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Network-wide safety impacts of dedicated lanes for connected and autonomous vehicles

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ABSTRACT

Cooperative, Connected and Automated Mobility (CCAM) enabled by Connected and Autonomous Vehicles (CAVs) has potential to change future transport systems. The findings from previous studies suggest that these technologies will improve traffic flow, reduce travel time and delays. Furthermore, these CAVs will be safer compared to existing vehicles. As these vehicles may have the ability to travel at a higher speed and with shorter headways, it has been argued that infrastructure-based measures are required to optimise traffic flow and road user comfort. One of these measures is the use of a dedicated lane for CAVs on urban highways and arterials and constitutes the focus of this research. As the potential impact on safety is unclear, the present study aims to evaluate the safety impacts of dedicated lanes for CAVs. A calibrated and validated microsimulation model developed in AIMSUN was used to simulate and produce safety results. These results were analysed with the help of the Surrogate Safety Assessment Model (SSAM). The model includes human-driven vehicles (HDVs), 1st generation and 2nd generation autonomous vehicles (AVs) with different sets of parameters leading to different movement behaviour. The model uses a variety of cases in which a dedicated lane is provided at different type of lanes (inner and outer) of highways to understand the safety effects. The model also tries to understand the minimum required market penetration rate (MPR) of CAVs for a better movement of traffic on dedicated lanes. It was observed in the models that although at low penetration rates of CAVs (around 20%) dedicated lanes might not be advantageous, a reduction of 53% to 58% in traffic conflicts is achieved with the introduction of dedicated lanes in high CAV MPRs. In addition, traffic crashes estimated from traffic conflicts are reduced up to 48% with the CAVs. The simulation results revealed that with dedicated lane, the combination of 40-40-20 (i.e., 40% human-driven – 40% 1st generation AVs– 20% 2nd generation AVs) could be the optimum MPR for CAVs to achieve the best safety benefits. The findings in this study provide useful insight into the safety impacts of dedicated lanes for CAVs and could be used to develop a policy support tool for local authorities and practitioners.

1. Introduction

Cooperative, connected and automated mobility (CCAM), enabled by connected and autonomous vehicles (CAVs), has the potential to change the transport systems fundamentally (Fagnant and Kockelman, 2015). In particular, the advancements of CAVs are expected to improve the driving experience, efficiency, and reduce vehicle emission, especially enhance road safety by removing driver-related errors, which is reported to be a factor in 94 % of vehicle crashes by the National Highway Traffic Safety Administration (NHTSA, 2018). It has been recognised that there must be a transition phase in which human-driven vehicles (HDVs), autonomous vehicles or connected and autonomous vehicles will be operating with as mixed traffic in a long period (e.g., Calvert and Arem, 2020; Ye and Yamamoto, 2018, Gong and Du, 2018; Lee et al., 2019;

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Olia et al., 2018). Hence, the operation of CAVs on a dedicated lane with an uncomplicated environment has been suggested in the literature (Machiani et al., 2021; Mohajerpoor and Ramezani, 2019; Vander Laan and Sadabadi, 2017; Ye and Yamamoto, 2018). Theoretically, the introduction of dedicated AV lanes is supposed to provide an incentive to people to use an automated vehicle, especially during the early stage of AV deployment so as to limit the interactions between humans and AVs which could be proven problematic (Hamad and Alozi, 2022). The aim of proactively examining the feasibility and implications of dedicated lanes for CAVs is to empower decision-makers to make well-informed choices that maximise the positive impacts of automated mobility. By planning ahead and considering the potential benefits and challenges, stakeholders and planners can make informed decisions that will ensure successful implementation that accommodates the needs of all road users.

According to Connected Automated Driving Roadmap from the European Road Transport Research Advisory Council (ERTRAC, 2019), a Dedicated AV Lane is a lane where the vehicle(s) with specific automation level(s) are allowed, but the area is not constrained by a barrier (it would be segregated in that case). It is envisaged that where a dedicated public transport lane is in operation, the dedicated AV lane would be integrated with the dedicated public transport lane, allowing both types of vehicles. In principle, the concept of dedicated lanes originates from the high occupancy vehicle (HOV) and toll (HOT) lanes. This type of lane was reserved for the exclusive use of vehicles with a driver and one or more passengers, including carpools, vans and transit buses. The first application of HOV lane was made around the 1970s. In theory, the implementation of this type of lane was supposed to encourage people to car share and carpool. However, the evaluation of the HOV lanes showed that they were underutilised, and hence the concept of HOT lanes was introduced where single-person vehicles are allowed to drive in these lanes if they pay a fee. Theoretically, the introduction of dedicated AV lanes is supposed to provide an incentive to people to buy an automated vehicle and simultaneously, to optimise the traffic benefits of CAVs. This is especially true during the initial phase of AV deployment to limit the interactions between humans and AVs, which could raise potential crash risks.

Quantifying how CAVs dedicated lanes (CAV DL) affect the safety of a transport network in real-world conditions is very challenging due to the lack of real-world data on CAV operations at a network or a corridor level. Although the impact assessment is basically demand-led, the primary inputs are CAV deployment scenarios based on the scenario captured, the development and the specification of the models. In addition, a review of existing literature reveals a lack of knowledge on safety impacts of CAVs dedicated lanes (Razmi Rad et al., 2020). In this regard, this study used traffic microsimulation techniques to analyse the safety impacts of CAV DL and provided the methodology for estimating the safety impacts in terms of the expected number of crashes. While many studies rely only on traffic conflicts in evaluating the safety impact, this paper utilises a new probabilistic approach to estimate the expected number of crashes through traffic conflicts identified through microsimulation. The study is based on one of the sub-use cases in the LEVITATE (Societal level impacts of connected and automated vehicles) project, which was a European Commission supported H2020 project that aimed to develop a new impact assessment framework that would help European cities regions and policymakers to prepare and manage the introduction of automated vehicles in passenger cars, urban transport services and urban logistics (LEVITATE, 2021).

The remaining parts of this paper are structured in five more sections. Section 2 presents a comprehensive literature review that focuses on a simulation-based approach and safety evaluation through surrogate safety measures, Section 3 discusses the methodology of the microsimulation platform and a probabilistic approach proposed by Tarko (2018) and followed by the simulation results presented in Section 4. Finally, a discussion and conclusion, including future work, are presented in Sections 5 and 6, respectively.

2. Literature review

This literature review explores the investigation of the safety impacts of dedicated lanes using microsimulation platform approach and surrogate safety measures that have been applied in the study. It is worth noting that few of the studies reviewed evaluated the safety impact of dedicated lanes. Understanding the limitations of current technology is necessary as there is very limited availability of data to investigate the impacts of CAVs in the operational context.

2.1. Impact of dedicated lanes with CAVs and HDVs

Several studies attempted to predict the impacts of dedicated lanes using a traffic simulation approach (Razmi Rad et al., 2021; Mohajerpoor and Ramezani, 2019; Rahman & Abdel-Aty, 2018). For instance, Ye and Yamamoto (2018) presented a study to analyse the behaviour of CAVs with a dedicated lane in mixed traffic conditions with the help of fundamental diagrams. In this study, a two-lane cellular automaton model was developed, and the findings indicated that the benefit of establishing a dedicated CAV lane is only achievable at a modest CAV density range. The penetration rate of CAVs and their individual performance are critical factors in determining how efficiently a CAV dedicated lane performs. A similar study conducted by Mohajerpoor and Ramezani (2019) analysed the characteristics of the mixed-traffic flow of AVs and NVs (Normal Vehicles) based on headways on a two-lane arterial link road with interrupted traffic flow (i.e., traffic signals) and derived a model via microsimulation experiments. The main aim of this study was to test this model, but along with this, the delay effects of various lane allocations, including dedicated AV lanes, were investigated. Four-lane allocation policies were analysed for their delay effects on the specified two-lane link road: (a) dedicated lanes (one AV, one NV), (b) mixed-mixed lanes (both lanes for mixed traffic), (c) mixed-NV lanes (one for NV and one for mixed traffic), and (d) mixed-AV lanes (one for AV and one for mixed traffic). The best lane-allocation policies were found to be the mixed-NV lanes policy where the Expected Penetration Rate (EPR) ranges between 0 % and 50 %; the dedicated lanes policy for 50 %< EPR < 65 %; and the mixed-AV lanes policy for 65 % EPR 100 %.

Vander Laan and Sadabadi (2017) investigated the impact of the operational performance of autonomous vehicles (AVs) on a multi-lane freeway corridor with separate lanes dedicated to AV and non-AV traffic. Newell's linear car-following model applied to a 22-mile stretch of the 4-lane I-95 corridor between Washington, DC and Baltimore, MD during the afternoon peak period (16:00–18:00). The impact of introducing an AV-only lane is assessed at numerous AV penetration rates, with Vehicle Hours Travelled (VHT), Vehicle Miles Travelled (VMT), average speed and vehicle throughput all observed against AV penetration rate. Under one AV dedicated lane, the results showed that as penetration rates increased up to 30, 40 or 50 %, overall corridor performance metrics (VHT, VMT, speed, throughput) improved; however, further AV penetration considerably worsened the overall traffic performance since AVs were the dominant type of car but were restricted to only one lane.

A conceptual framework for the design and operation of dedicated lanes on motorways was designed by Razmi Rad et al. (2020), accounting for changes in driver behaviour, traffic flow performance, safety, and environment and the existing gaps in literature. Their research focused on dedicated lanes which are an "existing lane of the motorway dedicated only for fully or partially automated vehicles with or without connectivity". The research identified several gaps in the current state of knowledge, particularly in terms of understanding relations between dedicated lane design, MPR of CAVs, utilisation policy, driver behaviour, traffic efficiency, safety, and environment. Machiani et al. (2021) aimed to evaluate the safety and operational impacts of AVs based on an innovative infrastructure solution. A historical crash data analysis and a traffic simulation were conducted to investigate the implications of adding a narrow reversible AV-exclusive lane to the existing configuration of the I-15 expressway in San Diego. Three main scenarios were investigated including (i) baseline (current configuration), (ii) adoption of AVs with existing volumes/network and (iii) the introduction of AV exclusive lane alongside AV adoption. Crash data analysis revealed that AVs' automated longitudinal and lateral control systems could potentially reduce the types of collisions caused by excess speed, improper turning, and unsafe lane change on an AV-exclusive lane with proper infrastructure features for AV sensor operation. The microsimulation results also showed that an AV-exclusive lane could increase traffic flow and density by up to 14 % and 24 %, respectively.

