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Examining road safety impacts of Green Light Optimal Speed Advisory (GLOSA) system

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ABSTRACT

Mobility and environmental benefits of Green Light Optimal Speed Advisory (GLOSA) systems have been reported by many previous research studies, however, there is insufficient knowledge on the safety implications of such an application. For safe deployment of GLOSA system, it is most critical to identify and address potential safety issues in the design process. It can be argued that implementation of GLOSA system can improve safety by reducing traffic conflicts associated with the interrupted traffic flow at signalised intersections. However, more research findings are needed from field and simulation based studies to evaluate the impacts on safety under a variety of real-world scenarios. As part of the LEVITATE (Societal Level Impacts of Connected and Automated Vehicles) project under European Union's Horizon 2020 Programme, the main objective of this study is to examine the safety impacts of GLOSA under mixed traffic compositions with varying market penetration rates (MPR) of connected and automated vehicles (CAVs). A calibrated and validated microsimulation model (developed in Aimsun) of the greater Manchester area was used for this study where three signalised intersections in a corridor were identified for implementing GLOSA system. An improved algorithm was developed by identifying the potential issues/limitations in some of the GLOSA algorithms found in literature. Behaviours of CAVs were modelled based on the findings of a comprehensive literature review. Safety analysis was performed through processing the simulated vehicular trajectories in the surrogate safety assessment model (SSAM) by the Federal Highway Administration (FHWA). The surrogate safety assessment results showed small improvement in safety with the GLOSA implementation at multiple intersections in the test network only at low MPR (20%) scenarios of CAVs, as compared to the respective without GLOSA scenarios. No or rather slightly lower improvement in safety was observed with GLOSA implementation under mixed fleet scenarios with 40 % or higher 1st Generation or 2nd Generation CAVs, as compared to the respective scenarios without GLOSA. The implementation of GLOSA system was also found to have some impact on the traffic conflict types (although not consistent across all MPR scenarios), where rear-end conflicts were found to decrease while a slight increase was observed in lane-change conflicts.

1. Introduction

Road transport undoubtedly entails benefits to the society, but it does not come without externalities. The negative effects on the environment and society include traffic crashes, pollution, and congestion (Santos et al., 2010). Congestion entails interrupted flow, lower speeds,

larger travel times and delays. This has an environmental impact as well. This is because when a vehicle faces delays on the road with multiple stops and waiting at the traffic lights, due to mostly speed alterations and frequent acceleration and deceleration manoeuvres, the fuel consumption and pollution increase.

In recent years, technological achievements have rendered vehicle

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wireless communications available. Connected vehicle technology includes vehicle to vehicle (V2V) and vehicle-to-infrastructure (V2I) communication and has several safety and mobility applications (Radivojevic et al., 2016). As traffic information becomes accessible, connected vehicles are able to adapt their behaviour according to traffic conditions and this adaptation can contribute to beneficial changes in traffic flow and emissions (Masera et al., 2019). One emerging vehicle to infrastructure application that intends to improve emissions through optimizing traffic flow on signalised road networks is the Green Light Optimal Speed Advisory (GLOSA). An overview of GLOSA system application is demonstrated in Fig. 1.

Green Light Optimal Speed Advisory (GLOSA) is a Day 1 Cooperative Intelligent Transport Systems (C-ITS) signage application, enabled by the C-ITS service "Signalised Intersections". The application utilises traffic signal information and the current position of the vehicle to provide a speed recommendation in order for the drivers to pass the traffic lights during the green phase and therefore, reduce the number of stops, fuel consumption and emissions. The distance to stop, the plans for signal timing and the speed limit profile for the area are taken into account to calculate the speed recommendation displayed to the driver. GLOSA service is provided through ETSI G5 into the on-board computer of the vehicle or via mobile network into a smartphone application.

Potential benefits of GLOSA application on mobility, fuel consumption and emissions have been investigated in literature, however, little is known with regard to its impacts on safety. Particularly, in the era of connected and automated vehicles (CAVs), it would be useful for cities, various stakeholders, and transport planners to assess the societal impacts of such an application in an urban area and attempt to evaluate the benefits in relation to the relevant costs. In this context, this research study aims to investigate the road safety impacts of GLOSA under various mixed traffic composition scenarios with CAVs. In addition, the safety impacts of GLOSA implementation on single versus multiple

successive signalised intersections are also examined.

The remaining parts of the paper are structured as follows. Section 2 provides a review of previous literature, covering studies performed on safety impacts of GLOSA, measures for surrogate safety assessment, and estimation of crashes from identified traffic conflicts. Section 3 describes the methodology and provides details on the study area, micro-simulation model specifications, CAVs functional parameters, GLOSA algorithm, surrogate safety assessment method, and estimation of crashes from conflicts. Analysis and results are presented in Section 4, followed by discussion on results and insights on safety implications under Section 5. Final section provides conclusions, limitations and directions for future work.

2. Literature review

With regard to previous studies exploring the impacts of the GLOSA system, Mellegård and Reichenberg (2020) provided a review of 64 publications between 2006 and 2019 (Fig. 2). Most of them based their findings on simulation, with a much smaller amount using real-world methods (e.g., pilots, field operational tests). The on-board GLOSA algorithm was proposed as the main solution in the majority of the studies, which involves determining advisory speed within a feasible range of minimum and maximum speeds to enable vehicles to move through the intersection during green phase. According to the findings of this review, fewer studies proposed the whole system design (including infrastructure for communication) and/or predicting signal changes as the solution. The focus was on the equipped vehicle in most studies, as opposed to fellow road users or other societal issues as indicated in Fig. 2. No publications examined drivers' ability/behaviour to follow the advised speed.

