffic conditions, IEEE Trans. Intell. Transp. Syst. 19 (10) (2018) 3196–3207, https://doi.org/10.1109/TITS.2017.2769158.
[19] M. Saad, M. Abdel-Aty, J. Lee, L. Wang, Safety analysis of access zone design for managed toll lanes on freeways, J. Transp. Eng., Part A: Syst. 144 (11) (2018) 1–13, https://doi.org/10.1061/jtepbs.0000191.
[20] S. Cafiso, C. D'Agostino, M. Kieć, R Bak, Safety assessment of passing relief lanes using microsimulation-based conflicts analysis, Accid. Anal. Prevent. 116 (April 2017) (2018) 94–102, https://doi.org/10.1016/j.aap.2017.07.001.
[21] C. Lee, J.(Jason) So, J. Ma, Evaluation of countermeasures for red light running by traffic simulator–based surrogate safety measures, Traffic. Inj. Prev. 19 (1) (2018) 1–8, https://doi.org/10.1080/15389588.2017.1328551.
[22] Y. Qi, Q. Zhao, Safety impacts of signalized lane merge control at highway work zones, Transp. Plan. Technol. 40 (5) (2017) 577–591, https://doi.org/10.1080/03081060.2017.1314499.
[23] E. Jeong, C. Oh, Evaluating the effectiveness of active vehicle safety systems, Accid. Anal. Prevent. 100 (2017) 85–96, https://doi.org/10.1016/j.aap.2017.01.015.
[24] S. Li, Q. Xiang, Y. Ma, X. Gu, H. Li, Crash risk prediction modeling based on the traffic conflict technique and a microscopic simulation for freeway interchange merging areas, Int. J. Environ. Res. Public Health 13 (11) (2016), https://doi.org/10.3390/ijerph13111157.
[25] M. Essa, T. Sayed, Simulated traffic conflicts: do they accurately represent field-measured conflicts? Transp. Res. Rec. 2514 (2015) 48–57, https://doi.org/10.3141/2514-06.
[26] H. Behbahani, N. Nadimi, S.S. Naseralavi, New time-based surrogate safety measure to assess crash risk in car-following scenarios, Transp. Lett. 7 (4) (2015) 229–238, https://doi.org/10.1179/1942787514Y.0000000051.

[27] J. So, B. Park, S.M. Wolfe, G. Dedes, Development and validation of a vehicle dynamics integrated traffic simulation environment assessing surrogate safety, J. Comput. Civil Eng. 29 (5) (2015) 1–13, https://doi.org/10.1061/(ASCE)cp.1943-5487.0000403.
[28] M. Essa, T. Sayed, Transferability of calibrated microsimulation model parameters for safety assessment using simulated conflicts, Accid. Anal. Prevent. 84 (2015) 41–53, https://doi.org/10.1016/j.aap.2015.08.005.
[29] J. So, I.K. Lim, Y.J. Kweon, Exploring traffic conflict-based surrogate approach for safety assessment of highway facilities, Transp. Res. Rec. 2513 (2015) 56–62, https://doi.org/10.3141/2513-07.
[30] P. Vedagiri, D.V. Killi, Traffic safety evaluation of uncontrolled intersections using surrogate safety measures under mixed traffic conditions, Transp. Res. Rec. 2512 (2015) 81–89, https://doi.org/10.3141/2512-10.
[31] F.G. Habtemichael, L De Picado Santos, Crash risk evaluation of aggressive driving on motorways: microscopic traffic simulation approach, Transp. Res. Part F: Traffic Psychol. Behav. 23 (2014) 101–112, https://doi.org/10.1016/j.trf.2013.12.022.
[32] C. Lima Azevedo, B. Ciuffo, J.L. Cardoso, M.E. Ben-Akiva, Dealing with uncertainty in detailed calibration of traffic simulation models for safety assessment, Transp. Res. Part C: Emerg. Technol. 58 (2015) 395–412, https://doi.org/10.1016/j.trc.2015.01.029.
