Implementing traffic simulation for road safety assessment: A systematic literature review

Maria Oikonomou[1], Apostolos Ziakopoulos[2], George Yannis[3]

[1]National Technical University of Athens, Department of Transportation Planning and Engineering,
5 Heroon Polytechniou Str., Athens, GR-15773, Greece
E-mail: moikonomou@mail.ntua.gr
[2]National Technical University of Athens, Department of Transportation Planning and Engineering,
5 Heroon Polytechniou Str., Athens, GR-15773, Greece
E-mail: apziak@central.ntua.gr
[3]National Technical University of Athens, Department of Transportation Planning and Engineering,
5 Heroon Polytechniou Str., Athens, GR-15773, Greece
E-mail: geyannis@central.ntua.gr

Abstract

The family of traffic simulation methodologies has been widely used and become a common practice in transportation engineering by offering capabilities to analyze complex transportation aspects. In terms of safety, the use of microscopic simulation is becoming progressively feasible as well, as several approaches using suitable methodological frameworks quantifying surrogate safety measures become readily available. The present study attempts to review the existing literature findings systematically and to further identify road safety assessment aspects in which traffic simulation is applicable. Through the present systemic review, the schemes of safety evaluation that traffic simulation can be applied were identified. The trend of past research shows promising applications of traffic simulation in several pillars & approaches of improving road safety. Hence, developers of traffic simulation software, practitioners and researchers can be supported in enhancing the existing microsimulation applications by enabling the acquisition of proactive and reactive surrogate safety measures.

Keywords: *Traffic simulation, Microsimulation, Road safety, Risk assessment.*

Περίληψη

Η προσομοίωση της κυκλοφορίας έχει χρησιμοποιηθεί ευρέως και έχει γίνει κοινή πρακτική στον σχεδιασμό των μεταφορών, προσφέροντας τη δυνατότητα ανάλυσης πολύπλοκων πτυχών. Όσον αφορά την ασφάλεια, η χρήση της μικροσκοπικής προσομοίωσης καθίσταται επίσης εφικτή, καθώς διάφορες προσεγγίσεις που χρησιμοποιούν κατάλληλα μεθοδολογικά πλαίσια και ποσοτικοποιούν υποκατάστατα μέτρα ασφάλειας καθίστανται άμεσα διαθέσιμες. Η παρούσα μελέτη επιχειρεί να εξετάσει συστηματικά τα ευρήματα της υπάρχουσας βιβλιογραφίας και να προσδιορίσει περαιτέρω τις πτυχές αξιολόγησης της οδικής ασφάλειας, στις οποίες είναι εφαρμόσιμη η προσομοίωση της κυκλοφορίας. Μέσω της συστηματικής ανασκόπησης προσδιορίστηκαν τα στοιχεία αξιολόγησης της ασφάλειας που μπορεί να εφαρμοστεί η προσομοίωση της κυκλοφορίας. Η τάση των υπαρχουσών ερευνών έδειξε υποσχόμενες εφαρμογές της προσομοίωσης της κυκλοφορίας σε διαφόρους τομείς ερευνών βελτίωσης της οδικής ασφάλειας. Ως εκ τούτου, οι προγραμματιστές ανάπτυξης λογισμικών προσομοίωσης, οι επαγγελματίες συγκοινωνιολόγοι και οι ερευνητές θα μπορούσαν να ενισχύσουν την υπάρχουσα εφαρμογή της υποστηρίζοντας τον υπολογισμό έμμεσων δεικτών ασφάλειας.

Λέξεις-κλειδιά: *Προσομοίωση κυκλοφορίας, μικροσκοπική προσομοίωση, Οδική ασφάλεια, Αξιολόγηση κινδύνου,*

1. Introduction

Traffic simulation analysis have gained significant traction in transportation engineering, providing valuable insights into complex transportation dynamics. Specifically, microscopic simulation refers to the modeling and analysis of individual vehicles and their interactions within a traffic system. It simulates the behavior and movements of each vehicle, taking into account factors such as acceleration, deceleration, lane changes, and interactions with other vehicles and infrastructure elements. By simulating traffic at a microscopic level, transportation engineers can gain a detailed understanding of the dynamics and potential risks within a road network.

This methodology offers the ability to analyze various aspects of traffic systems, including road safety as well. More specifically, microscopic simulation has emerged as a feasible approach for evaluating safety by utilizing surrogate safety measures and methodological frameworks. Surrogate safety measures are indicators that correlate with the likelihood or severity of crashes, allowing engineers to assess safety without relying solely on actual crash data. Examples of surrogate measures commonly used in microscopic simulation include time-to-collision, gap-acceptance behavior and traffic conflicts. These measures provide valuable insights into potential safety issues and can guide the development of effective countermeasures.

By employing microscopic simulation, transportation engineers can assess and evaluate safety-related aspects of transportation systems more effectively. They can investigate the impact of various factors, such as geometric design features, traffic signal timings, speed limits, and driver behavior, on safety performance. The ability to simulate high-risk locations and complex traffic scenarios without the need for real-world crash data is particularly beneficial. This approach allows engineers to identify potential safety issues proactively, develop targeted interventions, and evaluate their effectiveness before implementing them on real-road networks.

All these stands as a motivation for the present paper, which aims to emphasize the applications of traffic simulation on road safety assessment by synthesizing past research findings. This study establishes a comprehensive understanding of the applications and benefits of traffic simulation methodologies. The systematic review serves as a valuable resource for transportation engineers and researchers, facilitating informed decision-making and contributing to the ongoing efforts in improving road safety. Overall, this comprehensive review paper provides an in-depth analysis of the role of traffic simulation in evaluating safety, highlighting its importance, feasibility, and applicability in various road safety assessment aspects. Finally, the present study conducted within the EU PHOEBE project. Its framework aims to advance the application of traffic simulation tools and road safety assessment to enable transport planners and managers to fully understand and address the safety implications of changes in road conditions, mode choice, new modes, road user behaviours and other factors as well as their impacts on safety.