The review also identified only fewer studies which investigated the safety implications of GLOSA system. As indicated by Fig. 2, most of the

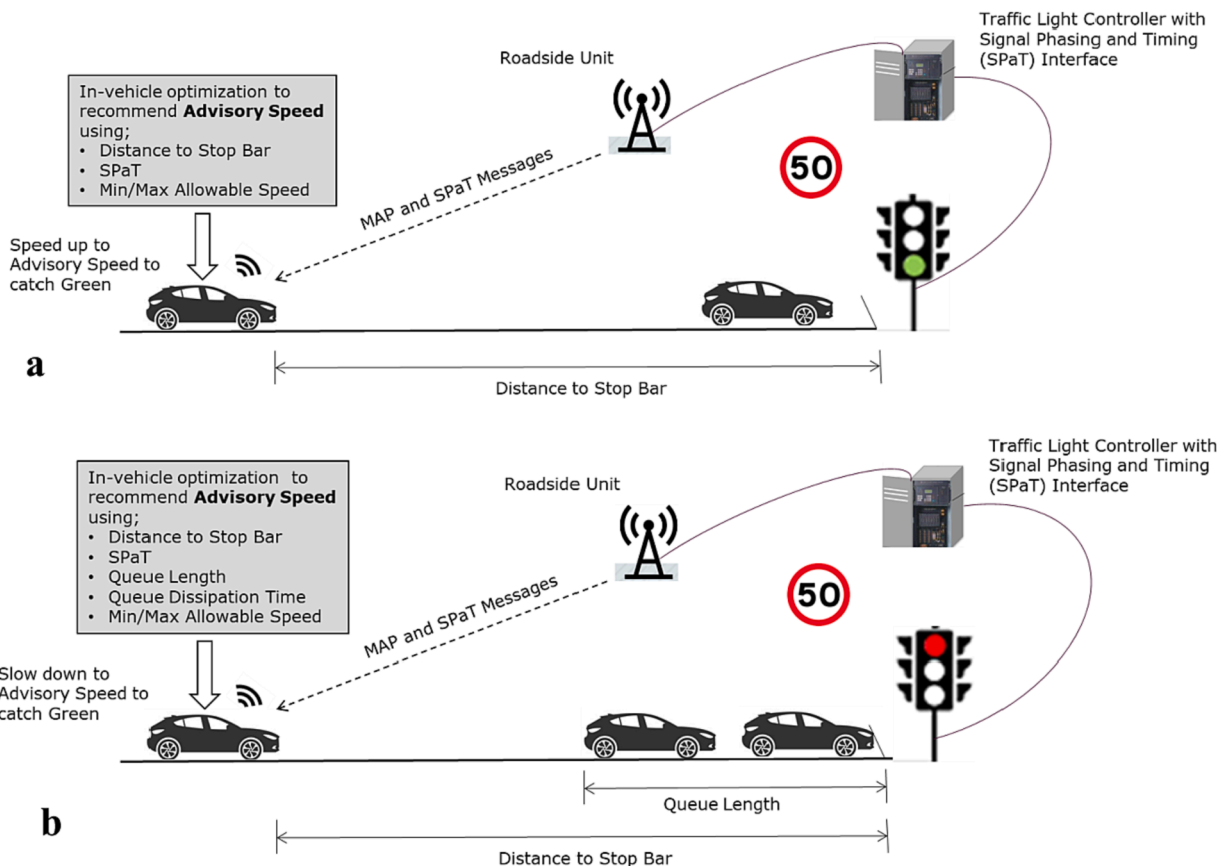


Fig. 1. GLOSA system and application overview: (a) Communication initiated when current phase is Green, (b) Communication initiated when current phase is Red.

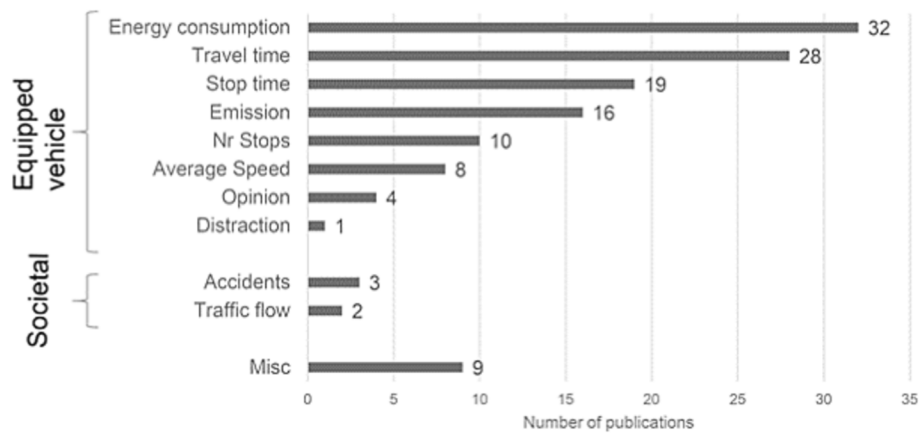


Fig. 2. Overview of the effects/impacts evaluated across the 64 papers (Mellegård and Reichenberg, 2020).

previous studies have examined impacts on energy consumption, travel time, stop time, and emissions. Many of them have reported benefits of GLOSA implementation in reducing average fuel consumption, travel times, and emissions (Gajananan et al., 2013; Xia et al., 2012; Chen et al., 2012). In this regard, previous studies have also reported that benefits of GLOSA system can be achieved if used with fixed time signal controllers. For instance, Stevanovic et al. (2013), who used a calibrated simulation model (developed in VISSIM) of a network comprising of two signalised intersections, reported better traffic performance in case of fixed time controllers but not under actuated-coordinated (difficult to accurately predict) signal operations. Under fixed-time controllers, the authors also reported improvement in traffic performance with higher market penetration rate (MPR) of GLOSA equipped vehicles and increased frequency of GLOSA system activation.

As mentioned before, with regard to safety, there are relatively fewer studies in literature exploring the impacts of GLOSA system. More specifically, with regard to GLOSA implementation, Stevanovic et al. (2015a) performed surrogate safety assessment on an urban corridor segment, modelled in VISSIM software, including 5 intersections in Salt Lake City, Utah. Various signal control schemes including optimised, fixed time as well as actuated were tested with GLOSA application. Vehicular conflicts were analysed through microsimulation trajectories post-processed through FHWA's surrogate safety assessment model (SSAM). The results showed a reduction in the number of conflicts under fixed-time controller operation. Further reduction was found under optimised signal timings with pretimed signals. In terms of types of conflicts, the results showed a considerable decrease in rear-end conflicts whereas the number of lane-change conflicts were found to increase with the GLOSA application. The study also indicated increased conflicts under mixed fleet scenarios due to increased disruptions in the traffic. In another research study, Stevanovic et al. (2015b) tested signal timings that ensure a balance between mobility, safety and environment employing a 3-dimensional Pareto Fronts methodology. GLOSA operation for fixed and optimised signals, although initially developed for fuel consumption reduction, appeared to benefit safety on arterials as the number of vehicular conflicts were reduced.

Another aspect of examining the road safety impacts of GLOSA system can be through analysing the effects on driver-decisions in dilemma zones at the onset of traffic signal clearance interval, which are critical for road safety at signalised intersections. In this regard, Saldivar-Carranza et al. (2020) examined the impact of phase probability based GLOSA system on the exposure of drivers to dilemma zone and tested the concept using simulation model of an arterial with actuated-coordinated traffic signals. The study utilised traffic signal controller data to determine the phase probabilities based on the previous week's same day and time data. Based on the analysis of nearly 486,000 vehicular trajectories, a comparison of without GLOSA and with GLOSA advised trips was

performed, which showed high percentage of reductions in hard braking (93 %) and running through red light (96 %).