Another study recently conducted by Razmi Rad et al. (2021) investigated the behavioural adaptation in car-following and lane-changing behaviour when HDVs drive next to a dedicated lane for CAVs in a mixed traffic situation. A driving simulator was conducted with 51 participants on a 3-lane motorway in three different traffic scenarios. The results showed that there is no significant difference in the driving behaviour between baseline and mixed scenarios. However, human drivers tend to drive closer to their leaders when driving on the middle lane adjacent to the platoons in a dedicated lane scenario. A similar study using a driving simulator experiment was conducted to investigate the behaviour of human drivers in a dedicated lane with different road design configurations on motorways (Schoenmakers et al., 2021). A repeated-measures ANOVA was applied, and 34 licensed drivers between ages 20–30 participated in the study. The study revealed that the behaviour of human drivers operating in the proximity of AV platoons was influenced significantly by the type of separation between the dedicated lane and the other lanes. The results also indicated that human drivers kept a much lower time headway when driving close to a continuous access dedicated lane compared to a limited-access dedicated lane for AV platoon.

In He et al. (2022), a theoretical method for discussing the influence of implementing a CAV dedicated lane policy on traffic efficiency using calculations from previous studies is proposed. The main impacts measured were capacity and throughput. The effects of various CAV dedicated lanes were analysed. Dedicated lane policies were made up of 3 main aspects, these being eligibility, a number of dedicated lanes and access control type (i.e., "mandatory" and "optional"). The effects of lane types (Dedicated, General Purpose and Mixed) and different types of headways were also considered. One of the main observations made in this study is that when the Market Penetration Rate (MPR) of CAVs on a section of freeway is low, implementing a CAV dedicated lane doesn't lead to a significantly positive impact on traffic efficiency. In this scenario, "mandatory" use dedicated lane would be recommended to maximise any limited positive effects. Whereas when MPR becomes high, "optional" use of dedicated lanes would be more effective.

2.2. Safety evaluation through surrogate safety measures

Previous studies have also made efforts to analyse the safety impacts of CAV dedicated lanes, through surrogate safety measures, for the safe deployment of CAVs in the transport system. In this regard, Otero-Niño et al. (2019) provided a dedicated bus lane and observed its safety impact with the help of SSAM (Pu and Joshi, 2008). It was found that dedicated lanes improve safety. Campisi (2020) also evaluated the safety of cyclists and concluded that safety could be significantly improved with dedicated lanes. Further, Chai et al. (2020) investigated the safety effects of varying CAVs penetration rates with the External Intelligent Driver Model for modelling the CAVs behaviours. A microsimulation software was used to model the dedicated lane on a 7 km segment of the four-lane Ninghu Freeway in China with mixed traffic, including freight vehicles. TTC (Time to Collision), Time Exposed Time-to-collision (TET) and Time Integrated Time-to-collision (TIT) indicators were used to build a relationship between simulation data and longitudinal crash risk. Rear-end Crash Risk Index (RCRI) was used to determine the rear-end crashes. Lateral safety (e.g., angle and sideswipe crash risk) was evaluated by analysing the number of lane change conflicts (LCC) using the SSAM. The study concluded that one dedicated lane could improve safety in low volume scenarios, whereas for high volume demand, two exclusive lanes provide more safety. Moreover, the presence of Heavy Goods Vehicle (HGVs) can significantly worsen the longitudinal safety in low MPRs.

Rahman and Abdel-Aty (2018) have also attempted to assess the longitudinal safety of Connected Vehicle (CV) platoons on a busy congested expressway. The Intelligent Driver Model (IDM) and the concept of platooning were utilised to define the behaviours of CV. In this study, an expressway in Florida with 17 weaving segments was specifically selected to apply the IDM model. A comparison of the implementation of (i) managed-lane CV platoons and (ii) all-lane CV platoons with a non-CV scenario was undertaken. Five measures were used as indicators for safety evaluation, which were (i) standard deviation of speed, (ii) TET, (iii) TIT, (iv) time exposed rear-end crash risk index (TERCRI), and (v) sideswipe crash risk (SSCR). Both CV approaches were found to significantly improve the longitudinal safety compared to the non-CV scenario and the managed-lane CV platoons significantly outperformed all lanes CV platoons in terms of all five surrogate safety measures.

A study by Jantarathaneewat (2019) aimed to evaluate different passing lane configurations on a CAV dedicated lane and looked at the main impacts on safety in addition to capacity and traffic operation. The three main configurations were (i) dedicated lane without passing, (ii) dedicated lane with partial passing section or 2 + 1 configuration, and (iii) CAV allowed to use the manual lane as a passing lane. The Surrogate Safety Assessment Model (SSAM) software was used to evaluate the impacts on safety, and to measure this, rear-end collision rates and lane change collision rates were used. The results highlighted that having a dedicated lane with a partial passing section or 2 + 1 configuration gave lower accident rates than other scenarios, optimally, when both flow and the heavy vehicle penetration rates are high. When the AVs are allowed to use both types of lanes (i.e., use the manual lane as a passing lane), it can negatively impact the traffic in adjacent manual lanes, leading to a higher rate of accidents.

A recent study by Abdel-Aty et al. (2020) attempted to analyse the safety and operational impact of connected vehicles (CVs) on a 9-mile managed lanes network with a dynamic toll pricing system in Miami-Dade County, Florida. Traffic conflicts were collected and analysed by SSAM in both peak and off-peak traffic conditions. A Negative Binomial model and a Tobit model were developed to identify the optimal CV lane configuration and MPR% scenarios that affect the safety and traffic operation performance measures (i.e., average speed, average delay). The results revealed that there was no significant improvement when MPR was at or below 10 % compared to the base case scenario with no CVs. MPR between 10 % and 30 % was recommended when the CVs were only permitted in the managed lanes. The finding suggested that the optimal MPR% might range between 70 % and 100 % if CVs were given access to all network lanes (managed lanes, general-purpose lanes, and CV lane).

Evaluation of Dedicated AV Lane literature showed that the impact of dedicated lanes on traffic and safety could vary based on the MPR of AVs and the number of lanes (both dedicated and total number). Generally, the implementation of dedicated AV lanes shows promising potential for enhancing overall safety on the roads. Furthermore, it can be deduced that traffic performance experiences significant improvements when dedicated lanes are introduced, leading to enhanced VHT, VMT, speed, throughput, and other related parameters (Vander Laan and Sadabadi, 2017; Machiani et al., 2021).

3. Methodology

The evaluation of the safety impacts of a dedicated lane for CAVs was conducted in a suburban environment using a calibrated and validated microsimulation model of the road network of Manchester area (made available by the city of Greater Manchester). The methodology for safety evaluation was based on surrogate safety assessment by identifying traffic conflicts through vehicular trajectories obtained by integrating a microsimulation framework (AIMSUN Next) with the SSAM (Pu and Joshi, 2008). Traffic conflicts were then translated to estimate the number of crashes using a probabilistic methodology proposed by Tarko (2018). The flow chart in Fig. 1 presents the steps involved in the methodology.

In the following sub-sections, the details are presented on key characteristics of (i) the simulation network, (ii) CAVs parametric assumptions and deployment scenarios, (iii)the SSAM that was used to extract the potential conflicts from the vehicle trajectory data, and (iv), the probabilistic approach proposed by Tarko (2018) to estimate the crash rates.

3.1. *Simulation network*

A calibrated and validated traffic microsimulation model of the Manchester sub-urban area (provided by Transport for Greater Manchester) was used for this sub-use case. The Manchester network is around a 13 km^2 area from the Greater Manchester Area (UK) that contains 308 nodes, 732 road sections, and an OD matrix of 58x58 centroids from the network. Traffic data of evening peak hours (17:00–18:00) was used, with an estimated traffic demand of 23,226 cars, 1,867 large goods vehicles (LGV), and 63 heavy goods vehicle (HGV) trips. This model was used to evaluate the impact of dedicated AV lanes.

A comprehensive set of traffic counts was used to calibrate and validate the modelled flows with observed traffic counts (e.g., peak hour traffic demand, vehicle types, signal timing data, vehicular behaviour, lane usage, journey times, bus routes, stations, and timetable information). Modelled journey times were also compared and validated against observed journey times during peak hours. This model provided a good foundation for the experiment as it included a motorway and a major arterial road (M602 and A6, respectively) that have been selected to introduce CAV-dedicated lanes and study their safety impacts (Fig. 2).

According to the Department of Transport (DfT), a motorway in the UK is a strategic road that facilitates significant traffic movement between densely populated areas. It is classified as a ‘Special Road’ where specific types of traffic are prohibited. Motorways typically consist of three or more lanes in each direction and have a maximum speed limit of 70mph. Additionally, A-road, often referred to as the ‘main’ roads, accommodate significant traffic flows, although generally not as high as motorways. These roads play a crucial role in facilitating efficient and convenient travel for both individuals and goods across various locations.

The following assumptions were made for this study:

- CAVs are always in automated mode.
- When introduced, the dedicated lane will be mandatory for CAVs and public transport. This means that the CAVs are not allowed to travel in any other lane unless they cannot follow their route in any other way.
- The dedicated lane is either the innermost or the outermost lane of the motorway or the A-road according to the scenario studied.