[33] A. Arun, M.M. Haque, S. Washington, T. Sayed, F. Mannering, A systematic review of traffic conflict-based safety measures with a focus on application context, Anal. Methods Accid. Res. 32 (2021), https://doi.org/10.1016/j.amar.2021.100185.
[34] J. Joseph, A.M. Rao, S. Velmurugan, S.S. Puwar, Analysis of surrogate safety performance parameters for an interurban corridor, J. Sci. Ind. Res. (India) 80 (11) (2021) 956–965, https://doi.org/10.56042/jsir.v80i11.41272.
[35] B.K. Pathivada, P. Vedagiri, Investigating dilemma zone boundaries for mixed traffic conditions using support vector machines, Transp. Lett. 14 (4) (2022) 378–384, https://doi.org/10.1080/19427867.2020.1870307.
[36] V. Astarita, C. Caliendo, V. Pasquale, I. Russo, Surrogate safety measures from traffic simulation: validation of safety indicators with intersection traffic crash data, Sustainability (Switzerland) 12 (17) (2020), https://doi.org/10.3390/SU12176974.
[37] S. Bouhsissin, N. Sael, F. Benabbou, Driver behavior classification: a systematic literature review, IEEe Access. 11 (2023) 14128–14153, https://doi.org/10.1109/ACCESS.2023.3243865.
[38] L. Zheng, T. Sayed, M. Essa, Y. Guo, Do Simulated traffic conflicts predict crashes? An investigation using the extreme value approach, in: 2019 IEEE Intelligent Transportation Systems Conference, ITSC 2019, 2019, pp. 631–636, https://doi.org/10.1109/ITSC.2019.8916905.
[39] M. Rezapour, S.S. Wulff, K. Ksaibati, Examination of the severity of two-lane highway traffic barrier crashes using the mixed logit model, J. Safety. Res. 70 (2019) 223–232, https://doi.org/10.1016/j.jsr.2019.07.010.
[40] A.P. Tarko, Studies on the conflict-crash relationship, Measur. Road Saf. Using Surrogate Events (2020) 67–87, https://doi.org/10.1016/b978-0-12-810504-7.00005-7.
[41] M. Paul, I. Ghosh, Development of conflict severity index for safety evaluation of severe crash types at unsignalized intersections under mixed traffic, Saf. Sci. 144 (2021), https://doi.org/10.1016/j.ssci.2021.105432.
[42] G. McSwiggan, A. Baddeley, G. Nair, Estimation of relative risk for events on a linear network, Stat. Comput. 30 (2) (2020) 469–484, https://doi.org/10.1007/s11222-019-09889-7.
[43] Cui, D., & Xue, S. (2022). *A risk early warning perception system for safety production based on IoT technology*. 17. 10.1117/12.2645390.
[44] R. Wang, Z. Liu, S. Yang, J. Wang, Implementation of driving safety early warning system based on trajectory prediction on the internet of vehicles environment, Secur. Commun. Netw. 2022 (2022), https://doi.org/10.1155/2022/2922507.
[45] Y. Ma, Z. Zhang, J. Wu, Conflict probability prediction and safety assessment of straight-left traffic flow at signalized intersections, J. Adv. Transp. 2022 (2022), https://doi.org/10.1155/2022/8233424.
[46] L. Marcheggiani, F. Clementi, A. Formisano, Static and dynamic testing of highway bridges: a best practice example, J. Civ. Struct. Health Monit. 10 (1) (2020) 43–56, https://doi.org/10.1007/s13349-019-00368-1.
[47] M. Islam, F. Mannering, A temporal analysis of driver-injury severities in crashes involving aggressive and non-aggressive driving, Anal. Methods Accid. Res. 27 (2020), https://doi.org/10.1016/j.amar.2020.100128.
[48] S. Park, C. Oh, Y. Kim, S. Choi, S. Park, Understanding impacts of aggressive driving on freeway safety and mobility: a multi-agent driving simulation approach, Transp. Res. Part F: Traffic Psychol. Behav. 64 (2019) 377–387, https://doi.org/10.1016/j.trf.2019.05.017.
[49] B. Wu, C. Zou, Y. Li, D. Fan, S. Zhu, Impact of road environment on drivers' preference to merging location selection in freeway work zone merging areas, J. Adv. Transp. 2022 (2022), https://doi.org/10.1155/2022/2996081.