Suzuki and Marumo (2020), evaluated the performance of their previously proposed GLOSA system that advises the drivers for the vehicle position instead of the optimal speed. They simulated an existing signalised intersection to test how the proposed system performs with real-world traffic flows in an actual traffic environment. The results from the traffic simulation study showed that the proposed GLOSA system increased the vehicles' time headway while simultaneously there was a drop in the need for deceleration near the intersection, suggesting safer traffic flows.

Drivers need some time to process the information they receive from their surroundings. The amount of time it takes to comprehend general information, on the road about signals and other objects, has been observed to vary from one study to the next. In the context of GLOSA, driver response time is critical to consider for GLOSA system's performance, as indicated by Karoui et al. (2019). The researchers found most beneficial results with respect to average stop time and fuel consumption under 0.1 s reaction time considering autonomous driving, as compared to the human driving scenarios with higher reaction times (1 s, 1.5 s, and 2 s).

Overall, limited literature exists specifically on the road safety impacts of GLOSA or similar systems, however, the available evidence suggests potential reduction in rear-end crashes with the application of GLOSA on pre-timed signals. With more accurate predictions on the signal timings, probability of drivers getting in dilemma zone and running red light can be potentially reduced, which can directly impact safety outcome at the signalised intersections.

2.1. Surrogate safety measures

For identifying potential collisions through microsimulation trajectories, surrogate safety measures are used in SSAM such as Time to Collision (TTC) and Post-encroachment time (PET). TTC is "the time that remains until a collision between two vehicles would have occurred if the collision course and speed difference are maintained" (Hydén, 1996). PET refers to the time that elapses between the leading vehicle leaving the area of potential collision point to the time when following vehicle reaches there (Cooper, 1984). In the literature, a TTC value of less than 1.5 s for human-driven vehicles denotes a hazardous situation, while this threshold has been assumed to be 1 s or 0.75 s for automated vehicles (Sinha et al., 2020; Viridi et al., 2019; Morando et al., 2018). TTC threshold value of 1.5 s for manual vehicles (as used in various other studies) is calibrated value and recommended by the FHWA based on previous research studies (Gettman et al., 2008; Gettman and Head, 2003). The decreased TTC threshold value for automated vehicles is due to their technological capabilities to respond quicker than humans under

safety critical situations (Morando et al., 2018; 2017). Viridi et al. (2019) assumed TTC and PET values for defining CAV conflicts to be one-third of those for human-driven vehicles. The assumption was made in accordance with the reduction in standstill and following distance for CAVs. Another study by Ukkusuri et al. (2019) assigns different TTC thresholds by levels of autonomy. The default value for TTC and PET in the SSAM are 1.5 and 5.0 s respectively (Gettman et al., 2008; Gettman and Head, 2003). Under the condition of $0 < TTC \leq 1.5$ s, and $0 < PET \leq 5$ s, SSAM identifies the event as a conflict. The conflict severity is defined according to the TTC values, a small value of TTC and PET indicate high severity levels of expected crashes (Habtemichael et al., 2014).

2.2. Conversion of conflicts to crashes

Although conflicts have been used as valid safety surrogates for crash analyses (Guo et al., 2010), the relationship between them and the number of crashes is to be further investigated. Previous studies have used either a simple computation through a ratio between crashes and conflicts (e.g., Amundsen and Larsen, 1977; Hauer, 1982; Migletz et al., 1985; Peesapati et al., 2013; Charly & Mathew, 2019) or through a statistical model (e.g., El-Basyouny and Sayed, 2013; Peesapati et al., 2018; Zhao & Lee, 2018), often confirming a relationship but limited by the availability and generalizability of empirical data. Some studies in the previous literature use a theoretical model for the prediction of crash occurrence based on inferences about the relationship between conflicts and crashes, such as those involving variations on the causal model (Davis et al., 2011; Tarko, 2018; Tarko, 2020) and those using extreme value theory models (e.g. Songchitruksa & Tarko, 2006; Zheng et al., 2014). However, crash data are still required for validation of such models.

The translation of SSAM output conflicts into crash predictions could be very challenging as the models to be used can only be validated or calibrated with a large sample of conflict and crash data to produce such a distribution (Tarko, 2020). Tarko (2018, 2020) proposed a probabilistic method based on the counterfactual causal framework provided by Davis et al. (2011) which considers a crash as one potential outcome of an observable conflict, such that the probability of collision depends on time to collision (TTC). The method hence relies on TTC distribution. The methodological assumption is based on the theory that a crash is avoided if the necessary evasive manoeuvre is performed quickly enough. The response delay of the evasive manoeuvre has been shown to follow a Lomax distribution in initial validation efforts (Tarko, 2021; Tarko, 2020; Tarko & Lizarazo, 2021). In the present paper Tarko’s method was employed to provide an estimate on the potential number of crashes based on the traffic conflicts output from SSAM.

3. Methodology

Quantification of safety impacts was performed through surrogate

safety assessment which involved processing the simulated vehicular trajectories in FHWA’s SSAM to identify traffic conflicts based on time to collision (TTC). In order to assess the impact of GLOSA application on safety, the surrogate safety assessment was performed with and without GLOSA implementation on the study network. The total number of identified conflicts from surrogate safety assessment were then used to estimate number of crashes through a probabilistic approach using Lomax distribution (Tarko, 2018). The following flow chart (Fig. 3) presents various steps involved in the safety assessment methodology. The subsequent sections provide the details of the study area, CAV parameters, GLOSA application programming interface (API), surrogate safety assessment, and conversion of conflicts to crashes, respectively.

3.1. Study area

A calibrated and validated traffic microsimulation model, used within this study, was provided by the Transport for Greater Manchester. The model of Greater Manchester provides a sufficiently large and complex transport network with various signalised intersection configurations, rendering it suitable for the specific experiment. For implementing GLOSA, a corridor near the Salford area was selected in Manchester including three signalised intersections (Fig. 4), where the distance between the first and second intersection is around 400 m whereas that between the second and third intersection is around 800 m. The study area is around 1.22 km² and contains 53 nodes, 95 road sections, and an OD matrix of 11 × 11. Traffic data of evening peak hour (17:00 – 18:00) was used, with an estimated traffic demand of 3738 cars trips, 308 light goods vehicles (LGV) trips, and 127 heavy goods vehicles (HGV) trips. The impact of GLOSA was analysed under fixed time co-ordinated traffic control at the marked study intersections in Fig. 4.