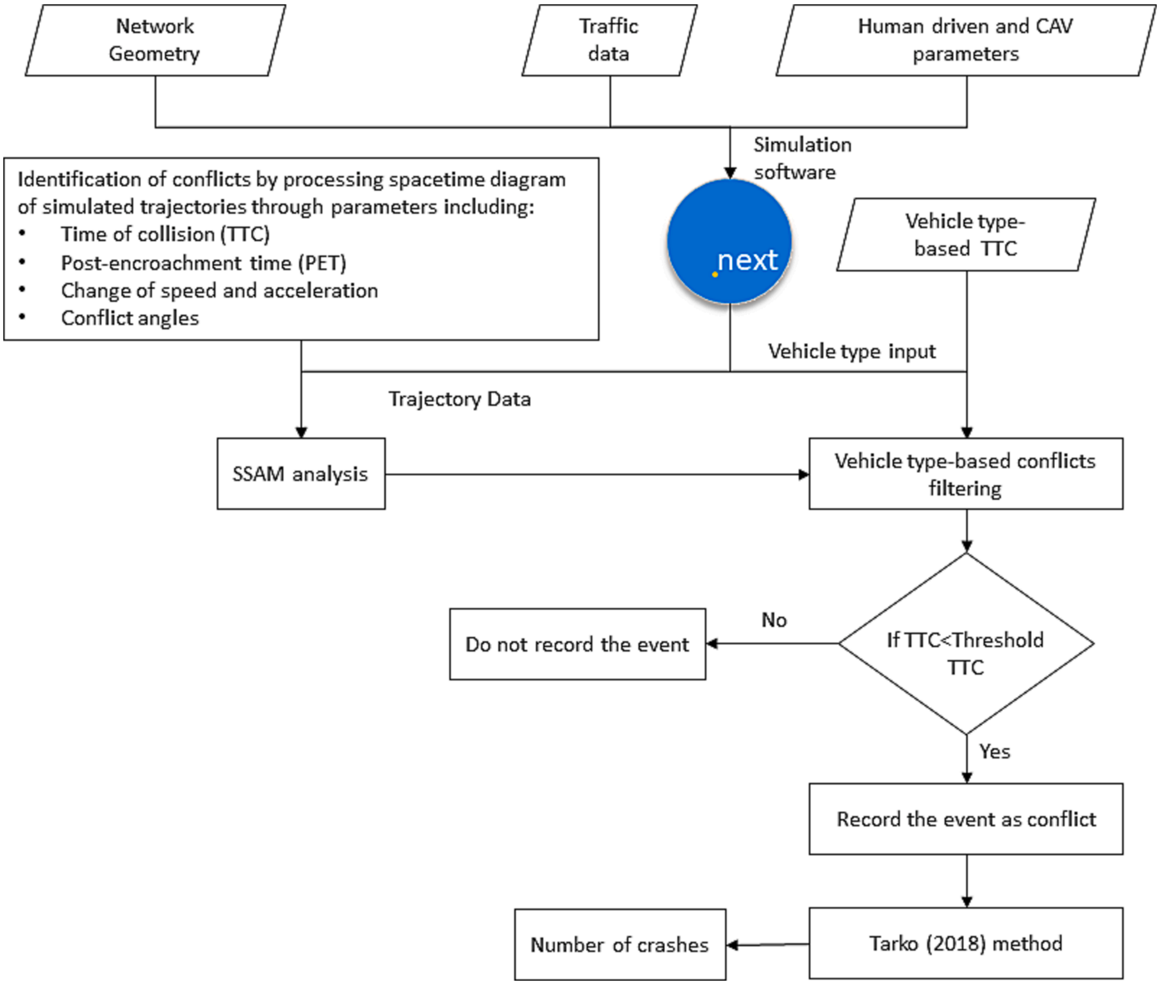
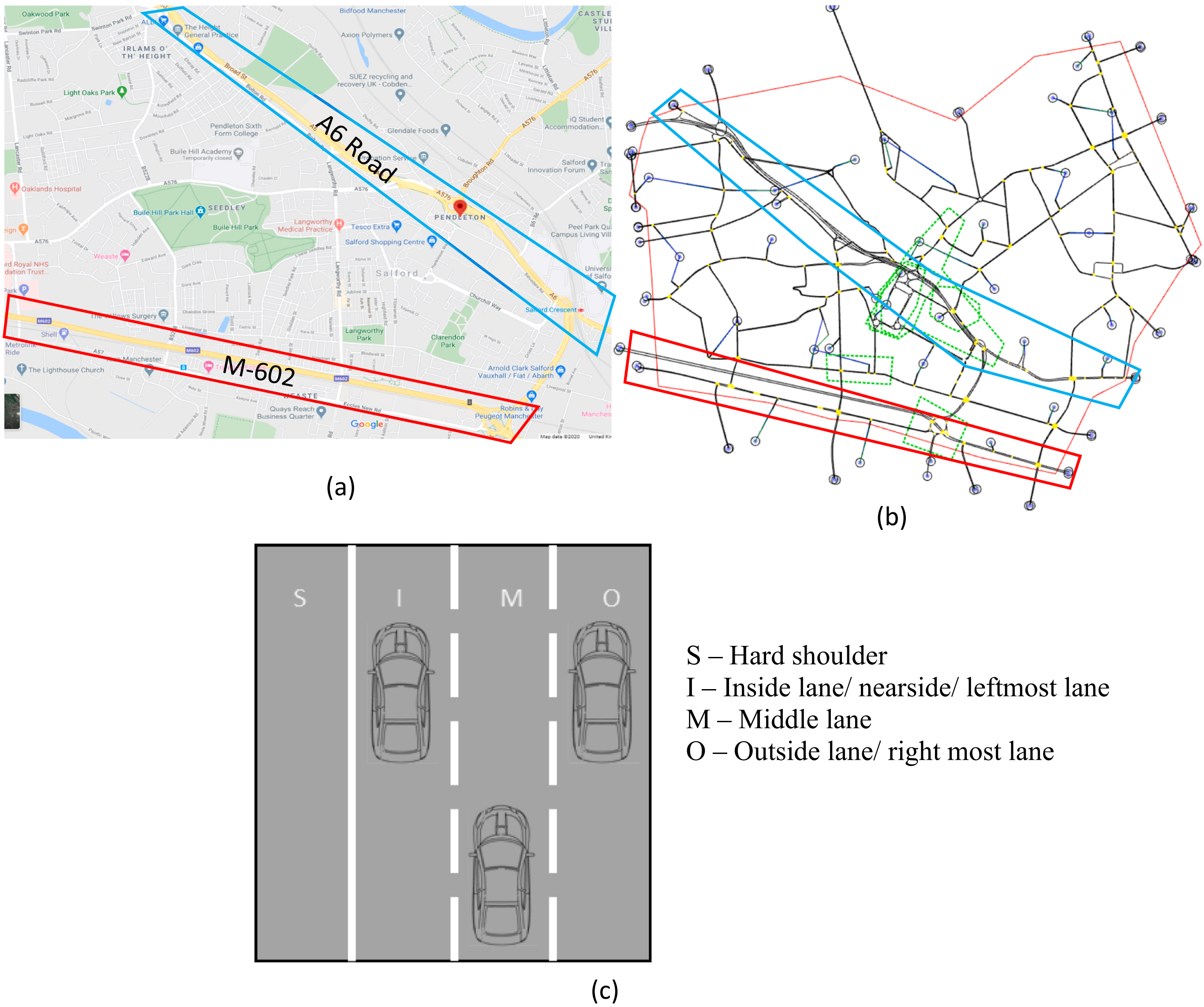


Fig. 1. Methodology flow chart.



(a)

(b)

(c)

Fig. 2. (a) The modelling area in the city of Manchester (b) and network in AIMSUN Next software (c) Road configuration in the UK.

- The A-road consists of several consecutive segments which comprise of either two or three lanes. It is always assumed that one of these lanes is a dedicated lane, except in intersections when one cannot define a dedicated lane due to software constraints.

In order to address the question of what the minimum required MPR for dedicated lanes should be to be a viable option, several mixed fleet combinations including HDVs and CAVs with different market penetration rates were tested in each of the aforementioned scenarios. It is important to note that in most scenarios, the innermost lanes were utilised as dedicated lanes. This choice was made based on the common practice of allowing traffic to freely flow in these lanes. The allocation of these lanes as dedicated lanes serves the purpose of facilitating a more streamlined and efficient traffic flow, while also maximising the utilisation of the available road space. A scenario for outermost ones was also tested to observe the effects of dedicated lanes on overtaking lane. The placement of dedicated lane was investigated under various scenarios including:

- No policy intervention “No CAV Dedicated Lane” (CAV DL) – CAV implementation without a dedicated lane;
- Motorways innermost lane (inside/nearside/leftmost lane) placement (Fig. 2c)– CAVs use a dedicated lane in the motorway;
- Motorway and A-roads innermost lane (inside/nearside/ leftmost lane) placement – CAVs use a dedicated lane in the motorway and the A-road;
- A-roads innermost lane (inside/nearside/ leftmost lane) – CAVs use a dedicated lane in the A-road;
- A-road outermost lane (outside/right most lane) – CAVs use a dedicated lane in the A-road;

3.2. CAV parameters and deployment scenarios

The traffic microsimulation method was applied to examine the potential impacts of connected and autonomous vehicles (CAVs) under different traffic conditions. In this study, the AIMSUN Next microsimulation tool was used. Within LEVITATE, two types of CAVs were considered: 1st Generation (Gen) CAVs and 2nd Gen CAVs. Both types were assumed to be fully automated vehicles with level 5 automation. The main idea behind modelling these two types was that technology will gradually advance with time. Therefore, 2nd Gen CAVs will have improved sensing and cognitive capabilities, decision making, driving characteristics, and anticipation of incidents etc. In general, the main assumptions of CAV characteristics were as follows:

- 1st Gen: limited sensing and cognitive ability, long gaps, earlier anticipation of lane changes than HDVs and longer time in give way situations.
- 2nd Gen: advanced sensing and cognitive ability, data fusion usage, faster decision making, smaller gaps, earlier anticipation of lane changes than HDVs and less time in give way situations.