The paper is organized as follows: in the next section information regarding the studies identification is presented. Afterwards, the schemes of safety evaluation that traffic simulation is applied are described, namely conflict-based risk assessments as well as risk assessments for: infrastructure, road type-specific, urban environments, automated mobility and road geometric configuration. In the next sections, applications of traffic simulation in road safety assessment while emerging data sources are presented, concerning studies using automated video image analysis and real-time traffic data. In addition, findings regarding studies used traffic simulation while incorporating driving behavior are discussed. In the last section of the paper, key findings and needs are also identified.

2. Systematic Review Methodology

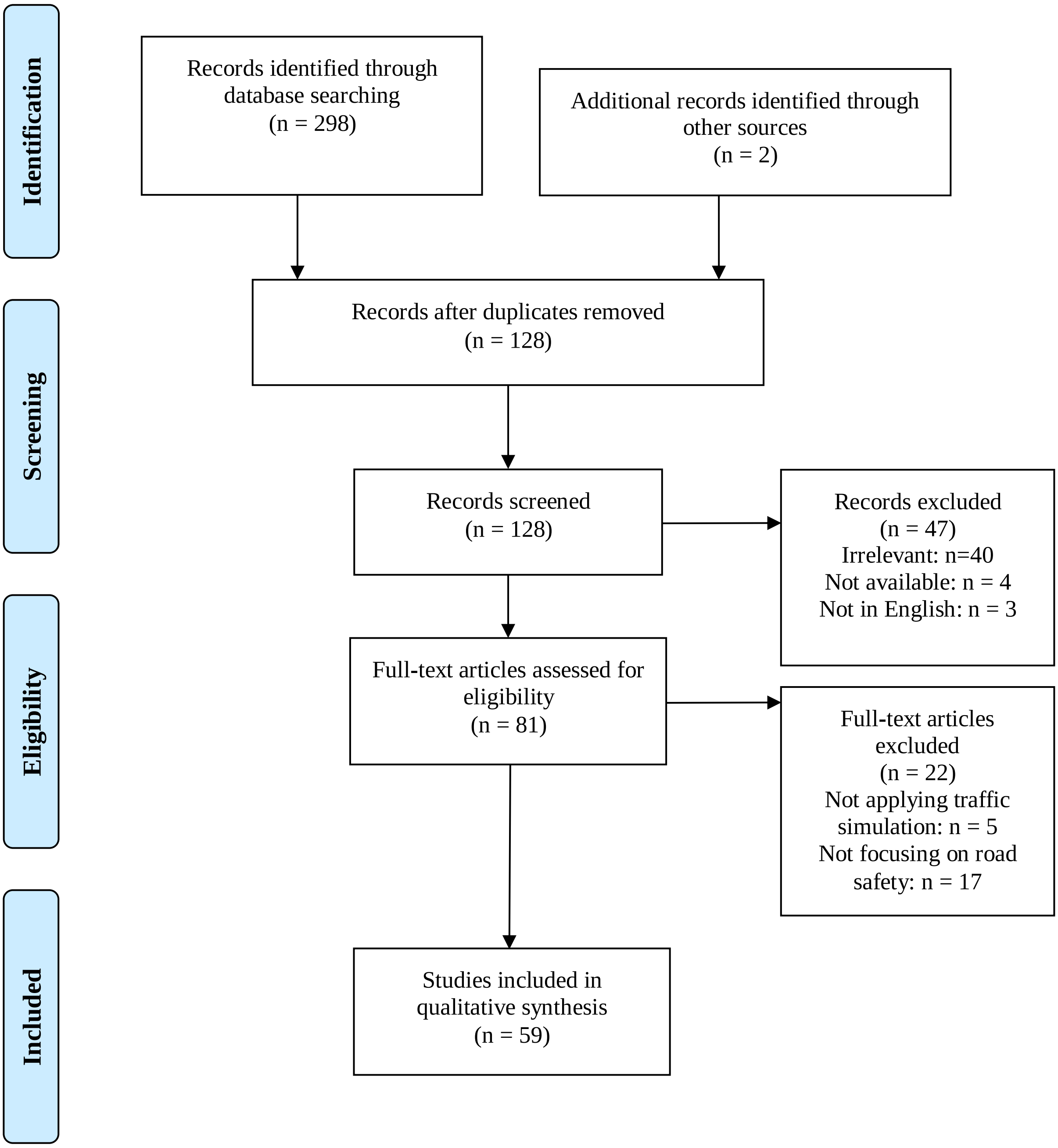

Figure 1: *Study flow diagram*

This paper aims to systematically review existing literature findings to synthesize past research and identify the road safety assessment aspects where traffic simulation applications prove effective. Therefore, the systematic review method was performed based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) standard (Moher et al., 2009). The search terms “road safety assessments” OR “road assessments” OR “safety assessments”) AND “traffic simulation” were applied to the Scopus electronic database and the respective records were identified, while no limits were applied for article type or subject area. The last search was conducted on 22 December 2022.

The study flow diagram is presented in Figure 1. Specifically, the search provided a total number of 126 records. Of these, 40 records were excluded after reviewing both titles and abstracts and it was found that did not meet the inclusion criteria. In addition, four studies were discarded because the full text was not available and three additional papers since were not in English. Therefore, the full-text of the remaining 79 records was examined in more detail and 57 studies were found to meet the criteria to be included in the systematic review. Two relevant studies were also added by checking the references of the identified papers and searching for studies that have cited them, resulting in 59 papers in total.

3. Road safety assessment methods

3.1 Conflict-based road safety assessment using traffic microscopic simulation

Traffic simulation methodology has been widely used and become a common practice in transportation engineering by offering the ability of analyzing complex transportation aspects. In terms of safety, the use of microscopic simulation (or microsimulation) is becoming progressively feasible as well, as several approaches using suitable methodological frameworks and tools quantifying surrogate safety measures become readily available. For this case, the most common technique is the conflict-based approach that enable transportation engineers to investigate high-risk locations without the need of field crash data (Ghanim et al., 2020).