The test scenarios for GLOSA implementation and CAV deployment are as follows:

Baseline scenario – No GLOSA, CAV market penetration from 0 % to 100 % in 20 % increments.

Scenario 1 – GLOSA on intersection 1,

Scenario 2 – GLOSA on intersections 1 and 2, and

Scenario 3 – GLOSA on intersection 1, 2 and, 3.

Simulations were performed on baseline and all three analysis scenarios with the following CAV deployment, as shown in Table 1.

The following assumptions were made in the frame of GLOSA application.

1. The quality of communication between signals and vehicles is ideal and all messages are delivered successfully and without delay,
2. All the drivers accept and comply with the recommended speed,
3. GLOSA is applied at each simulation step, and
4. Only CAVs will have the capability to communicate with traffic signal controllers.

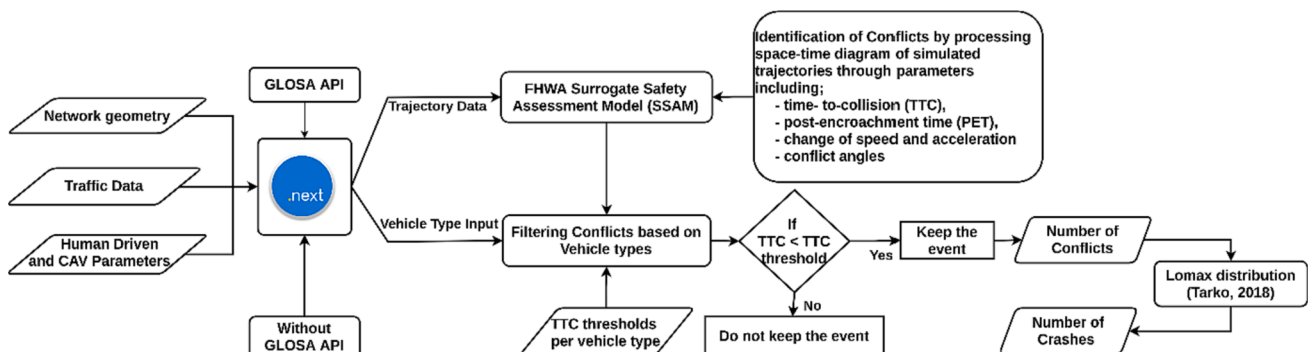


Fig. 3. Methodology flow chart.

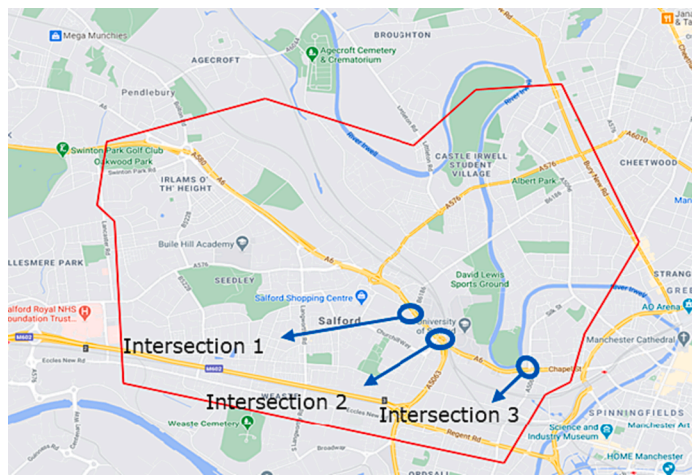


Fig. 4. Test corridor in Manchester network for GLOSA application.

Table 1
CAV deployment scenarios.

Type of vehicle	CAV deployment scenarios							
	100-0-0	80-20-0	60-40-0	40-40-20	20-40-40	0-40-60	0-20-80	0-0-100
Human-Driven	100	80	60	40	20	0 %	0 %	0 %
Vehicle - passenger vehicle	%	%	%	%	%			
1st Generation CAV - passenger vehicle	0 %	20 %	40 %	40 %	40 %	40 %	20 %	0 %
2nd Generation CAV - passenger vehicle	0 %	0 %	0 %	20 %	40 %	60 %	80 %	100 %

3.2. Functional parameters of CAVs

Two CAV types were considered within this study: 1st Generation CAVs and 2nd Generation CAVs. Both types were assumed to be fully automated vehicles with level 5 automation. The main idea behind modelling these two types is based on the assumption that technology will gradually advance with time, which means that the 2nd Generation of CAVs will have improved sensing and cognitive capabilities, decision-making, driver characteristics, the anticipation of incidents, etc. In general, the main assumptions on CAVs characteristics are as follows:

- 1st Generation: limited sensing and cognitive ability, long gaps, earlier anticipation of lane changes than human-driven vehicles, and longer time in give way situations.
- 2nd Generation: advanced sensing and cognitive ability, confidence in taking decisions, small gaps, later anticipation of lane changes than human-driven vehicles, and less time in give way situations.

The road safety impact of GLOSA and CAVs was assessed in mixed traffic conditions that contain passenger cars and freight vehicles (Light Goods Vehicle (LGV) and Heavy Goods Vehicle (HGV)). Due to limited knowledge on the characteristics of freight CAVs, only a few parameters were adjusted to model the behaviours of these vehicles.

The CAVs behaviours were modelled using Gipps car-following model (Gipps, 1981; 1986). To simulate human-driven vehicles and CAVs behaviours, various parameters related to the car-following, lane-changing and other behaviours were adjusted. The assumptions on CAV

behavioural parameters and their values were derived based on a comprehensive literature, which included both empirical and simulation-based studies as well as discussion with experts during the LEVITATE project meetings. The details on each parametric assumption, within LEVITATE project, on CAV driving behaviours can be found in Chaudhry et al. (2022).

3.3. GLOSA algorithm

An algorithm was developed for emulating the GLOSA system in microsimulation, by reviewing some of the previously developed algorithms (Stevanovic et al., 2013) and identifying their limitations, while several considerations were made according to the test network and analysis scenarios. The flow chart in Fig. 5 presents the sequence of various steps involved in calculating the advisory speed message.

The communication range or the distance upstream from the intersection at which the GLOSA system can be activated was selected based on testing different values and selecting the most optimal one. Similarly, the frequency at which the speed advisory messages are updated (GLOSA frequency) was also based on test experiments in the microsimulation model. The most optimal results, based on the test experiments, were obtained at 400 m activation distance and when GLOSA was applied more frequently (per time step in microsimulation). The minimum allowable speed was selected as half of the speed limit based on guidelines provided in the literature (Katsaros et al., 2011; Masera et al., 2019). The maximum allowable speed was kept to be 5mph above the speed limit.