The two types of CAVs (1st Gen CAVs and 2nd Gen CAVs) were assumed to be electric vehicles (EVs) and all HDVs are non-EVs. The deployment of CAVs was tested from 0 to 100 % MPR with 20 % increments across the LEVITATE project as shown in Table 1. It is worth noting that creating a dedicated lane in a simulation with only one type of mode can lead to underutilisation of the roads. In order to address this, dedicated lanes were provided for mixed fleets. In line with the recommendations of (Abdel-Aty et al., 2020), when the proportion of connected autonomous vehicles (CAVs) reaches 70–100 %, any lane can be utilised without the need for dedicated lanes. As a result, the study adopted mixed fleets with MPRs of 80-20-0, 60-40-0, 40-40-20, and 20-40-40 (HDVs –1st Gen CAVs- 2nd Gen CAVs) (highlighted in orange colour in Table 1). For each scenario, 10 replications with different random seeds were simulated to replicate the stochastic nature of the traffic flow. The simulation was run for the peak hour (17:00–18:00) duration with a warm-up time of 20 min while the simulation time step was set to 0.1 sec.

The Gipps lane-changing model was applied in AIMSUN Next (Gipps, 1981, 1986). The CAV parameters used in this study were derived from the LEVITATE project (Table 2). The assumption on CAV parameters and their values was based on a comprehensive literature review (e.g., Cao et al., 2017; Eilbert et al., 2019; Goodall and Lan, 2020; de Souza et al., 2021; Shladover et al., 2012) and discussion in meetings with experts. The details on the parametric assumptions and values of key parameters can be found in a study by Chaudhry et al. (2022).

3.3. *Identifying traffic conflicts*

To quantify the potential safety impacts, the SSAM was applied to identify the traffic conflicts from vehicular trajectories data. SSAM is a safety evaluation application provided by the Federal Highway Administration (FHWA) of the United States. In SSAM, conflicts are identified based on the specific thresholds for time-to-collision (TTC), and post-encroachment time (PET) and the conflict angle. Based on the conflict angle, conflicts were classified into four manoeuvre types: rear-end, lane-change, crossing conflicts and unclassified (see Fig. 3). A rear-end conflict is defined as a potential collision while car following and changing lanes (Virdi et al., 2019). A lane-change conflict occurs when a vehicle is changing lanes and there is a trajectory cross-point with another fast-approaching vehicle (Li et al.,). The crossing conflict determines potential collisions in head-on situations, such as during intersection manoeuvres (Virdi et al., 2019). The default value for TTC and PET are 1.5 and 5.0 s which were suggested by previous studies (Gettman and Head, 2003; Gettman et al., 2008). A low TTC and PET value indicate high severity levels of expected crashes (Habtemichael and Santos, 2014). The lower the TTC value, the more severe the conflict, if TTC = 0 and/or PET = 0, then SSAM marks the event to be a crash; if 0 < TTC<=1.5 s, and 0 < PET<=5s, then SSAM identifies this event as a conflict.

Table 1
CAV Deployment scenarios in LEVITATE project.

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 Vehicle - passenger vehicle	100 %	80 %	60 %	40 %	20 %	0 %	0 %	0 %
1st Gen CAV - passenger vehicle	0 %	20 %	40 %	40 %	40 %	40 %	20 %	0 %
2nd Gen CAV - passenger vehicle	0 %	0 %	0 %	20 %	40 %	60 %	80 %	100 %
Human-Driven LGV	100 %	80 %	40 %	0 %	0 %	0 %	0 %	0 %
LGV-CAV	0 %	20 %	60 %	100 %	100 %	100 %	100 %	100 %
Human-Driven HGV	100 %	80 %	40 %	0 %	0 %	0 %	0 %	0 %
HGV-CAV	0 %	20 %	60 %	100 %	100 %	100 %	100 %	100 %

Although SSAM is considered a very useful tool, there are several limitations that should be taken into account while assessing road safety. For example, due to the small headways between CAVs, a safe interaction could be misclassified as a conflict (Virdi et al., 2019). Therefore, different TTC thresholds values for every vehicle type were considered based on the literature (Morando et al., 2018; Sinha et al., 2020; Virdi et al., 2019). Within LEVITATE, the TTC threshold was set to 1.5 s for HDVs, 1.0 s for 1st Gen CAVs and 0.5 s for 2nd Gen CAVs. In addition, there are still some controversies remain regarding the using of simulated conflicts to assess safety. One of the major concerns was that the vehicle trajectory files generated by microsimulation models cannot accurately reflect the complex driving behaviour in the real world (Huang et al., 2013). It is worth noting that in this study, the PET threshold of 5.0 s was set as the default value in SSAM. Conducting sensitivity analysis using both TTC and PET values for all scenarios can be very time-consuming, hence only TTC values for different types of vehicles were considered in this study. Furthermore, using TTC as a surrogate safety measure for safety assessment is one of the most common approaches, which has been adopted by many other researchers (i. e., Shi et al., 2020; Zhang et al., 2020; Mahmud et al., 2019; Li et al., 2017).

3.4. *Converting the number of conflicts to the number of crashes*

Even though conflicts as a surrogate safety measure provide a number of practical advantages from a research perspective, it is still important to link conflicts to crash rates in order to draw conclusions about the resulting traffic safety implications. Previous research using the observed number of crashes and conflicts proposed an empirical relationship between crashes and conflicts based on the crash-conflict ratio (Hauer, 1982; Hydén, 1987; Migletz et al., 1985). However, this is limited by the availability and generalisability of empirical data. Therefore, a theoretical model is particularly useful in translating conflict output from SSAM to crash predictions. Due to the lack of adequate empirical crash data involving autonomous cars, the number of conflicts in the LEVITATE project was translated to the number of crashes using a probabilistic technique given by Tarko (2018). A theoretical and numerical basis for validating the Lomax distribution for estimating the chance of an observed conflict resulting in a crash within the reported time period of vehicular conflicts was discussed in the author's approach. This technique uses TTC distribution to predict the expected number of crashes and does not require crash data. In this method a collision is avoided if the necessary evasive manoeuvre is predicted to be performed quickly enough. Initial validation efforts show that the evasive manoeuvre response delay follows a Lomax distribution (Tarko, 2021; Tarko, 2020; Tarko and Lizarazo, 2021). The Lomax distributions used in the method proposed by Tarko (2018) are based on the properties of the traffic conflict phenomenon. It is represented by the following equation:

Table 2
Human-driven vehicle and CAV parameters in LEVITATE project (Chaudhry et al., 2022).

Parameter	Description	Human-Driven Vehicle	1st Generation CAV	2nd Generation CAV
Reaction time in car following (Reaction Time) (s)	It is related to the time gap that elapses between rear end of the lead vehicle and front bumper of following vehicle.	0.8	0.9	0.4
Max. acceleration (m/s^2)	Maximum acceleration that a vehicle can achieve under any circumstances	5 (3, 0.2, 7) Mean (min, dev, max)	4.5 (3.5, 0.1, 5.5) Mean (min, dev, max)	3.5 (2.5, 0.1, 4.5) Mean (min, dev, max)
Normal deceleration (m/s^2)	Maximum deceleration a vehicle can use under normal conditions	3.4 (2.4, 0.25, 4.4) Mean (min, dev, max)	4 (3.5, 0.13, 4.5) Mean (min, dev, max)	3 (2.5, 0.13, 3.5) Mean (min, dev, max)
Max. deceleration (m/s^2)	Maximum deceleration a vehicle can use under special circumstances, such as emergency braking.	5 (4.0, 0.5, 6.0) Mean (min, dev, max)	7 (6.5, 0.25, 7.5) Mean (min, dev, max)	9 (8.5, 0.25, 9.5) Mean (min, dev, max)
Clearance (m)	The distance a vehicle keeps between itself and the leading vehicle when stopped.	1 (0.5, 0.3, 1.5) Mean (min, dev, max)	1 (0.8, 0.1, 1.2) Mean (min, dev, max)	1 (0.8, 0.1, 1.2) Mean (min, dev, max)
Safety margin factor	It generates give-way behaviour at unsignalised junctions. The higher the value indicated more cautious behaviour.	1	[1;1.25]	[0.75;1]
Look ahead distance factor (anticipation of lane change)	It determines where the vehicles consider their lane change	[0.8;1.2]	[1.1;1.3]	[1;1.25]
Overtaking	It controls overtaking manoeuvres when a vehicle changes lanes to pass another.	Begin at 90 %, Fall back at 95 %	Begin at 90 %, Fall back at 95 %	Begin at 85 %, Fall back at 95 %

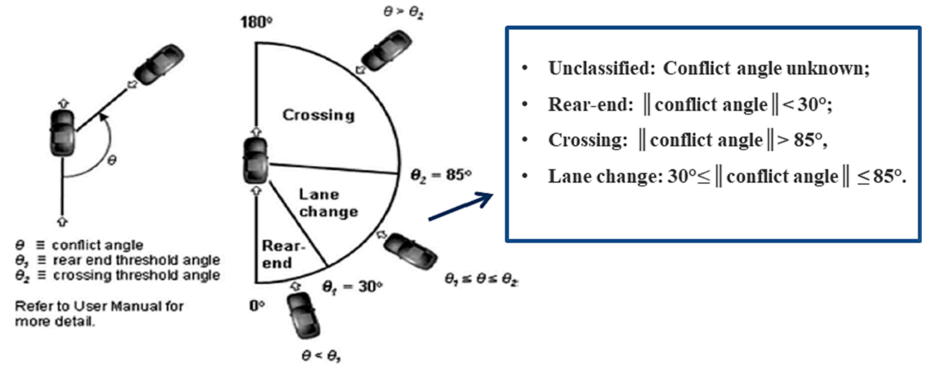


Fig. 3. Conflict types classified by angle (Pu and Joshi, 2008).