One of the most common way to estimate conflicts using microscopic models is the Surrogate Safety Assessment Model (SSAM) software, a model developed by Federal Highway Administration (Pu & Joshi, 2008). The software analyzes the vehicle trajectory data and identifies conflicts. Specifically, a conflict is identified when the Time-To-Collision (TTC) and Post-Encroachment Time (PET) are lower from preset thresholds, as identified in early studies exploring the possibility of using microscopic simulation for road safety assessments (Astarita et al., 2011). In addition, the identified conflicts are also classified into three manoeuver types, namely rear-end, lane change and crossing conflicts based on conflict angle. A variety of microsimulation studies have been identified conflicts using the SSAM to evaluate consequences of different transportation planning (Goh et al., 2014; Preston and Pulugurtha, 2021), control policies (Ribeiro et al. 2019; Li and Sun, 2019; Kronprasert et al., 2020; Shahdah and Azam, 2021), road configurations (Giuffrè et al., 2019; Ghanim et al., 2020; Bahmankhah et al., 2022) as well as transportation innovations (Xin et al., 2019; Mourtakos et al., 2021; Elawady et al., 2022) in terms of traffic safety.

As mentioned, the microscopic simulation has been extensively used with regards to the surrogate safety measures evaluation. For this reason, several studies have attempted to examine the validity of the results derived from microscopic models. Findings from a simulation study indicated a strong relationship between surrogate safety measures of traffic simulation and real accident data (Ozbay et al., 2008). Specifically, the accuracy of conflict prediction was revealed when comparing simulated conflicts with field conflicts (Zheng et al., 2019; Essa and Sayed, 2020). In a different study, So et al. (2015) proposed an approach of integrating vehicle dynamics models with traffic simulation models aiming in generating realistic vehicle trajectories, and compared its results with traditional traffic simulation model ones proving that the proposed approach integrate a stronger correlation with real crashes. Finally, conflicts derived from microscopic simulation models were also compared to predicted conflicts using statistical modeling, and it was revealed that the simulated conflict-based method indicated a significant correlation in the resulting outcomes and had a better performance in identifying high-risk locations (So et al., 2015).

Astarita et al. (2020a) proposed a novel surrogate safety indicator founded on vehicle trajectories, while simultaneously considering roadside objects. The theoretical model is validated through comparisons between the calculation of surrogate safety measures on trajectories obtained from microsimulation and crash risk obtained through real crash data obtained by several urban intersection scenarios. Apart from conflict generation, when the trajectories were overlapping (or close enough), TTC and PET indicators were also examined, while the authors concluded that a model including mean energy is statistically equivalent to a collision-based model.

One major limitation of applying traffic simulation in evaluating safety is the absence of complete and established models for simulating potential crashes. A few studies have attempted to overcome this issue through proposing alternative methodologies. In particular, Guido et al. (2019) presented some applications of a new procedure based on potential crash events for evaluating of safety levels in microscopic simulation models taking into account also potential crashes with road side objects and barriers. In addition, a similar study conducted by Habtemichael and De Picado Santos (2014) used simulated conflicts to evaluate odds ratio of crash involvement. Moreover, Shahdah et al. (2014) used simulated conflicts linked formally to observed crashes to investigate an alternative approach for estimating Crash modification factors (CMFs). Furthermore, a recent study by Oikonomou et al. (2023) proposed a methodological framework for estimating crash rates along with network characteristics and traffic measures using a microsimulation conflict-based analysis. Finally, a validation of estimated crashes from simulated conflicts showed that crashes were underestimated, nevertheless more accurate and reliable predicted crashes were derived with a proper simulation network calibration (Zheng et al., 2019).

3.2 Infrastructure risk assessments

In an earlier study, Gregoriades (2007) proposed a safety prediction early warning system to allow more time for authorities to react to highly unsafe/risky situations. The aim of the study was to enhance traditional agent-based simulation with Bayesian Belief Networks (BBN) and, as a result, improve crash probability predictions. To achieve this, the author exploited real-time observations from a simulated network, enhanced them with a multi-agent model that provided real-time information on the state of the network and introduced crash scenarios via Monte Carlo simulation. The BBN model was ultimately developed by exploiting data including traffic volumes, road network characteristics, weather conditions, and driving behaviours, among others, and the application was characterized as successful overall.

Furthermore, Gregoriades et al. (2010) expanded on this research direction with the intent of providing validation for safety requirements of considered road safety designs of networks. This is achieved once again by integrating BBN technologies on agent-based simulations. A noteworthy strength of BBN is that it can be informed by prior knowledge, whether empirical or from estimations based on past literature. The conditional probability tables exploited by the model were populated by variables that were significant predictors in correlation with past crash records. The developed Road Safety Analyser (RoSA) tool achieved satisfactory performance, though the authors noted that further refinements were needed.

Regarding particular infrastructure elements, microsimulation models can become increasingly composite to reflect the element or environment under consideration. Specifically, Tan et al. (2012) developed a microscopic simulation model to assess the safety of signalized intersections. To create it, a number of key behavioral aspects of road users were considered, such as the stop–go decision at the onset of a yellow light, turning paths, turning speeds, start-up response time, and pedestrian gap acceptance. These aspects were independently developed as simulation sub-models and integrated in the overall model, while limited validation with a real intersection enhanced by image processing also took place in the study.

Other infrastructure elements have been also considered from different scopes, such as by the study of Testa et al. (2022) who investigated ways to obtain values for structural loads from traffic for the assessment of bridges. The authors utilized microscopic simulation to obtain OD values in order to explore the structural safety of bridges, using pay-toll data and regional registration data as simulation inputs, along with certain assumptions for traffic behavior. While this is not a strictly crash-based or road safety assessment per se, the traffic simulations employed in this work provided the means of solving this network-level issue.