3.4. Surrogate safety assessment

The surrogate safety analysis involved using FHWA SSAM model which is a software application designed to perform statistical analysis of vehicle trajectory data output from microscopic traffic simulation models. SSAM analyses interactions between vehicles and calculates several surrogate safety measures for each interaction in order to identify conflict events. The conflicts are identified based on the specific thresholds for TTC and PET and the conflict angle. The default value for TTC and PET are 1.5 s and 5.0 s respectively, which are suggested by previous research studies (Gettman and Head, 2003; Gettman et al., 2008). The conflict severity is defined according to the TTC values, low values of TTC and PET indicate high severity levels of expected crashes (Habtemichael and de Picado Santos, 2014), and the lower the TTC value, the more severe the conflict. If $TTC = 0$ and/or $PET = 0$, then SSAM marks the event as a crash; if $0 < TTC \leq 1.5$ s, and $0 < PET \leq 5$ s, then SSAM identifies this event as a conflict. Based on the conflict angle, conflicts are classified into four manoeuvre types: rear-end, lane-change,

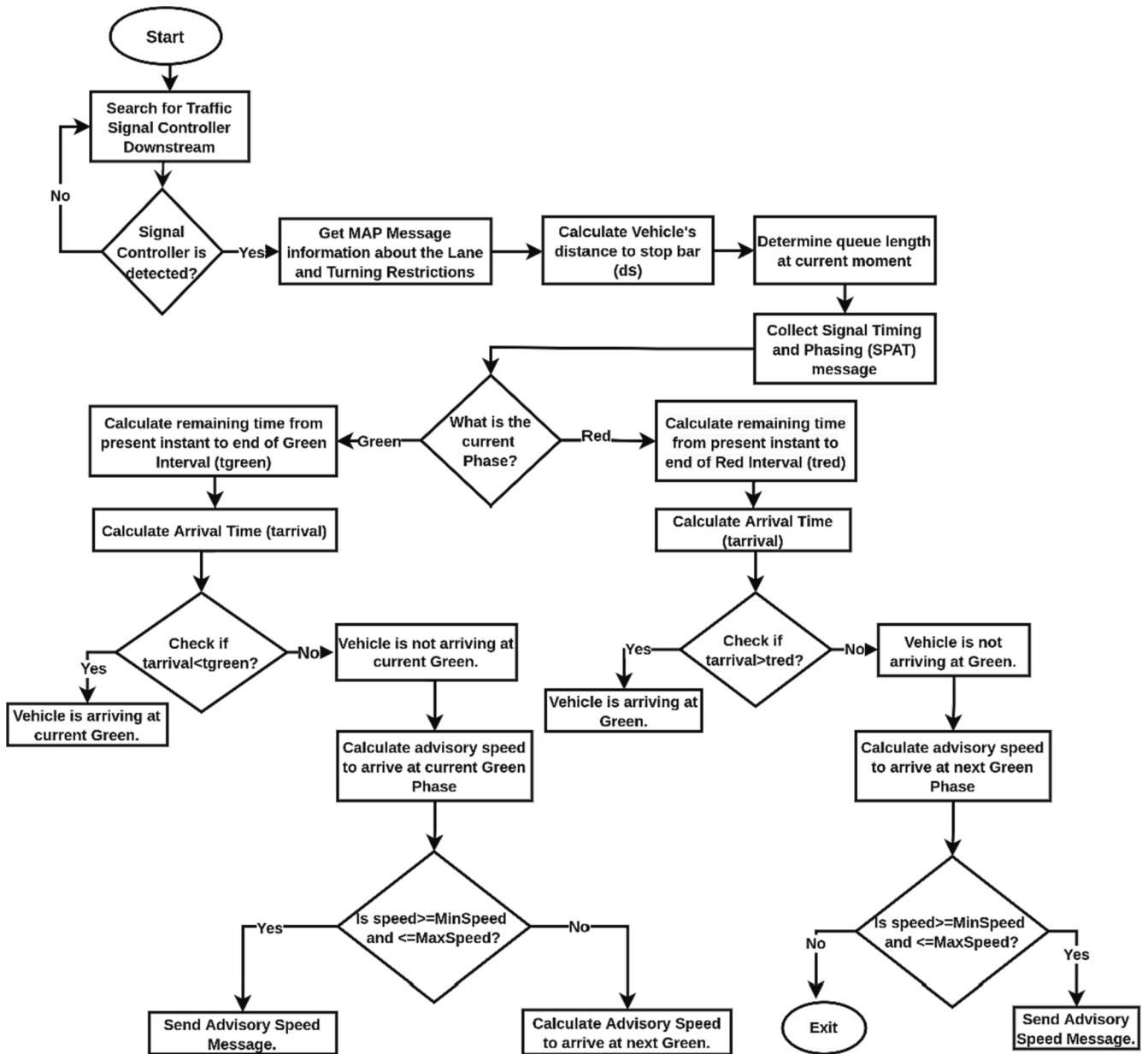


Fig. 5. GLOSA flow chart.

crossing conflicts and unclassified.

In spite of the fact that SSAM is a very useful tool, there are limitations that should be considered while performing the road safety assessment such as the potential misclassification of safe interactions between CAVs as a conflict due to their small headways (Viridi et al., 2019). For this reason, different values of TTC thresholds for every vehicle type were defined based on the literature findings, as presented under Section 2.1. The TTC threshold was set to 1.5 s for human-driven vehicles, 1.0 s for 1st Generation CAVs and 0.5 s for 2nd Generation CAVs.

3.5. Estimating crashes based on conflicts

As discussed earlier, efforts have been made to establish a relationship between conflicts and crashes using both empirical crash data (resulting in a crash-conflict ratio) and theoretical models. Due to the absence of suitable empirical crash data involving automated vehicles, the causal theoretical model proposed by Tarko (2018) is adopted in this

study. Tarko (2018) provided a theoretical and numerical basis for justifying the Lomax distribution to estimate the probability of an observed conflict resulting in a crash during the traffic conflicts observation period. This method relies on TTC distribution and does not require crash data in order to estimate the expected number of crashes. The Lomax distributions used in the method proposed by Tarko (2018) are based on properties of the traffic conflict phenomenon. The Lomax distribution of exceedance x for the values of k (corresponding to traffic conflicts) can be expressed by the following mathematical equation.

$$F(x) = \begin{cases} 1 - (1 + \theta x)^k & \text{if } \theta > 0 \\ 1 - e^{-rx} & \text{if } \theta = 0 \end{cases}$$

Where, r = response rate (1/unit separation), while k and θ are the shape and scale parameter of the distribution, respectively. The response rate can be expressed as $r = k\theta$ (when θ reaches 0 k reaches infinity). Only for certain ranges of k , exceedance x has the mean value and variance. The parameter k can be estimated from the following equation.

$$\hat{k} = \frac{-\sum_{i=1}^n \log\left(1 - \frac{i-0.5}{n}\right) \log\left(1 + \frac{x_i}{s_c}\right)}{\sum_{i=1}^n \left[\log\left(1 + \frac{x_i}{s_c}\right)\right]^2}$$

where: s_c is the threshold separation, x_i is the i th exceedance ordered from the lowest value x_1 to the largest value x_n . The expected number of crashes during the observation period can be formulated as $Q_c = Q_N \times \bar{P}(C|N) = n \times 2^{-\hat{k}}$, where $Q_N = n$ corresponds to the observations on the number of traffic conflicts and crashes during the period of observation. More details of the method can be found in Tarko (2018).