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

The relationship between average response rate *r*, *k*, and θ can be expressed as $r = k\theta$ at the limit where θ reaches 0 while k reaches infinity (exponential distribution). Exceedance x, used as response delay, is measured as the difference between threshold separation s_c (such as TTC) and observed the smallest separation (s_m) i.e., x = s_c-s_m. In conducting initial validation efforts in other studies (Tarko, 2020; 2021; Tarko and Lizarazo, 2021), the response delay of the evasive manoeuvre is shown to follow a Lomax distribution. Due to the adequacy of the proposed method by Tarko (2018) to estimate the probability of crashes from identified conflicts, this approach was selected for translating conflicts to potential crashes.

Specific ranges of k are used to calculate the exceedance x. The k is calculated with the help of the following equation:

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

In this equation, threshold separation is represented by s_c, i_{th} exceedance ranging from lowest x_1 to largest x_n is represented by x_i. Expected number of crashes (Q_c) during the observation period are represented by Q_C as shown below:

$$Q_c = Q_N \times \overline{P}(C|N) = n \times 2^{-\hat{k}} \tag{3}$$

Where Q_N (=n) is the number of conflicts in the study period.

4. Analysis and results

In the following section, the results from the microsimulation and SSAM analysis are presented. The first subsection explains the results of the TTC distribution relating to traffic conflicts. It is followed by the results of the total conflicts normalised by distance travelled based on conflict type. The last subsection presents the approach to estimate crashes from conflicts proposed in a study by Tarko (2018).

4.1. TTC distribution

The TTC value distributions were examined to analyse the range of conflict events identified in the simulation. Fig. 4 illustrates a series of TTC distributions in the network based on the fleet market penetration rate. The TTC thresholds were set to 1.5 s for HDVs, 1.0 s for 1st Gen CAVs and 0.5 s for 2nd Gen CAVs, as discussed in the methodology section. In Fig. 4, it can be clearly observed that a significant number of events are falling at very low TTC values i.e., at 0.1 s. Theoretically, the low value of TTC (0.1 s) represents the crash/near-crash situation, although the simulation software is not able to model the crash events. It was observed that a large number of TTC values were equal to zero, which indicated that the microscopic simulation tools may produce unrealistic simulated crashes (Huang et al., 2013; Gettman et al., 2008). In addition, SSAM is likely to mark even safe interactions involving CAVs as conflicts due to shorter headways or potentially assign an event as a conflict incorrectly when vehicles begin a lane change at the same time that another vehicle enters the road (Papadoulis et al., 2019). Or also when a vehicle is unable to complete an initiated lane change due to a congested environment (Virdi et al., 2019), as demonstrated in Fig. 5. Thus, the number of events with very low values of TTC (0.1) can be

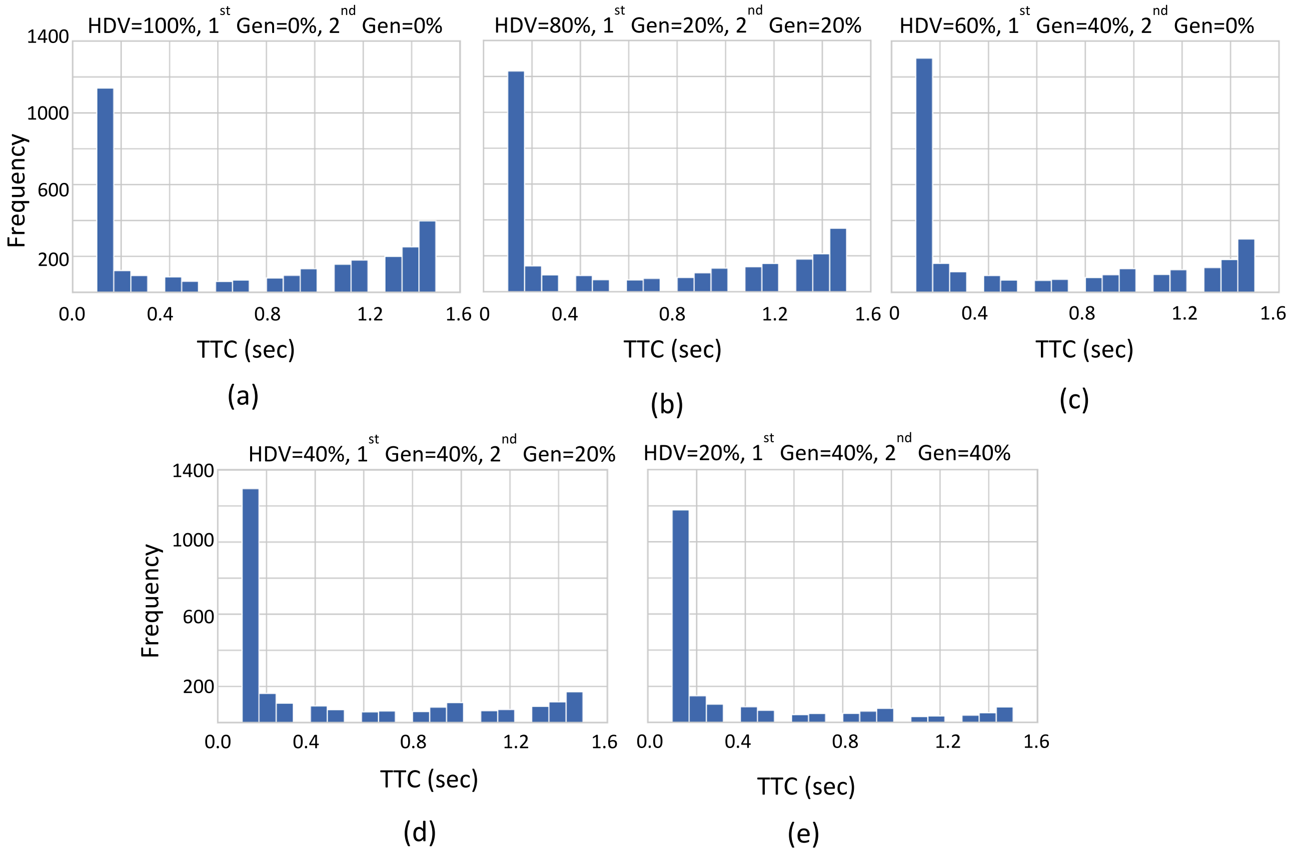


Fig. 4. TTC distribution based on CAVs market penetration rate.

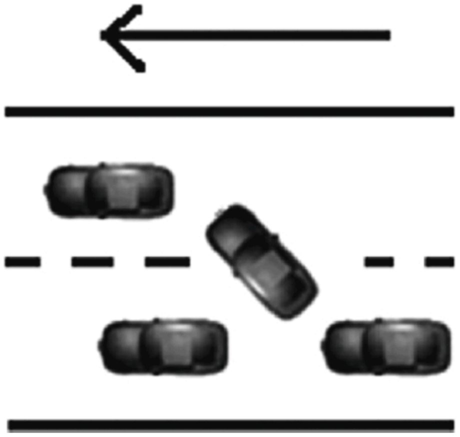


Fig. 5. An incorrectly identified conflict event in SSAM (Virdi et al., 2019).

considered as a noise/systematic bias which could be either from AIMSUN Next or/and SSAM.

In order to have a full understanding of the reasons behind the TTC distribution, a pragmatic approach with different simulation time steps was tested in this study. It should be noted that the simulation time step was set for 0.1 s for the networks due to a specific feature of Aimsun software, i.e., the setting of reaction time parameter needs to be a multiplier of the simulation time step, and it was set at 0.1 s for all vehicle types in the study. Figs. 6 and 7 display the TTC distribution in the Manchester network for 100-0-0 and 0-0-100 scenarios based on the 0.4 s and 0.1 s simulation step. It clearly shows that with 0.4 s simulation step, for 100-0-0 scenario the majority events are falling at TTC value around 1.4 s, and for 0-0-100 scenario there is a small number of events that falling below 0.4 s. This finding is consistent with the vast majority of the literature that the average human reaction time is approximately 1.5 s, and for conventional vehicles in an urban area the TTC equal or less than 1.5 s would reflect an unsafe situation (Dijkstra et al., 2018; Morando et al., 2018; Truong et al., 2015), and for autonomous vehicles the TTC value should be much less 1.5 s as the ability to react to a situation would be faster than a human driver (Penttinen et al., 2019; Ukkusuri et al., 2019; Das, 2018; Morando et al., 2017, 2018). This test experiment motivates that the low TTC values<=0.1 should be removed from the results in this study. Due to these reasons, it is decided to remove the noise in the conflicts data with very low TTC values (TTC<=0.1 s) within the LEVITATE project. More details on TTC distributions can be found on road safety related impacts within LEVITATE documentation (Weijermars et al., 2021).

4.2. *Identified traffic conflicts*

The results after removing TTC values ≤ 0.1 s are presented in Fig. 8. It shows the percentage change of conflicts against varying fleet composition based on the conflict type for the study network. The conflicts are normalised in terms of Vehicle Kilometres Travelled (VKT), in order to control for variations in traffic volume within simulated area. The figures in a fleet composition refer to the percentage of HDVs, 1st Gen CAVs, and 2nd Gen CAVs, respectively e.g., scenario 40-40-20 indicates 40 % fleet of HDVs, 40 % of 1st Gen CAVs and 20 % of 2nd Gen CAVs. For each scenario, 10 different replications with random seeds were simulated.