3.3 Country or road type-specific methodologies

Using the traffic conflict technique when using microscopic simulation, several safety implications were evaluated for highways in specific. For instance, a study conducted by Habtemichael and De Picado Santos (2014) investigated aggressive driving in motorways for different traffic conditions using simulated conflicts to determine crash-risk, and Post Encroachment Time (PET) and travel time to determine the severity levels of the expected crashes. A similar study explored freeway interchange merging areas by obtaining the hourly composite risk indexes as well as developing a multivariate linear regression model (Li et al., 2016). In addition, a recent study investigated specifically the influence of the left hard shoulder on the safety of vehicles traveling on multi-lane highways, based on conflict characteristics under different numbers of lanes (Zhao et al. 2022a). A critical characteristic of freeways is managed lanes, which can improve traffic mobility and generate revenue for transportation agencies. Therefore, research also focused on specifying the safest accessibility level and identifying the safest weaving length near access zones based on simulated traffic conflicts along with a conflict frequency analysis (Saad et al. 2018). Another relevant simulation study explored the traffic behavior and vehicle interactions in a road interchange of highway by quantifying the impacts of speed limit variations on both traffic and safety (Ribeiro et al. 2019). Finally, the impacts of low-speed vehicles on expressway traffic safety has been also examined and the characteristics of the affected vehicles were defined in a study conducted by Xu et al. (2022).

Focusing on rural road environments, the potential effects of an overtaking assistant for two-lane rural roads were identified through a microscopic traffic simulation study by Hegeman et al. (2009), indicating that a safety improvement can be accomplished without negative consequences for traffic efficiency and driver comfort.

3.4 Risk assessments for urban environments

The traffic microscopic simulation approach was used on investigating the risk assessment for urban networks as well. Due to traffic congestion noticed in urban environments, signal setting and multiple turning-lane assignment at intersections was explored in a microscopic simulation study conducted by Li and Sun (2019) taking into account road safety based on vehicle conflicts and pedestrian interference. Another safety issue of urban environments related to driving behavior is that drivers run red traffic lights at signalized intersections. Therefore, research efforts have been made in order to investigate the possible causes and effectiveness of countermeasures especially when crash data are not available or reliable for statistical analysis. Lee et al. (2018) proposed a traffic simulation conflict-based approach for evaluating the red light running countermeasures and tested the most prevalent scenarios, which were; increasing the yellow signal interval duration, installing an advance warning sign, and a camera. Moreover, a different simulation study explored the safety impacts of a protected intersection design for bicyclists concluding that improves road safety (Preston and Pulugurtha, 2022).

With regards to public transport, a microscopic traffic simulation modeling approach was also adopted in a study conducted by Goh et al. (2014) in order to quantify the road safety effects of implementation of bus lanes. On a similar note, Kaparias et al. (2020) wished to extend a previously created predictive evaluation tool, covering pollution and traffic efficiency, named CONDUITS_DST. The extension aimed to take into consideration correlations of traffic characteristics to road safety indicators. As a case study, a bus priority signaling system in the city of Brussels was investigated. The simulation models had been tested based on data from simulation models obtained before and after implementing the signaling system. Both the segment level and the network level were considered. The authors note a satisfactory performance for the tool extension, which detected both positive and negative effects of the public transport priority signaling system integration in the urban center of Brussels.

Olmez et al. (2021) noted the more frequent speeding instances in urban environments. Their study was thus incentivized to exploit agent-based microsimulation modelling and to correlate collisions with speeding and traffic density parameters. The authors used autonomous agents to achieve an overall heterogeneous global sample. In addition, the authors considered the utility of higher traffic density as a speeding deterrent tool to reduce crashes caused by speeding and thus increase road safety levels. The study slightly deviates from the literature in a sense that collisions increase disproportionately highly as traffic density increases at low and modest traffic densities; however, collisions behave more proportionately after a critical point in mid-range density. Moreover, vehicles adhering closer to speed limits were found to linearly reduce collisions.

Another study (Petrov et al., 2020) proposed a privacy ensuring emergency vehicle approaching warning system (PEEV-WS), which was determined as a sub-category of Vehicular Ad hoc NETworks (VANETs). An interesting subtask involving microscopic simulation was created in order to determine whether PEEV-WS provided simulated drivers with sufficient reaction times, which was confirmed to be the case. An earlier study had followed a similar vein, investigating the apriori introduction of Advanced Driver Assistance Systems (ADAS) through microsimulation (Lundgren & Tapani, 2005). The authors developed a longitudinal control part of the driving task described by a car-following microscopic simulation model; they concluded that ADAS-induced behavioural changes are important to consider while monitoring road safety levels.

3.5 Road safety assessment for automated mobility

Since there is lack of historical generalizable crash data especially in case of high market penetration rates of Connected and Automated Vehicles (CAVs), microscopic simulation method is considered as an ideal approach of studying automated mobility impacts on safety. For this reason, research has been also focused on this direction. In particular, a microsimulation study conducted by Elawady et al. (2022) investigated the impact of CAVs on intersection traffic safety using the SSAM under different penetration rates of CAV conditions. Additionally, Jeong and Oh (2017) proposed a methodology to assess the effectiveness of active vehicle safety systems (AVSSs) that correspond to Level 2 vehicle automation using a microscopic traffic simulator and SSAM to derive indirect safety measures. A similar research which focused on validating simulated conflicts, applied SSAM as well, for a case study of recently developed CAV application (Essa and Sayed, 2020).

An ongoing challenge facing the entire transport sector is the integration of CAVs together with conventional, human-driven traffic and Vulnerable Road Users (VRUs) such as pedestrians and cyclists. Koopmann et al. (2022) sought to investigate this issue by considering an intelligent controller installed on an urban intersection in a microscopic simulation scenario, which would integrate behavioral traits of conventional or automated mobility and all other road user types. The developed model featured a complex architecture per road user category, while also being enhanced by game theory applications to better express the interactions between road users while negotiating passage through the intersection. Results are mentioned to be yet preliminary and quite demanding in implementation efforts, with possible margins in traffic efficiency.