4. Analysis and results

The effects of increasing automation of the vehicle fleet together with the implementation of GLOSA on road safety are quantified based on the methodology described under Section 3. The analysis of the resulting change in conflicts is made for the following cases, including no policy intervention (No GLOSA) scenario as well as with GLOSA implementation scenarios.

1. No policy intervention: baseline scenario with No GLOSA implementation
2. GLOSA on 1 intersection: GLOSA is implemented at 1 intersection in the network.
3. GLOSA on 2 intersections: GLOSA is implemented at 2 intersections in the network.
4. GLOSA on 3 intersections: GLOSA is implemented at 3 intersections in the network.

The analysis of TTC distributions of the traffic conflicts results, obtained from microsimulation and SSAM analysis indicated a large number of TTC events falling at 0 or below 0.1 s (crash or near crash situation), as shown in Fig. 6. Theoretically, the low value of TTC (0.1 s) represents crash/near-crash situation, although the simulation software is not able to model the crash events. In addition, SSAM is likely to mark even safe interactions involving CAVs as conflicts due to shorter headways, and also can assign an event as conflict incorrectly when a vehicle

is unable to complete an initiated lane change due to a congested environment (Viridi et al., 2019). Thus, the number of events with very low values of TTC can be considered as noise/systematic bias which could be either from Aimsun or/and SSAM. Due to this reason, it was decided to remove the noise in the conflicts data with very low TTC values ($TTC \leq 0.1$ s).

The traffic conflicts results involving passenger cars, for the aforementioned analysis scenarios, are presented in Fig. 7. The numbers in the plots represent percentage change in conflicts (normalised per 1000 veh-km) against varying fleet compositions in the study network. The figures in fleet compositions refer to percentage of human-driven vehicles, 1st Generation CAVs, and 2nd Generation CAVs, respectively. These results represent average of 10 simulation runs with different random seeds.

It can be observed through the trends in Fig. 7 that the application of GLOSA system indicate slight changes in number of conflicts as opposed to the no GLOSA scenarios. There is also variation in reduction of conflicts under the implementation on single vs. multiple intersections in the study network. Table 2 presents the percentage change in conflicts under each GLOSA application case with respect to the 100-0-0 scenario.

The results have been further segregated in Fig. 7 into conflict types, i.e., rear-end, lane-change or crossing conflicts. As can be clearly seen, the rear-end conflicts dominate all scenarios. Overall, an interesting trend on conflict types can be observed indicating a slight increase in lane change conflicts with GLOSA application as compared to the baseline scenario. Similar trends on lane change conflicts were also reported by an earlier study investigating the safety impacts of GLOSA system through surrogate safety assessment (Stevanovic et al., 2015b). Rear end conflicts under GLOSA scenarios were only found to decrease at low MPRs of 1st and 2nd Generation CAVs where the maximum reduction was found to be approximately 12 % (under low MPR of 1st Generation CAVs) in case 3 when GLOSA is applied on all 3 intersections as compared to the respective baseline scenario. Overall, a minor increase was observed on crossing conflicts with multiple intersections implementation as compared to the respective baseline and single intersection application, however, the increase was not found to be consistent across all the MPR scenarios.

It can be observed that there is an inherent reduction in conflicts

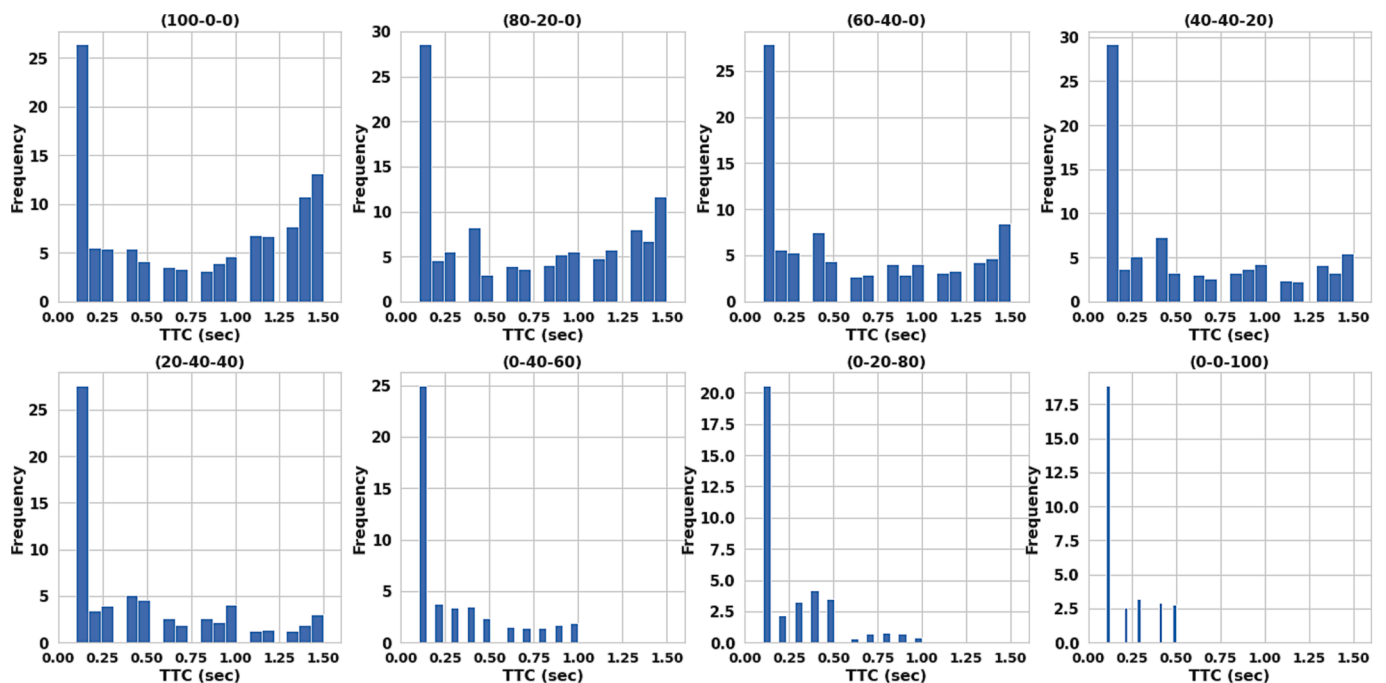


Fig. 6. TTC distribution for baseline scenario.