As seen from Fig. 8, the overall decreasing trend for all tested scenarios in conflicts with higher MPR of CAVs can be observed. However, the reduction rate varies between the CAV DL scenarios, for example, the number of conflicts increases in lower market penetration rate scenarios i.e., 80-20-0 for Motorway and A-Road', 'Motorway innermost lane' and

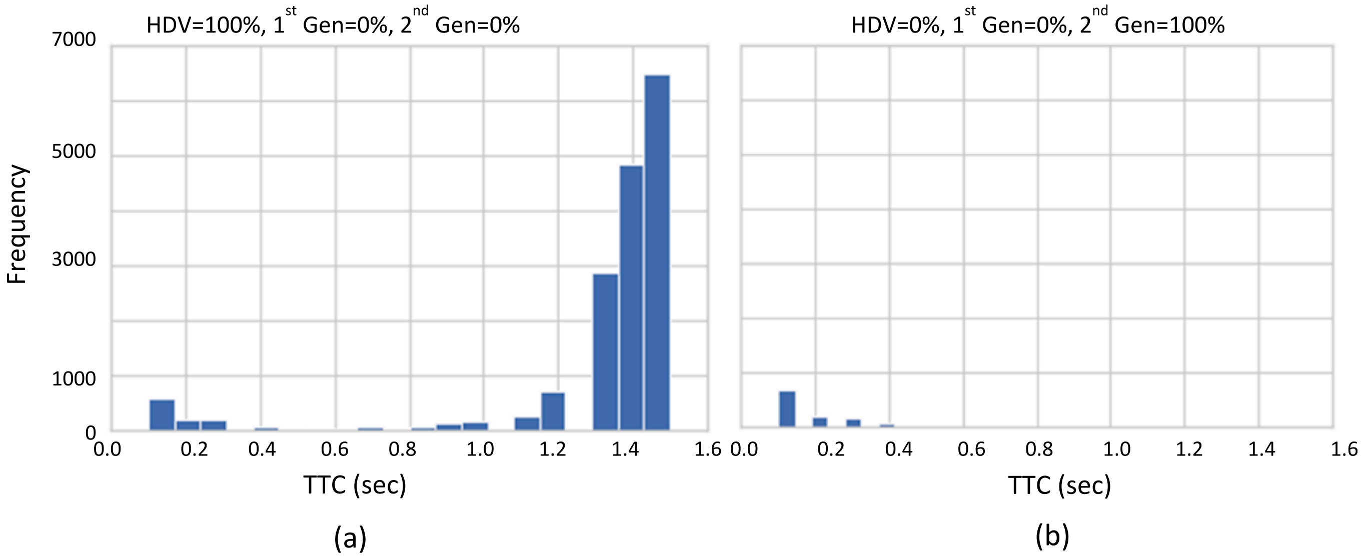


Fig. 6. TTCs Distribution with 0.4 s simulation step.

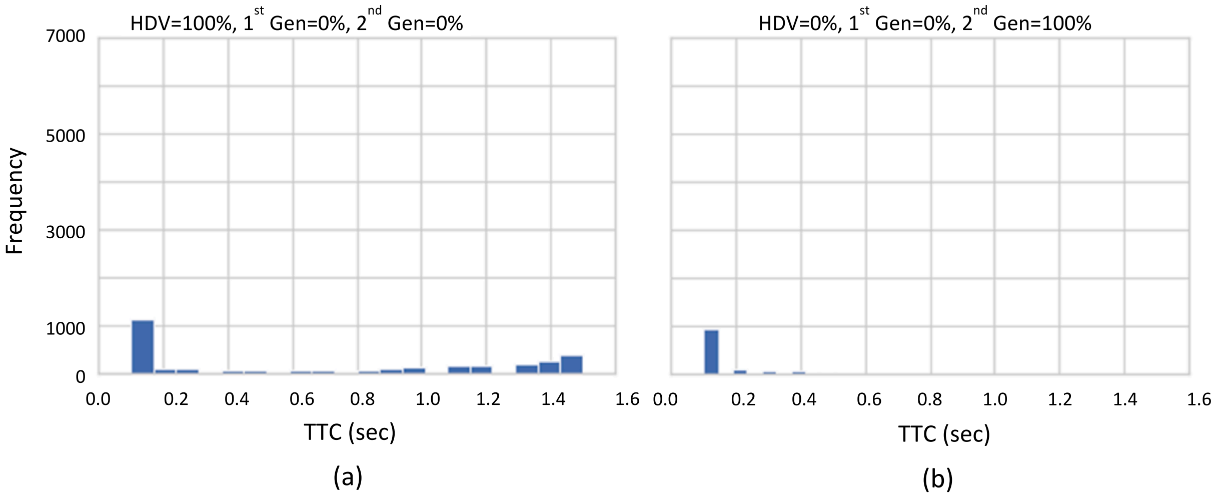


Fig. 7. TTCs Distribution with 0.1 s simulation step.

'A-Road outermost lane' scenarios. This is a result of incompatibilities between the driving characteristic of CAVs and HDVs as represented within the simulations. Findings from previous studies reported a similar trend of a small increase in conflicts at low MPRs, especially when the market penetration of AVs is lower than 40 % compared to traffic flow consisting of human drivers only (Shi et al., 2020; Yu et al., 2019). Another potential reason is the fact that when CAV penetration rates are low, human-driven lanes are expected to get more congested which might result in more conflicts in these lanes. At higher market penetration, i.e., 20-40-40, a significant reduction in the number of conflicts compared to the baseline scenario (representing the current situation with a distribution of 100 % HDVs and 0 % CAVs on the road) could be seen. A reduction between 53 % and 58 % in conflicts can be achieved for all scenarios. Under CAV DL scenarios the reduction in conflicts at higher MPR could also be associated with traffic congestion caused by the CAV DL becoming busier, which might impact the number of vehicles entering the network and, thus, the number of conflicts.

The conflict results are further disaggregated into types, i.e., rear-end, lane-change or crossing conflict and presented in Fig. 9. It can be seen that the rear-end type conflicts contribute to the majority of the conflicts across all scenarios. This is consistent with the findings from previous studies, which indicated that the rear end conflicts were the most common type of collision for HDVs, particularly in urban areas (Stylianou and Dimitriou, 2018; Xue et al., 2018). In addition, autonomous vehicles are also likely to be involved in rear-end conflicts in both simulation experiments (Tibljaš et al., 2018; Favarò et al., 2017) and real-world driving situations (Petrović et al., 2019). This happens because vehicles are forced run in the dedicated lanes and follow each other resulting in higher rear end conflicts.

To gain a better understanding of the conflict results, the conflicts based on the different vehicle type involved in conflict were examined. The Lomax distribution utilised in the Tarko, (2018) is based on properties of the phenomena of traffic conflict. The use of this approach to all events claimed as conflicts could potentially overestimate the expected number of crashes if conflicts are not adequately identified. Therefore, it is critical to define and identify conflicts between different vehicle types. Figs. 10 to 12 present the heatmap of conflicts caused by different vehicle type under low (80-20-0), medium (60-40-0) and high (20-40-40) CAV MPR scenarios.

The heatmap results in Fig. 10 show an increase in potential conflicts between HDVs under the CAV DL scenarios compared to No CAV DL, especially the conflicts involving passenger cars (consisting more than

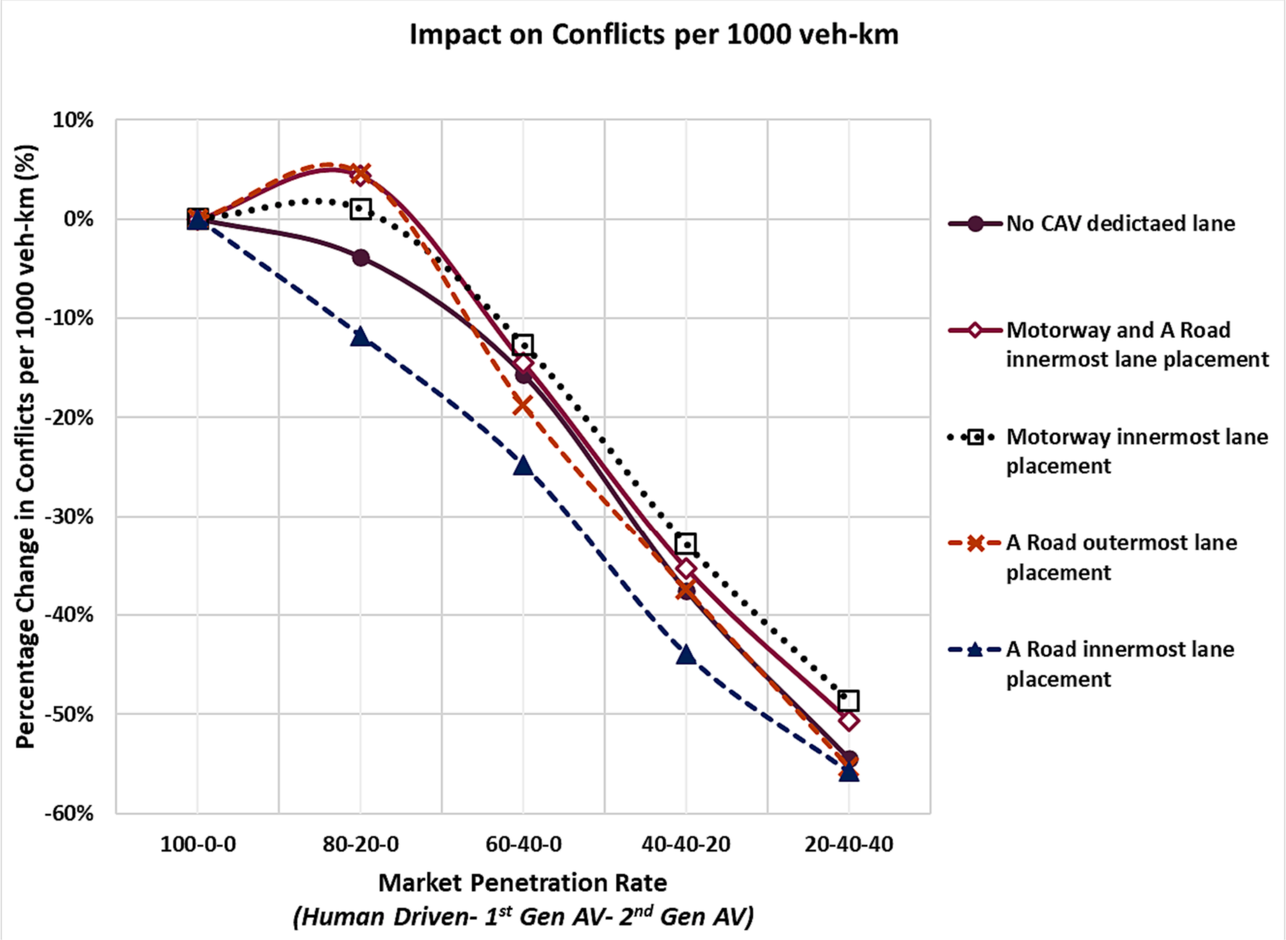


Fig. 8. Percentage change in conflicts per 1000 veh-km travelled.