In case of connected vehicles, there is a continuous stream of location data susceptible to tracking attacks. To that end, a microscopic traffic simulation framework was developed, synthesizing several silence-based location privacy schemes by Xin et al. (2019). Nevertheless, there is a critical element with regards to automated vehicle control systems relying on the use of either onboard range sensors or vehicle-to vehicle wireless communications, which is the delay in data acquisition. Hence a microsimulation study by Liu et al. (2006) attempted to assess the safety impacts of delayed information of intelligent vehicle control system applications and highlighted that the vehicle control systems operation is significantly affected. Moreover, the steadily increasing of CAV levels is a fact in transit services as well, and hence insights about transit services safety such as automated point-to-point shuttle bus services (Oikonomou et al., 2020) and autonomous on-demand mobility services (Mourtakos et al., 2021) have been also given based on simulated traffic conflicts.

It is worth highlighting that connected mobility might enable the calculations of new indicators, or to facilitate application opportunities of existing ones, such as the crash potential index (CPI) computed in a study by Jo et al. (2021) with data that were also compatible with DRAC calculation. Furthermore, as the traditional surrogate safety metrics have been mostly established for conventional vehicles, there are many difficulties when they are used for the assessment of automated vehicles. For this reason, proactive metrics were used instead by Mattas et al. (2019). Specifically, the proactive fuzzy surrogate safety metric (PFS) and the critical fuzzy surrogate safety metric (CFS) for rear end collisions have been developed and the results indicated their robustness on evaluating the safety level in the longitudinal direction. These fuzzy surrogate safety metrics were further used in a different study by Mattas et al. (2021), in which a fuzzy controller was developed for adaptive cruise control (ACC) and validated using real-world data and traffic simulation. In addition, the existing models used to simulate vehicular traffic are considered as not valid to predict traffic flows under increasing amounts of vehicle automation. Hence in a study by van Lint et al. (2016), an advanced open-source simulation framework named OpenTrafficSim was proposed, offering the incremental extension of microscopic models with explanatory mental models, and going one step further for the next generation of traffic simulation models that are needed in the coming decades.

3.6 Risk assessment of road geometric configuration

Focusing on road design, usually there is a lack of naturalistic driving data, resulting in not reliable road geometric designs implementation with limited operational and safety performances. In addition, the identification of the optimum geometric design requires detailed observations and evaluations of different geometric configurations. The traffic microsimulation method is consider as an ideal method of this kind of investigations as there is the ability to test different configuration scenarios and evaluate both safety and performance. Therefore, the microscopic simulation method has been extensively used to evaluate consequences of different traffic planning and control policies. For instance, several recent studies investigated traffic operations at roundabouts (Giuffrè et al., 2017; Giuffrè et al., 2018; Giuffrè et al., 2019; Ghanim et al., 2020; Bahmankhah et al., 2022) by testing different configurations. Furthermore, another microsimulation study examined impacts of passing lanes as well as merging area lengths, which represent a critical element in geometric design of passing lanes (Cafiso et al., 2018). In addition, a research conducted by Appiah et al. (2020) investigated the risk of left-turn crash occurrence at a signalized intersection using a calibrated traffic microsimulation model.

There are also approaches focusing on particular elements of the road environment, such as the study by Astarita et al (2020b), focusing on potential conflicts with roadside objects. The authors developed a dedicated add-on to enable the estimation of new road safety indicators that can be used with Tritone, Visum and Aimsun, utilizing the ‘Zombie driver’ methodology to assess road safety levels. The core of the methodology is reported to be based on earlier ideas that include economical assessment of risks posed by the various roadside objects or obstacles, highlighting dangerous locations as ones with high crash energy values, such as trees or sharp turns that are potentially hazardous for run-off crash occurrences.

4. Road safety assessment and emerging data sources

4.1 Automated video image analysis

Using video data and following the corresponding video processing techniques, the identification of traffic conflicts is applicable as have been done in many studies aiming to validating conflicts extracted through traffic simulation (Astarita et al., 2012; Li et al., 2016; Essa and Sayed, 2020) and to investigate transferability of model parameters (Essa and Sayed, 2015).

4.2 Real-time traffic data

Using highly disaggregated vehicle-based traffic data and exported conflicts from traffic microsimulation have been also used for estimating real-time crash risk in a study conducted by Katrakazas et al. (2018). Specifically, the traffic conflicts were derived using the SSAM and three classifiers (i.e., support vector machines, k-nearest neighbours, and random forests) were then employed to detect traffic conflict-prone traffic conditions in real-time. The classification results showed that traffic microsimulation along with conflicts identification from the SSAM could be used in real-time safety assessment as long as attention will be given to the calibration and validation of the simulation model.

5. Incorporating behaviour into road assessments

An earlier study endeavored to create what was termed a 'nanoscopic' model of driver agent-based behavior through macroscopic simulation focusing on traffic safety network assessment (Yuhara & Tajima, 2006). The authors enriched their approach by considering the integration of driver activities to better validate and approach real traffic conditions. Specifically, the developed simulation models are assisted by receiving driver intentions as inputs, through real-time adjustments of the steering sub-system of vehicles. Tapani (2012) investigated the effects of Adaptive Cruise Control (ACC) on acceleration and deceleration functions of vehicles utilizing driver simulation. Based on the findings, it is noted that ACC plays a considerable role and lowers acceleration and deceleration rates compared to non-ACC equipped vehicles, a result which hints positive safety benefits but also contradicts earlier relevant research. Moreover, the author notes that the effects of ACC systems in vehicles depend largely on underlying researcher assumptions on driver behavior.