[50] L. Zhao, N. Farhi, Z. Christoforou, N. Haddadou, Analysis of driver behavior and Intervehicular collision: a data-based traffic modeling and simulation approach, J. Adv. Transp. 2022 (2022), https://doi.org/10.1155/2022/1068311.
[51] J. Chen, K. Wang, H. Bao, T. Chen, A design of cooperative overtaking based on complex lane detection and collision risk estimation, IEEe Access. 7 (2019) 87951–87959, https://doi.org/10.1109/ACCESS.2019.2922113.
[52] T. Choudhari, A. Budhkar, A. Maji, Modeling overtaking distance and time along two-lane undivided rural highways in mixed traffic condition, Transp. Lett. 14 (2) (2022) 75–83, https://doi.org/10.1080/19427867.2020.1815142.
[53] S.A. Fadhil, A.H Al-Bayatti, Developing a new driver assistance system for overtaking on two-lane roads using predictive models, Periodica Polytechnica Transp. Eng. 50 (4) (2022) 400–413, https://doi.org/10.3311/PPtr.19218.
[54] S.M. Mousavi, O.A. Osman, D. Lord, K.K. Dixon, B. Dadashova, Investigating the safety and operational benefits of mixed traffic environments with different automated vehicle market penetration rates in the proximity of a driveway on an urban arterial, Accid. Anal. Prevent. 152 (2021), https://doi.org/10.1016/j.aap.2021.105982.
[55] M.M.R. Komol, J. Pinnow, M. Elhenawy, S. Yasmin, M. Masoud, S. Glaser, A. Rakotonirainy, A review on Drivers' red light running behavior predictions and technology based countermeasures, IEEe Access. 10 (2022) 25309–25326, https://doi.org/10.1109/ACCESS.2022.3154088.
[56] A. Deliali, N. Campbell, M. Knodler, E. Christofa, Understanding the safety impact of protected intersection design elements: a driving simulation approach, Transp. Res. Rec. 2674 (3) (2020) 179–188, https://doi.org/10.1177/0361198120909382.
[57] H. Lazar, Comparison of MICROSCOPIC CAR following models, in: Proceedings - 2019 4th International Conference on Systems of Collaboration, Big Data, Internet of Things and Security, SysCoBIoTS 2019, 2019, https://doi.org/10.1109/SysCoBIoTS48768.2019.9028040.
[58] N. Raju, H. Farah, Evolution of traffic microsimulation and its use for modeling connected and automated vehicles, J. Adv. Transp. 2021 (2021), https://doi.org/10.1155/2021/2444363.
[59] F. Farouk, Y. Alkady, R. Rizk, Efficient privacy-preserving scheme for location based services in VANET system, IEEe Access. 8 (2020) 60101–60116, https://doi.org/10.1109/ACCESS.2020.2982636.
[60] T. Petrov, P. Pocta, J. Roman, L. Buzna, M. Dado, A feasibility study of privacy ensuring emergency vehicle approaching warning system, Appl. Sci. (Switzerland) 10 (1) (2020), https://doi.org/10.3390/app10010298.
[61] M.M. Antony, R. Whenish, Advanced driver assistance systems (ADAS), EAI/Springer Innovat. Commun. Comput. (2021) 165–181, https://doi.org/10.1007/978-3-030-59897-6_9.
[62] L. Ye, T. Yamamoto, Evaluating the impact of connected and autonomous vehicles on traffic safety, Physica A: Stat. Mech. Appl. 526 (2019), https://doi.org/10.1016/j.physa.2019.04.245.
[63] J. Yang, T. Guo, Y. Chen, Optimization of signalized intersection based on VISSIM-SSAM simulation, 28, 2022, https://doi.org/10.1117/12.2627799.
[64] A. Matin, H. Dia, Impacts of connected and automated vehicles on road safety and efficiency: a systematic literature review, IEEE Trans. Intell. Transp. Syst. 24 (3) (2023) 2705–2736, https://doi.org/10.1109/TITS.2022.3227176.