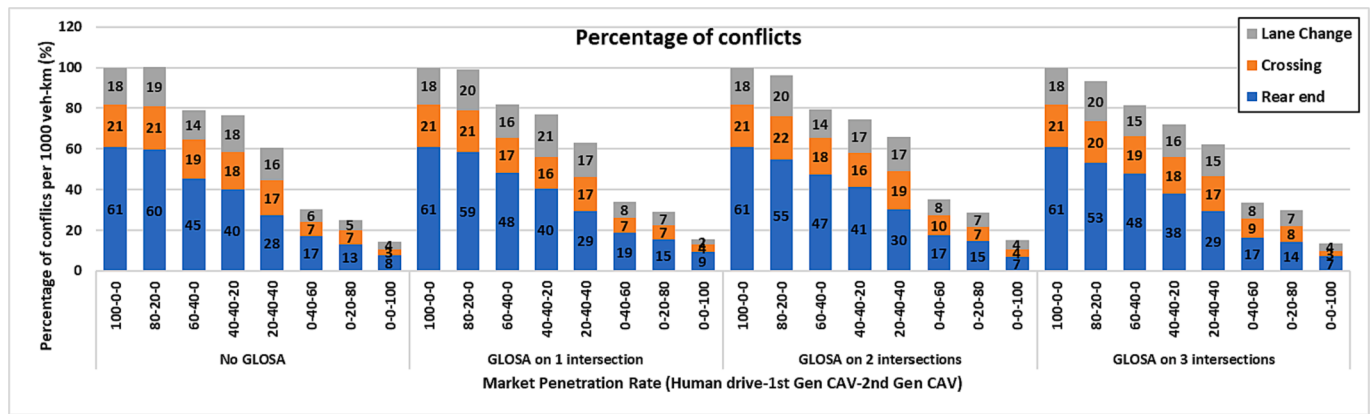


Fig. 7. Percentage of conflicts (w.r.t 100-0-0) per 1000 veh-km travelled based on conflicts type.

Table 2
Percentage change in conflicts (w.r.t 100-0-0) per 1000 veh-km travelled.

Penetration rate	No GLOSA	GLOSA on 1 intersection	GLOSA on 2 intersections	GLOSA on 3 intersections
80-20-0	0 %	-1 %	-4 %	-7 %
60-40-0	-20 %	-18 %	-20 %	-18 %
40-40-20	-23 %	-22 %	-25 %	-27 %
20-40-40	-39 %	-36 %	-33 %	-37 %
0-40-60	-70 %	-66 %	-64 %	-66 %
0-20-80	-74 %	-70 %	-71 %	-70 %
0-0-100	-85 %	-84 %	-85 %	-86 %

Note: Number of conflicts at 100-0-0 are approximately 17 per 1000 veh-km.

evident in results due to the increasing MPR of CAVs, under all the cases. However, when percentage reduction is compared between different cases to find the effect of GLOSA implementation, only the scenarios with low MPR of 1st Generation CAVs (80-20-0) and 2nd Generation CAVs (40-40-20) (Table 2) show potential improvement in safety especially under multiple intersections implementation. However, conflicts results under mixed fleet scenarios especially with higher 1st and 2nd Generation CAVs show either no or slightly lower safety improvement as compared to the without GLOSA implementation scenarios. The 100 % 2nd Generation CAVs MPR scenario (0-0-100) more or less have the same impact as under No GLOSA scenario. It should be noted that some minor variation in percentage figures between Fig. 7 and Table 2, under some scenarios, is due to rounding of the values.



Fig. 8. Impact of Green Light Optimal Speed Advisory (GLOSA) scenarios on the predicted crash rate with increasing automation in the vehicle fleet, compared with no automation and no GLOSA (100-0-0) scenario.

The results on conflicts are further used to estimate the number of expected crashes based on the method explained earlier under section 3.5. Fig. 8 presents the estimated crash rate with and without GLOSA implementation under the increasing MPR of CAVs in the vehicle fleet, presented as percentage change in crashes per 1000 veh-km as compared with 100–0–0 scenario.

Without implementation of GLOSA, the results on estimated crashes show an increase in crash rates at lower MPR scenarios with 1st and 2nd Generation CAVs. This can be explained due to potential disruptions in the traffic stream caused by the inclusion of CAVs in the network, and the resulting interactions between human-driven vehicles and CAVs. Due to the differences in driving styles (e.g., different headways) and capabilities (e.g., human drivers' longer reaction times) between human-driven vehicles and CAVs, this may lead to an initial increase in risks when many human drivers are still on the road. As CAVs become a major part of the fleet composition in the higher MPR scenarios and when conventional human-driven vehicles are no longer present (from 0-40-60 scenario), a significant improvement in safety can be observed.

With regard to safety impacts due to GLOSA, overall, a lower crash rate was found for the implementation of the GLOSA system at multiple intersections as opposed to a single intersection implementation. This difference is most prominent at scenarios with low MPR of 1st and 2nd Generation CAVs, suggesting that its implementation on multiple signalised intersections along the stretch of a road can potentially be useful in some mixed (human-driven and automated) traffic scenarios.

5. Discussion and safety implications

In the following sub-sections, the analysis results from this study and findings from previous literature are discussed collectively with regard to various direct and indirect safety implications of GLOSA system.