Regarding aggregation approaches, it was determined by Azevedo et al (2015) that calibrations of driving behaviour models using aggregated data are likely to produce biased detailed outputs. This study endeavored to reduce the parameters involved in traffic microsimulation calibration mathematically. In particular, the authors introduced a multi-step sensitivity analysis and exploited both vehicle trajectory and aggregated traffic data to assess the impact of model parameters uncertainty and different types of input data on relevant outputs. Crash and non-crash scenarios were also considered. The authors concluded that multi-step global sensitivity analysis can make calibration much more efficient, and that calibration of complex driving behaviour models with higher detail can improve replications of more analytic traffic variables. Moreover, Outay et al. (2021) sought to investigate the behavior of connected driving devices in extreme weather conditions using agent-based simulation. The study claimed providing detailed findings on both driving and communication aspects of connected vehicles, as well as shedding light on the behavior of the transport network under extremely adverse weather conditions. The authors built a considerably complex microscopic simulation model which requires considerable computational power. A recurrent theme was again encountered in this study, where agent interactions with the environment needed to be closely defined, along with the manner in which these interactions will occur.

A recent study depending heavily on behavioral aspects is that of Zhao et al. (2022b), who assumed that collisions are mostly caused by particular driver profiles. The authors used the Next Generation Simulation (NGSIM) 101 dataset to derive three driver profiles, namely aggressive, inattentive, and normal drivers. Subsequently, simulation scenarios were tested with varying profile percentages, linking crash occurrence with the aforementioned driver profiles. The study utilized SUMO Traffic Simulator and the IDM car-following model, noting that SUMO can detect traffic collisions when front and rear ends of simulated vehicles show any overlap of their positions. The study delved into crash severity investigations as well by calculating the speed difference of the colliding vehicles of different driver profiles. The authors conclude that both aggressive and inattentive driver percentages play a role in crash occurrence and injury severity levels. SUMO is known to utilize the Krauss car-following model, which at is core is a safe-distance model. This framework was also used by Sroczyński et al. (2022), who used a traffic simulator to collect network speed data and to make the analogous speed recommendations, also in relation to average traffic volume, weather conditions and surface conditions. A key indicator was determined to be the minimal mean distance of all vehicles, and the equations to derive the closely related maximum recommended safe speed are similar to those applied in the Gipps model. In conclusion, the authors advocate in favor of installing adaptive local systems to enforce multi-stage speed reduction on sections of ‘exceptionally high risk of sudden traffic disruption’ in order to increase road safety levels; however it should be noted that the study assumed perfect compliance of simulated drivers against the imposed speed limits.

6. Conclusions

Based on the above findings, it noticeable that various traffic simulation methodologies have been widely used in transportation engineering not purely aiming to analyze complex transportation aspects in terms of traffic, as it is already known, but in terms of road safety as well. Specifically, using microsimulation the road safety assessment is feasible, as several approaches using suitable methodological frameworks and tools were identified. In addition, it was revealed that one of the most common technique is the conflict-based approach that enables the investigation of safety without the need of field crash data, since in many cases there is lack of historical generalizable data.

Despite the significant progress achieved, there is still serious concern regarding road safety assessment when applying traffic simulation, due to the absence of complete and established models for simulating potential crashes. Only a few studies have attempted to overcome this issue through proposing alternative approaches and hence further research is required. Furthermore, in most of the past research modeling efforts, there is a need for better evaluating the crash data used as well as the corresponding modeling methods followed (e.g. limited sample size, under-reporting, unreliability are noticing). Therefore, validation as well as further investigation of past modelling approaches for road safety assessment is essential.

Acknowledgements

The present research was carried out within the research project “PHOEBE - Predictive Approaches for Safer Urban Environment”, which has received funding from the European Union’s Horizon Europe research and innovation programme under grant agreement No 101076963.

7. References-Bibliography

Appiah, J., King, F. A., Fontaine, M. D., & Cottrell, B. H. (2020). Left turn crash risk analysis: Development of a microsimulation modeling approach. Accident Analysis & Prevention, 144, 105591.

Astarita, V., Caliendo, C., Giofrè, V. P., & Russo, I. (2020a). Surrogate safety measures from traffic simulation: Validation of safety indicators with intersection traffic crash data. Sustainability, 12(17), 6974.

Astarita, V., Festa, D. C., & Giofrè, V. P. (2020b). Microsimulation and the evaluation of safety levels in the presence of roadside obstacles. Eur. Transp. Trasp. Eur., 77, 1-12.

Astarita, V., Guido, G., Vitale, A., & Giofré, V. (2012). A new microsimulation model for the evaluation of traffic safety performances.

Astarita, V., Giofré, V., Guido, G., & Vitale, A. (2011). Investigating road safety issues through a microsimulation model. Procedia-Social and Behavioral Sciences, 20, 226-235.

Azevedo, C. L., Ciuffo, B., Cardoso, J. L., & Ben-Akiva, M. E. (2015). Dealing with uncertainty in detailed calibration of traffic simulation models for safety assessment. Transportation research part C: emerging technologies, 58, 395-412.

Bahmankhah, B., Macedo, E., Fernandes, P., & Coelho, M. C. (2022). Micro driving behaviour in different roundabout layouts: pollutant emissions, vehicular jerk, and traffic conflicts analysis. Transportation research procedia, 62, 501-508.

Cafiso, S., D'Agostino, C., Kieć, M., & Bak, R. (2018). Safety assessment of passing relief lanes using microsimulation-based conflicts analysis. Accident Analysis & Prevention, 116, 94-102.

Elawady, A., Abuzwidah, M., & Zeiada, W. (2022). The benefits of using connected vehicles system on traffic delay and safety at urban signalized intersections. In 2022 Advances in Science and Engineering Technology International Conferences (ASET) (pp. 1-6). IEEE.

Essa, M., & Sayed, T. (2020). Comparison between surrogate safety assessment model and real-time safety models in predicting field-measured conflicts at signalized intersections. Transportation research record, 2674(3), 100-112.

Essa, M., & Sayed, T. (2015). Transferability of calibrated microsimulation model parameters for safety assessment using simulated conflicts. Accident Analysis & Prevention, 84, 41-53.