[65] Z. Guo, D. Sun, L. Zhou, Game algorithm of intelligent driving vehicle based on left-turn scene of crossroad traffic flow, Comput. Intell. Neurosci. 2022 (2022), https://doi.org/10.1155/2022/9318475.
[66] G. Guido, A. Vitale, V. Astarita, V.P. Giofrè, Comparison analysis between real accident locations and simulated risk areas in an urban road network, Safety 5 (3) (2019), https://doi.org/10.3390/safety5030060.

[67] D. Tsiktsiris, N. Dimitriou, A. Lalas, M. Dasygenis, K. Votis, D. Tzovaras, Real-time abnormal event detection for enhanced security in autonomous shuttles mobility infrastructures, Sensors (Switzerland) 20 (17) (2020) 1–24, https://doi.org/10.3390/s20174943.
[68] A. Bucchiarone, S. Battisti, A. Marconi, R. Maldacea, D.C. Ponce, Autonomous Shuttle-as-a-Service (ASaaS): challenges, opportunities, and social implications, IEEE Trans. Intell. Transp. Syst. 22 (6) (2021) 3790–3799, https://doi.org/10.1109/TITS.2020.3025670.
[69] J. Ko, J. Jang, C. Oh, A multi-agent driving simulation approach for evaluating the safety benefits of connected vehicles, IEEE Trans. Intell. Transp. Syst. 23 (5) (2022) 4512–4524, https://doi.org/10.1109/TITS.2020.3045675.
[70] P. Tafidis, A. Pirdavani, Application of surrogate safety measures in higher levels of automated vehicles simulation studies: a review of the state of the practice, Traffic. Inj. Prev. 24 (3) (2023) 279–286, https://doi.org/10.1080/15389588.2023.2176711.
[71] Y.C. Lin, H.L.T. Nguyen, Adaptive neuro-fuzzy predictor-based control for cooperative adaptive cruise control system, IEEE Trans. Intell. Transp. Syst. 21 (3) (2020) 1054–1063, https://doi.org/10.1109/TITS.2019.2901498.
[72] H. Bi, T. Mao, Z. Wang, Z. Deng, A deep learning-based framework for intersectional traffic simulation and editing, IEEe Trans. Vis. Comput. Graph. 26 (7) (2020) 2335–2348, https://doi.org/10.1109/TVCG.2018.2889834.
[73] O. Giuffrè, A. Granà, M.L. Tumminello, T. Giuffrè, S. Trubia, A. Sferlazza, M. Rencelj, Evaluation of roundabout safety performance through surrogate safety measures from microsimulation, J. Adv. Transp. 2018 (2018), https://doi.org/10.1155/2018/4915970.
[74] J. Hu, L. He, R. Wang, Safety evaluation of freeway interchange merging areas based on driver workload theory, Sci. Prog. 103 (3) (2020), https://doi.org/10.1177/0036850420940878.
[75] Y. Guo, M. Essa, T. Sayed, M.M. Haque, S. Washington, A comparison between simulated and field-measured conflicts for safety assessment of signalized intersections in Australia, Transp. Res. Part C: Emerg. Technol. 101 (2019) 96–110, https://doi.org/10.1016/j.trc.2019.02.009.
[76] S. Rourke, How does virtual reality simulation compare to simulated practice in the acquisition of clinical psychomotor skills for pre-registration student nurses? A systematic review, Int. J. Nurs. Stud. 102 (2020), https://doi.org/10.1016/j.ijnurstu.2019.103466.
[77] B. Kustowski, J.A. Gaffney, B.K. Spears, G.J. Anderson, J.J. Thiagarajan, R. Anirudh, Transfer learning as a tool for reducing simulation bias: application to inertial confinement fusion, IEEE Trans. Plasma Sci. 48 (1) (2020) 46–53, https://doi.org/10.1109/TPS.2019.2948339.
[78] X. Meng, Q. Cheng, X. Jiang, Z. Fang, X. Chen, S. Li, C. Li, C. Sun, W. Wang, Z.L. Wang, Triboelectric nanogenerator as a highly sensitive self-powered sensor for driver behavior monitoring, Nano Energy 51 (2018) 721–727, https://doi.org/10.1016/j.nanoen.2018.07.026.