5.1. Surrogate safety assessment

The surrogate safety assessment performed within this study showed several inconsistencies in results across varying MPR scenarios and GLOSA implementation schemes. Overall, slight improvement in safety was indicated by results when GLOSA was applied particularly on all 3 intersections as compared to the single intersection implementation, along the study corridor. If the GLOSA implementation scenarios results are compared with No GLOSA scenarios, the impact on the reduction of conflicts was not found to be consistent across all MPR scenarios. Most prominent impact was found to be either under low MPR of 1st or 2nd Generation CAVs. The 100 % 2nd Generation CAVs MPR scenario (0–0–100) was found to have the same impact, more or less, as under No GLOSA scenario. Under mixed fleet scenarios especially with higher 1st and 2nd Generation CAVs, results indicated either no or slightly lower safety improvement as compared to the without GLOSA implementation scenarios. One potential reason could be the assumptions used on modelling behaviours of CAVs and the complexity of interactions under the mixed fleet scenarios with higher MPRs of 1st and 2nd Generation CAVs. The results also indicated a potential impact on the proportions of conflict types, as also reported by [Stevanovic et al. \(2015a\)](#), with potential decrease in rear-end conflicts and slight increase in lane-change conflicts. However, in this study, a slight increase has been observed in lane change conflicts with GLOSA application as compared to the baseline scenario while the rear end conflicts under GLOSA scenarios were only found to decrease at low MPRs of 1st and 2nd Generation CAVs. This study has only analysed safety impacts of GLOSA under a fixed time signal operation, however, [Stevanovic et al. \(2015a\)](#) surrogate safety evaluation with different signal timing schemes() has shown that the number of conflicts only significantly decreases when GLOSA is applied with fixed time signal controllers, and the GLOSA equipped vehicles penetration rate is 100 %.

5.2. Other potential safety impacts

5.2.1. Speed differences

In some situations, GLOSA-equipped vehicles might drive comparably slow. Previous studies have linked speed differences between vehicles to increased crash rates ([Aarts and Van Schagen, 2006](#)). Additionally, speed differences might cause irritation in human drivers, resulting in dangerous manoeuvres and accidents. A study ([Adviesdienst Verkeer en Vervoer, 2001](#)) regarding the implementation of intelligent speed assistant (ISA) systems found that drivers exhibited aggressive driving behaviours in response to the 'slow' driving vehicles.

5.2.2. Copying behaviour (human drivers)

Human drivers might adapt their behaviour due to other vehicles being equipped with GLOSA. A driving simulator study ([Preuk et al., 2018](#)) has shown that drivers mimicked the behaviour of GLOSA-equipped vehicles when they had received detailed information about the system compared to drivers that only received general information or no information about the system. The study also showed smaller minimum TTCs for drivers that received detailed information about the system compared to the other groups. However, both effects are only to be expected if human drivers are well informed about GLOSA and its functionalities and are able to recognize GLOSA-equipped vehicles. We expect that it will take some time after the initial implementation of GLOSA until human drivers are well-informed about the system. Therefore, the effects are only expected with higher penetration rates (assuming that higher penetration rates are linked to a longer period of GLOSA implementation).

5.2.3. Interactions with GLOSA application

In case when human-driven vehicles are equipped with GLOSA, human drivers are able to use a GLOSA application in order to make use of the speed advice. However, in contrast with CAVs, human drivers have to monitor the GLOSA application and manually adjust their driving speed. This might lead to mental overload and distraction, which can negatively affect driving skills and thereby decrease road safety ([Stelling-Konczak and Hagenzieker, 2012](#); [SWOV, 2020](#)). Additionally, humans likely need more time to respond to potentially changing speed advice, which might compromise the accuracy of GLOSA and result in dangerous situations.

5.2.4. Vulnerable road users' (VRU) safety

A well-designed GLOSA system can potentially prevent drivers from being caught up in a dilemma zone as well as reduce red light running incidents, and consequently contribute in decreasing potential red-light running crashes with vehicles and VRUs at signalised intersections. However, the deficiencies and limitations in the system leading to inaccuracies in the advisory speeds estimation could adversely impact the safety at signalised intersections for all road users.

6. Conclusions, Limitations, and future directions

This study has examined the safety impacts of GLOSA considering various traffic composition scenarios with CAVs MPR and assuming only CAVs to be GLOSA equipped. The implementation was tested using a microsimulation model (developed in Aimsun) of a corridor near Salford in Manchester, consisting of three signalised intersections under a fixed time signal scheme. The safety comparisons between **with** and **without** GLOSA scenarios have been performed using surrogate safety measures (traffic conflicts) obtained by post processing the simulated trajectories in SSAM.

While the results of this study show some irregularities in potential safety benefits due to implementation of GLOSA system under different CAVs MPR scenarios in the traffic composition, the scenarios with low MPR of 1st and 2nd Generation CAVs indicate potential improvement in safety especially under multiple intersections implementation. Overall,

the results on estimated crash rates suggest that potential benefits due to GLOSA implementation can be achieved by considering its implementation on multiple successive signalised intersections, adequately spaced along the stretch of a road as compared to the single intersection implementation along such a study corridor. Interestingly, results indicate further improvement under low CAVs MPR traffic scenarios. However, under mixed fleet compositions with 40 % or higher 1st and 2nd Generation CAVs, the results show several irregularities not showing any promising improvement in safety due to GLOSA.

It is important to note that these results are based on various assumptions including the quality of communication between signals and vehicles (ideal and without delay), only CAVs to be GLOSA equipped, and the 100 % advisory speed compliance rate. There are also several dependencies such as related to the network characteristics (e.g., intersection configuration, spacing between intersections, controller type) and GLOSA activation frequency. Additionally, there are limitations due to unavailability of real-world data to calibrate the simulation and SSAM models with respect to modelling CAVs characteristics and identifying interactions involving CAVs as real conflicts.

Nonetheless, the percentage change between the different MPR scenarios and GLOSA implementation schemes provide useful insights towards further investigating the most optimal scenarios of GLOSA implementation for improving safety as well as finding the trade-off between safety and other potential benefits (e.g. mobility and environmental). Future research should perform additional experiments considering some proportions of human-driven vehicles equipped with GLOSA and with varying compliance rates and reaction delays to advisory messages while also testing and analysing the safety impacts on different study areas to identify the variations and transferability of the results. Additionally, the experiments can be further expanded with varying activation frequencies of GLOSA, activation distances, as well as minimum and maximum speed thresholds.

CRedit authorship contribution statement

Amna Chaudhry: Conceptualization, Formal analysis, Methodology, Writing – original draft. **Rajae Haouari:** Formal analysis, Methodology, Writing – original draft. **Evita Papazikou:** Conceptualization, Writing – original draft. **Mohit Kumar Singh:** Formal analysis, Investigation, Writing – review & editing. **Hua Sha:** Formal analysis, Writing – original draft, Writing – review & editing. **Athina Tympakianaki:** Investigation, Methodology, Software. **Leyre Nogues:** Investigation, Methodology, Software. **Mohammed Quddus:** Conceptualization, Methodology, Supervision, Writing – review & editing, Funding acquisition. **Wendy Weijermars:** Formal analysis, Writing – review & editing. **Pete Thomas:** Resources, Supervision, Writing – review & editing, Funding acquisition, Project administration. **Andrew Morris:** Project administration, Resources, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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