Ghanim, M., Kharbeche, M., Hannun, J., Hannun, J., & Shamiyeh, K. (2020). Safety and operational performance of signalized roundabouts: a case study in Doha. Procedia Computer Science, 170, 427-433.

Ghanim, M. S., & Shaaban, K. (2019). A case study for surrogate safety assessment model in predicting real-life conflicts. Arabian Journal for Science and Engineering, 44, 4225-4231.

Giuffrè, O., Granà, A., Tumminello, M. L., Giuffrè, T., & Trubia, S. (2019). Surrogate measures of safety at roundabouts in AIMSUN and VISSIM environment. In Roundabouts as Safe and Modern Solutions in Transport Networks and Systems: 15th Scientific and Technical Conference "Transport Systems. Theory and Practice 2018", Katowice, Poland, September 17–19, 2018, Selected Papers (pp. 53-64). Springer International Publishing.

Giuffrè, O., Granà, A., Tumminello, M. L., Giuffrè, T., Trubia, S., Sferlazza, A., & Rencelj, M. (2018). Evaluation of roundabout safety performance through surrogate safety measures from microsimulation. Journal of Advanced Transportation, 2018, 1-14.

Giuffrè, T., Trubia, S., Canale, A., & Persaud, B. (2017). Using microsimulation to evaluate safety and operational implications of newer roundabout layouts for European Road networks. Sustainability, 9(11), 2084.

Goh, K. C., Currie, G., Sarvi, M., & Logan, D. (2014). Experimental microsimulation modeling of road safety impacts of bus priority. Transportation research record, 2402(1), 9-18.

Gregoriades, A., Sutcliffe, A., Papageorgiou, G., & Louvieris, P. (2010). Human-centered safety analysis of prospective road designs. IEEE Transactions on Systems, Man, and Cybernetics-Part A: Systems and Humans, 40(2), 236-250.

Gregoriades, A. (2007). Towards a user-centred road safety management method based on road traffic simulation. In 2007 Winter Simulation Conference (pp. 1905-1914). IEEE.

Guido, G., Giofrè, V. P., Astarita, V., & Vitale, A. (2019, October). Using traffic microsimulation to evaluate potential crashes: Some results. In 2019 IEEE/ACM 23rd International Symposium on Distributed Simulation and Real Time Applications (DS-RT) (pp. 1-4). IEEE.

Habtemichael, F. G., & de Picado Santos, L. (2014). Crash risk evaluation of aggressive driving on motorways: Microscopic traffic simulation approach. Transportation research part F: traffic psychology and behaviour, 23, 101-112.

Hegeman, G., Tapani, A., & Hoogendoorn, S. (2009). Overtaking assistant assessment using traffic simulation. Transportation research part C: emerging technologies, 17(6), 617-630.

Jeong, E., & Oh, C. (2017). Evaluating the effectiveness of active vehicle safety systems. Accident Analysis & Prevention, 100, 85-96.

Jo, Y., Jang, J., Park, S., & Oh, C. (2021). Connected vehicle-based road safety information system (CROSS): Framework and evaluation. Accident Analysis & Prevention, 151, 105972.

Kaparias, I., Liu, P., Tsakarestos, A., Eden, N., Schmitz, P., Hoadley, S., & Hauptmann, S. (2020). Predictive road safety impact assessment of traffic management policies and measures. Case studies on transport policy, 8(2), 508-516.

Katrakazas, C., Quddus, M., & Chen, W. H. (2017). A simulation study of predicting real-time conflict-prone traffic conditions. IEEE Transactions on Intelligent Transportation Systems, 19(10), 3196-3207.

Koopmann, B., Puch, S., Ehmen, G., & Fränzle, M. (2022). Cooperative maneuvers of highly automated vehicles at urban intersections: a game-theoretic approach. arXiv preprint arXiv:2211.01633.

Kronprasert, N., Kuwiboon, P., & Wichitphongsa, W. (2020). Safety and operational analysis for median U-turn intersections in Thailand. GEOMATE Journal, 18(68), 156-163.

Lee, C., So, J., & Ma, J. (2018). Evaluation of countermeasures for red light running by traffic simulator–based surrogate safety measures. Traffic injury prevention, 19(1), 1-8.

Li, S., Xiang, Q., Ma, Y., Gu, X., & Li, H. (2016). Crash risk prediction modeling based on the traffic conflict technique and a microscopic simulation for freeway interchange merging areas. International journal of environmental research and public health, 13(11), 1157.

Li, X., & Sun, J. Q. (2019). Turning-lane and signal optimization at intersections with multiple objectives. Engineering Optimization, 51(3), 484-502.

Liu, Y., Dion, F., & Biswas, S. (2006). Safety assessment of information delay on performance of intelligent vehicle control system. Transportation research record, 1944(1), 16-25.

Lundgren, J., & Tapani, A. (2006). Evaluation of safety effects of driver assistance systems through traffic simulation. Transportation research record, 1953(1), 81-88.

Mattas, K., Botzoris, G., & Papadopoulos, B. (2021). Safety aware fuzzy longitudinal controller for automated vehicles. Journal of traffic and transportation engineering (English edition), 8(4), 568-581.

Mattas, K., Makridis, M., Botzoris, G., Ciuffo, B., & Papadopoulos, B. (2019). Fuzzy surrogate safety metrics. In 2019 6th International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS) (pp. 1-11). IEEE.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G., Altman, D., Antes, G., Atkins, D., Barbour, V., Barrowman, N., Berlin, J. A., Clark, J., Clarke, M., Cook, D., D'Amico, R., Deeks, J. J., Devereaux, P. J., Dickersin, K., Egger, M., Ernst, E., … Tugwell, P. (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. PLoS Medicine, 6(7). https://doi.org/10.1371/journal.pmed.1000097

Mourtakos, V., Oikonomou, M. G., Kopelias, P., Vlahogianni, E. I., & Yannis, G. (2022). Impacts of autonomous on-demand mobility service: A simulation experiment in the City of Athens. Transportation Letters, 14(10), 1138-1150.