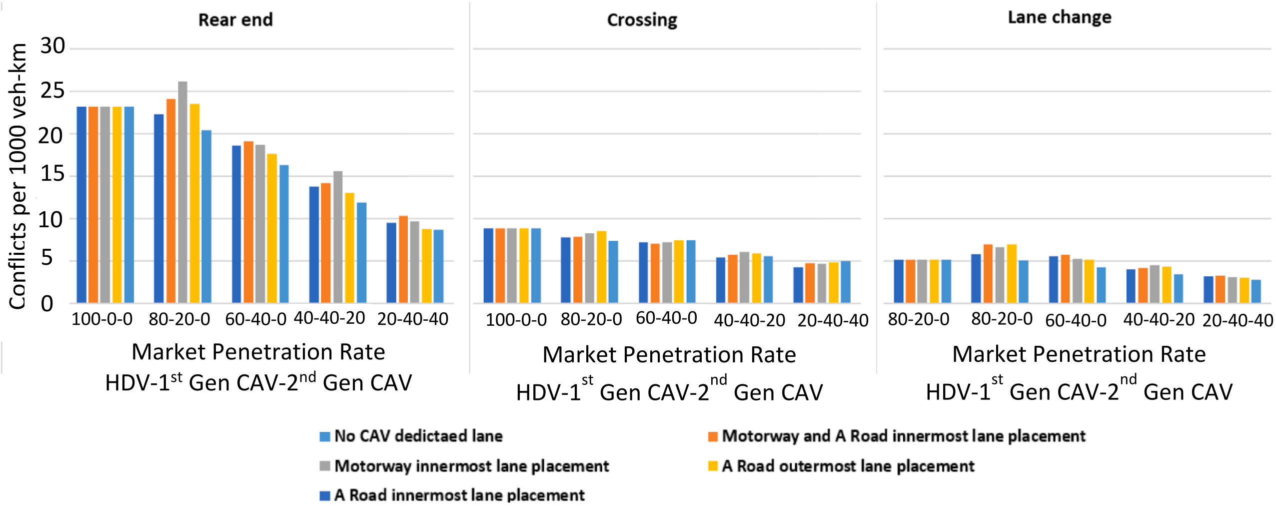
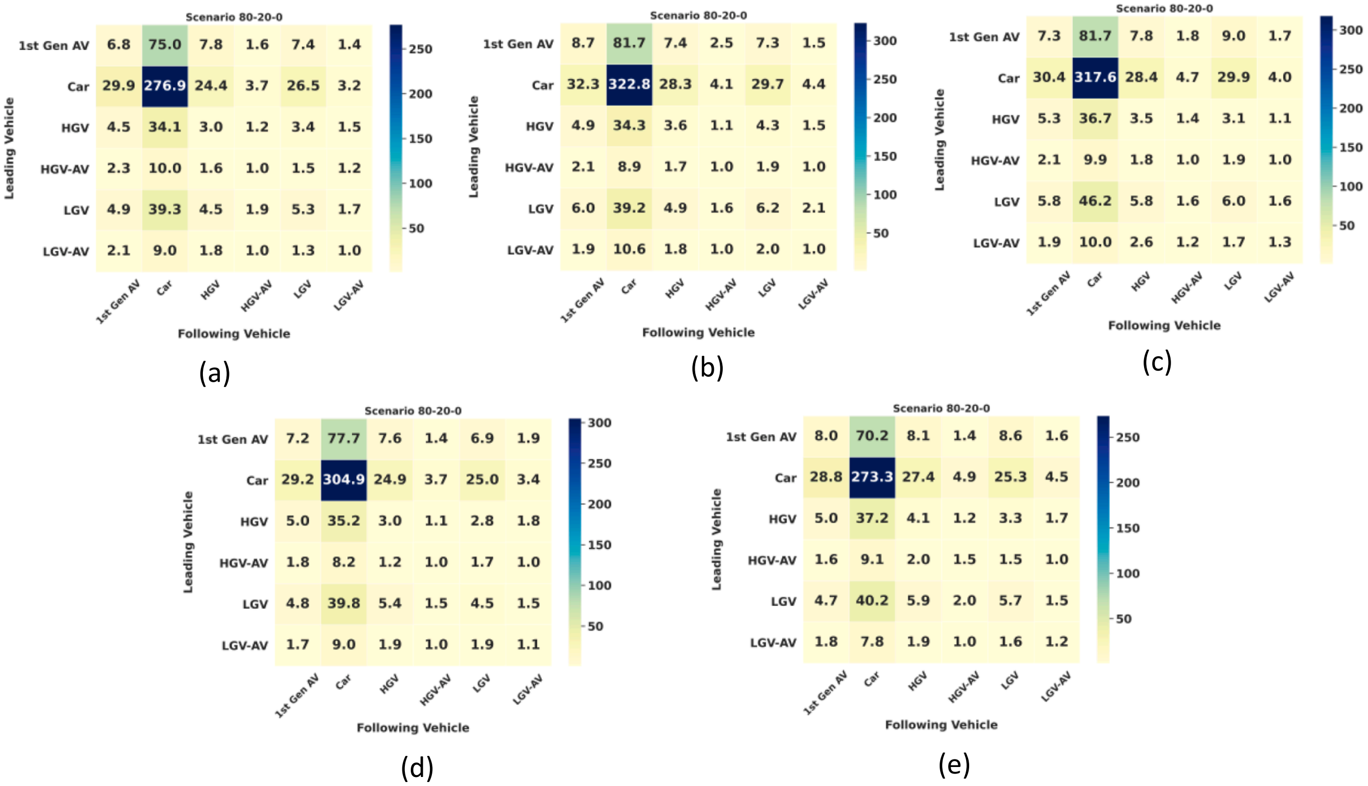


Fig. 9. Conflicts per 1000 veh-km travelled based on conflicts type.

80 % of traffic demand). This which could be expected with the reduction of lanes allocated for HDVs that still being the dominant mode in low MPR scenario, with the interactions involving HDVs being significantly more than those involving with CAVs. The results in Fig. 10 also reveal a slight increase in the interactions between HDVs and CAVs (Fig. 10b-e) compared with the No CAV DL scenario, particularly in cases where HDVs are the following vehicles. This can be attributed to the complexities that arise from merging and exiting manoeuvres, which pose challenges for both HDVs and CAVs. For instance, when CAVs utilise the dedicated lane, human drivers operating HDVs may need to perform more frequent merging manoeuvres to access other lanes or exit the road. This increased merging complexity can result in higher rates of interaction between HDVs and CAVs. Additionally, human drivers in HDVs may adjust their lane change behaviour when approaching the



(a) Scenario 80-20-0

	1st Gen AV	Car	HGV	HGV-AV	LGV	LGV-AV
1st Gen AV	6.8	75.0	7.8	1.6	7.4	1.4
Car	29.9	276.9	24.4	3.7	26.5	3.2
HGV	4.5	34.1	3.0	1.2	3.4	1.5
HGV-AV	2.3	10.0	1.6	1.0	1.5	1.2
LGV	4.9	39.3	4.5	1.9	5.3	1.7
LGV-AV	2.1	9.0	1.8	1.0	1.3	1.0

(b) Scenario 80-20-0

	1st Gen AV	Car	HGV	HGV-AV	LGV	LGV-AV
1st Gen AV	8.7	81.7	7.4	2.5	7.3	1.5
Car	32.3	322.8	28.3	4.1	29.7	4.4
HGV	4.9	34.3	3.6	1.1	4.3	1.5
HGV-AV	2.1	8.9	1.7	1.0	1.9	1.0
LGV	6.0	39.2	4.9	1.6	6.2	2.1
LGV-AV	1.9	10.6	1.8	1.0	2.0	1.0

(c) Scenario 80-20-0

	1st Gen AV	Car	HGV	HGV-AV	LGV	LGV-AV
1st Gen AV	7.3	81.7	7.8	1.8	9.0	1.7
Car	30.4	317.6	28.4	4.7	29.9	4.0
HGV	5.3	36.7	3.5	1.4	3.1	1.1
HGV-AV	2.1	9.9	1.8	1.0	1.9	1.0
LGV	5.8	46.2	5.8	1.6	6.0	1.6
LGV-AV	1.9	10.0	2.6	1.2	1.7	1.3