[79] N. Bao, A. Carballo, T. Kazuya, Prediction of personalized driving behaviors via driver-adaptive deep generative models, in: *IEEE Intelligent Vehicles Symposium, Proceedings, 2021-July*, 2021, pp. 616–621, https://doi.org/10.1109/IV48863.2021.9575671.
[80] M. Hoppe, J.C. Kirchhof, E. Kusmenko, C.Y. Lee, B. Rumpe, Agent-based autonomous vehicle simulation with hardware emulation in the loop, in: IEEE Intelligent Vehicles Symposium, Proceedings, 2022, pp. 16–21, https://doi.org/10.1109/IV51971.2022.9827215. *2022-June*.
[81] Q. Hussain, W.K.M. Alhajyaseen, A. Pirdavani, N. Reinolsmann, K. Brijs, T. Brijs, Speed perception and actual speed in a driving simulator and real-world: a validation study, Transp. Res. Part F: Traffic Psychol. Behav. 62 (2019) 637–650, https://doi.org/10.1016/j.trf.2019.02.019.
[82] D. Singh, P. Das, N.M. Parvez, Surrogate safety evaluation at uncontrolled intersection in non-lane base traffic conditions, Eur. Transp. - Trasporti Europei 93 (2023), https://doi.org/10.48295/ET.2023.93.11.
[83] P. Zhao, J. Ma, C. Xu, C. Zhao, Z. Ni, Research on the safety of the left hard shoulder in a multi-lane highway based on safety performance function, Sustainability (Switzerland) 14 (22) (2022), https://doi.org/10.3390/su142215114.
[84] M. Martin-Gasulla, L. Elefteriadou, Traffic management with autonomous and connected vehicles at single-lane roundabouts, Transp. Res. Part C: Emerg. Technol. 125 (2021), https://doi.org/10.1016/j.trc.2021.102964.
[85] A.S. Bovkun, L.A. Cherdakova, O.V. Arkhipkin, I.A. Korodyuk, E.A. Slepenko, Methodical approach to minimizing risks in road construction, in: Proceedings - 2021 3rd International Conference on Control Systems, Mathematical Modeling, Automation and Energy Efficiency, SUMMA 2021, 2021, pp. 397–400, https://doi.org/10.1109/SUMMA53307.2021.9632120.
[86] K. Chen, J. Zhao, V.L. Knoop, X. Gao, Robust signal control of exit lanes for left-turn intersections with the consideration of traffic fluctuation, IEEe Access. 8 (2020) 42071–42081, https://doi.org/10.1109/ACCESS.2020.2977134.
[87] V.S. Vinayaraj, V. Perumal, Analyzing the factors affecting the crash severity level at urban roundabouts in non-lane-based heterogeneous traffic, Int. J. Inj. Contr. Saf. Promot. 31 (2) (2024) 181–193, https://doi.org/10.1080/17457300.2023.2279967.
[88] U. Hasan, H. AlJassmi, A. Hasan, Microsimulation modelling and scenario analysis of a congested Abu Dhabi highway, Eng 4 (3) (2023) 2003–2014, https://doi.org/10.3390/eng4030113.
[89] S. Coropulis, N. Berloco, R. Gentile, P. Intini, V. Ranieri, Traffic microsimulation for road safety assessments of vehicle automation scenarios: Model comparison and sensitivity analysis, Simul. Model. Pract. Theory. 130 (2024), https://doi.org/10.1016/j.simpat.2023.102868.
[90] R. Dai, C. Ding, X. Wu, B. Yu, G. Lu, Coupling control of traffic signal and entry lane at isolated intersections under the mixed-autonomy traffic environment, IEEE Trans. Intell. Transp. Syst. 24 (10) (2023) 10628–10642, https://doi.org/10.1109/TITS.2023.3280953.
[91] K. Čulík, A. Kalašová, V. Štefancová, Evaluation of Driver's reaction time measured in driving simulator, Sensors 22 (9) (2022), https://doi.org/10.3390/s22093542.