Oikonomou, M. G., Orfanou, F. P., Vlahogianni, E. I., & Yannis, G. (2020). Impacts of autonomous shuttle services on traffic, safety and environment for future mobility scenarios. In 2020 IEEE 23rd International Conference on Intelligent Transportation Systems (ITSC) (pp. 1-6). IEEE.

Oikonomou, M. G., Ziakopoulos, A., Chaudhry, A., Thomas, P., & Yannis, G. (2023). From conflicts to crashes: Simulating macroscopic connected and automated driving vehicle safety. Accid. Anal. Prev. 187, 107087. https://doi.org/10.1016/j.aap.2023.107087

Olmez, S., Douglas-Mann, L., Manley, E., Suchak, K., Heppenstall, A., Birks, D., & Whipp, A. (2021). Exploring the Impact of Driver Adherence to Speed Limits and the Interdependence of Roadside Collisions in an Urban Environment: An Agent-Based Modelling Approach. Applied Sciences, 11(12), 5336.

Outay, F., Galland, S., Gaud, N., & Abbas-Turki, A. (2021). Simulation of connected driving in hazardous weather conditions: General and extensible multiagent architecture and models. Engineering applications of artificial intelligence, 104, 104412.

Ozbay, K., Yang, H., Bartin, B., & Mudigonda, S. (2008). Derivation and validation of new simulation-based surrogate safety measure. Transportation research record, 2083(1), 105-113.

Petrov, T., Pocta, P., Roman, J., Buzna, Ľ., & Dado, M. (2019). A feasibility study of privacy ensuring emergency vehicle approaching warning system. Applied Sciences, 10(1), 298.

Preston, A., & Pulugurtha, S. S. (2021). Simulating and assessing the effect of a protected intersection design for bicyclists on traffic operational performance and safety. Transportation research interdisciplinary perspectives, 9, 100329.

Pu, L., Joshi, R., & Energy, S. (2008). Surrogate Safety Assessment Model (SSAM)--software user manual (No. FHWA-HRT-08-050). Turner-Fairbank Highway Research Center.

Ribeiro, P., Araújo, C., Gonçalves, L. A., Dias, G. J., & Cunto, F. (2019). Micro-simulation of the impact of different speeds on safety road travel and urban travel time: case study in the city of Guimarães.

Saad, M., Abdel-Aty, M., Lee, J., & Wang, L. (2018). Safety analysis of access zone design for managed toll lanes on freeways. Journal of Transportation Engineering, Part A: Systems, 144(11), 04018067.

Sroczyński, A., Kurowski, A., Zaporowski, S., & Czyżewski, A. (2022). Examining Impact of Speed Recommendation Algorithm Operating in Autonomous Road Signs on Minimum Distance between Vehicles. Remote Sensing, 14(12), 2803.

Shahdah, U., Saccomanno, F., & Persaud, B. (2014). Integrated traffic conflict model for estimating crash modification factors. Accident Analysis & Prevention, 71, 228-235.

Shahdah, U. E., & Azam, A. (2021). Safety and mobility effects of installing speed-humps within unconventional median U-turn intersections. Ain Shams Engineering Journal, 12(2), 1451-1462.

So, J., Park, B., Wolfe, S. M., & Dedes, G. (2015). Development and validation of a vehicle dynamics integrated traffic simulation environment assessing surrogate safety. Journal of computing in civil engineering, 29(5), 04014080.

So, J., Lim, I. K., & Kweon, Y. J. (2015). Exploring traffic conflict-based surrogate approach for safety assessment of highway facilities. Transp. Res. Rec, 2513(1), 56-62.

Tan, D. M., Alhajyaseen, W. K., Asano, M., & Nakamura, H. (2012). Development of microscopic traffic simulation model for safety assessment at signalized intersections. Transportation research record, 2316(1), 122-131.

Tapani, A. (2012). Vehicle trajectory effects of adaptive cruise control. Journal of Intelligent Transportation Systems, 16(1), 36-44.

Testa, G., Zaccaria, G., Montanino, M., Baltzopoulos, G., Bilotta, A., Iervolino, I., & Punzo, V. (2022). Infrastructure-level traffic micro-simulation for probabilistic analysis of bridge loads. Computer-Aided Civil and Infrastructure Engineering.

van Lint, H., Schakel, W., Tamminga, G., Knoppers, P., & Verbraeck, A. (2016). Getting the human factor into traffic flow models: new open-source design to simulate next generation of traffic operations. Transportation Research Record, 2561(1), 25-33.

Xin, W., Moonam, H. M., Petit, J., & Whyte, W. (2019). Towards a balance between privacy and safety: microsimulation framework for assessing silence-based pseudonym-change schemes. Transportation research record, 2673(2), 71-84.

Xu, C., Ma, J., & Tang, X. (2022). A Simulation-Based Study of the Influence of Low-Speed Vehicles on Expressway Traffic Safety. Sustainability, 14(19), 12165.

Yuhara, N., & Tajima, J. (2006). Multi-driver agent-based traffic simulation systems for evaluating the effects of advanced driver assistance systems on road traffic accidents. Cognition, Technology & Work, 8(4), 283-300.

Zhao, P., Ma, J., Xu, C., Zhao, C., & Ni, Z. (2022a). Research on the safety of the left hard shoulder in a multi-lane highway based on safety performance function. Sustainability, 14(22), 15114.

Zhao, L., Farhi, N., Christoforou, Z., & Haddadou, N. (2022b). Analysis of driver behavior and intervehicular collision: a data-based traffic modeling and simulation approach. Journal of advanced transportation, 2022.

Zheng, L., Sayed, T., Essa, M., & Guo, Y. (2019). Do simulated traffic conflicts predict crashes? An investigation using the extreme value approach. In 2019 IEEE Intelligent Transportation Systems Conference (ITSC) (pp. 631-636). IEEE.