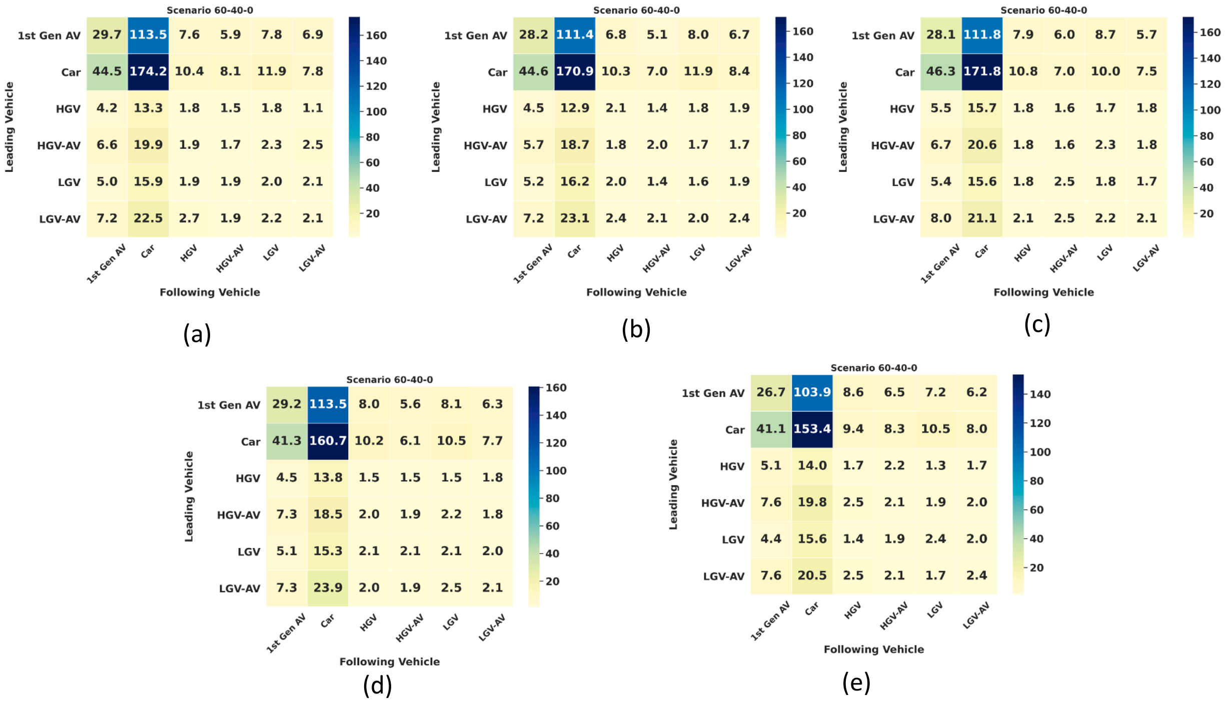
(d) Scenario 80-20-0

	1st Gen AV	Car	HGV	HGV-AV	LGV	LGV-AV
1st Gen AV	7.2	77.7	7.6	1.4	6.9	1.9
Car	29.2	304.9	24.9	3.7	25.0	3.4
HGV	5.0	35.2	3.0	1.1	2.8	1.8
HGV-AV	1.8	8.2	1.2	1.0	1.7	1.0
LGV	4.8	39.8	5.4	1.5	4.5	1.5
LGV-AV	1.7	9.0	1.9	1.0	1.9	1.1

(e) Scenario 80-20-0

	1st Gen AV	Car	HGV	HGV-AV	LGV	LGV-AV
1st Gen AV	8.0	70.2	8.1	1.4	8.6	1.6
Car	28.8	273.3	27.4	4.9	25.3	4.5
HGV	5.0	37.2	4.1	1.2	3.3	1.7
HGV-AV	1.6	9.1	2.0	1.5	1.5	1.0
LGV	4.7	40.2	5.9	2.0	5.7	1.5
LGV-AV	1.8	7.8	1.9	1.0	1.6	1.2

Fig. 10. Heatmap of conflicts by vehicle type based on leading and following vehicle type under low CAV MPR (80-20-0): (a) No CAV DL, (b) CAV DL on Motorway and A road innermost lane, (c) CAV DL only on Motorway innermost lane, (d) CAV DL on A Road outermost lane, and (e) CAV DL on A Road innermost lane.



(a) Scenario 60-40-0

	1st Gen AV	Car	HGV	HGV-AV	LGV	LGV-AV
1st Gen AV	29.7	113.5	7.6	5.9	7.8	6.9
Car	44.5	174.2	10.4	8.1	11.9	7.8
HGV	4.2	13.3	1.8	1.5	1.8	1.1
HGV-AV	6.6	19.9	1.9	1.7	2.3	2.5
LGV	5.0	15.9	1.9	1.9	2.0	2.1
LGV-AV	7.2	22.5	2.7	1.9	2.2	2.1

(b) Scenario 60-40-0

	1st Gen AV	Car	HGV	HGV-AV	LGV	LGV-AV
1st Gen AV	28.2	111.4	6.8	5.1	8.0	6.7
Car	44.6	170.9	10.3	7.0	11.9	8.4
HGV	4.5	12.9	2.1	1.4	1.8	1.9
HGV-AV	5.7	18.7	1.8	2.0	1.7	1.7
LGV	5.2	16.2	2.0	1.4	1.6	1.9
LGV-AV	7.2	23.1	2.4	2.1	2.0	2.4

(c) Scenario 60-40-0

	1st Gen AV	Car	HGV	HGV-AV	LGV	LGV-AV
1st Gen AV	28.1	111.8	7.9	6.0	8.7	5.7
Car	46.3	171.8	10.8	7.0	10.0	7.5
HGV	5.5	15.7	1.8	1.6	1.7	1.8
HGV-AV	6.7	20.6	1.8	1.6	2.3	1.8
LGV	5.4	15.6	1.8	2.5	1.8	1.7
LGV-AV	8.0	21.1	2.1	2.5	2.2	2.1

(d) Scenario 60-40-0

	1st Gen AV	Car	HGV	HGV-AV	LGV	LGV-AV
1st Gen AV	29.2	113.5	8.0	5.6	8.1	6.3
Car	41.3	160.7	10.2	6.1	10.5	7.7
HGV	4.5	13.8	1.5	1.5	1.5	1.8
HGV-AV	7.3	18.5	2.0	1.9	2.2	1.8
LGV	5.1	15.3	2.1	2.1	2.1	2.0
LGV-AV	7.3	23.9	2.0	1.9	2.5	2.1

(e) Scenario 60-40-0

	1st Gen AV	Car	HGV	HGV-AV	LGV	LGV-AV
1st Gen AV	26.7	103.9	8.6	6.5	7.2	6.2
Car	41.1	153.4	9.4	8.3	10.5	8.0
HGV	5.1	14.0	1.7	2.2	1.3	1.7
HGV-AV	7.6	19.8	2.5	2.1	1.9	2.0
LGV	4.4	15.6	1.4	1.9	2.4	2.0
LGV-AV	7.6	20.5	2.5	2.1	1.7	2.4

Fig. 11. Heatmap of conflicts by vehicle type based on leading and following vehicle type under medium CAV MPR (60-40-0): (a) No CAV DL, (b) CAV DL on Motorway and A road innermost lane, (c) CAV DL only on Motorway innermost lane, (d) CAV DL A Road outermost lane, and (e) CAV DL A Road innermost lane.

dedicated lane occupied by CAVs. Some HDV drivers might exhibit greater caution or hesitation when interacting with CAVs, leading to additional interactions. Moreover, the dedicated lane for CAVs may enforce stricter safety measures and maintain specific following distances between vehicles. As a result, HDVs merging into or exiting from lanes near the dedicated lane might need to adjust their driving behaviour to accommodate these safety measures, potentially leading to more interactions. However, an improvement could be observed when

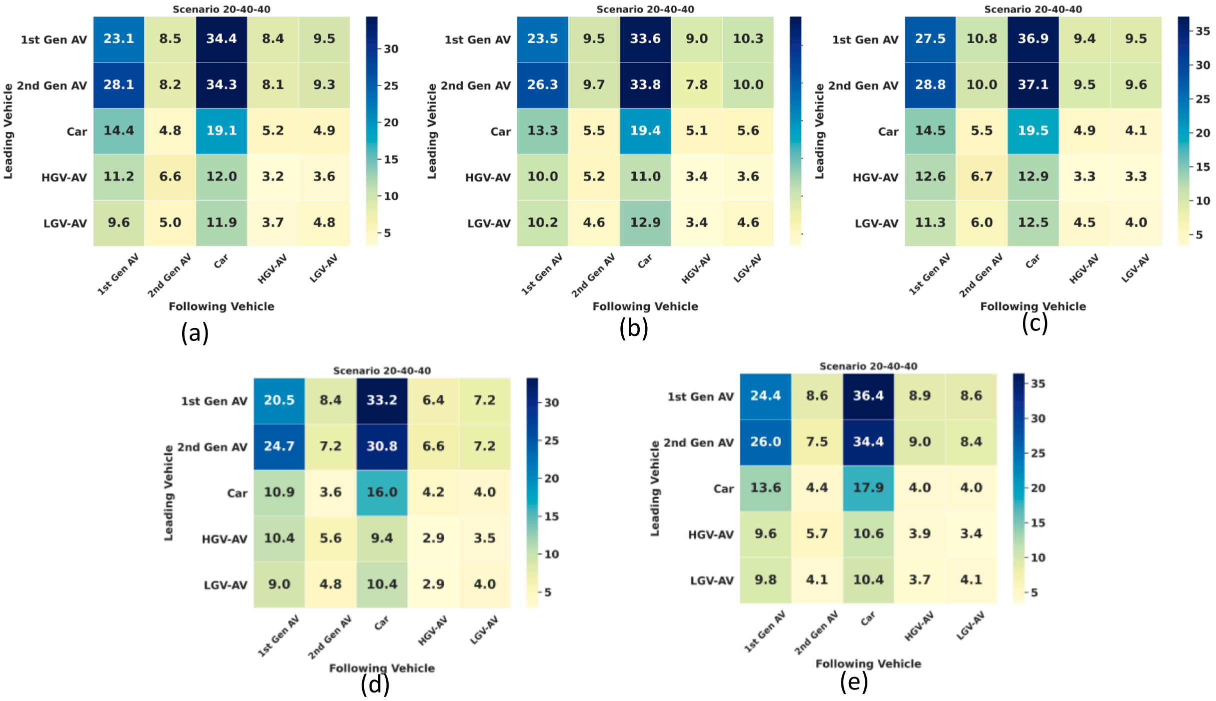


Fig. 12. Heatmap of conflicts by vehicle type based on leading and following vehicle type under high CAV MPR (20-40-40): (a) No CAV DL, (b) CAVDL on Motorway and A road innermost lane, (c) CAV DL only on Motorway innermost lane, (d) CAV DL A Road outermost lane, and (e) CAV DL A Road innermost lane.

allocating the A road innermost lane for CAVs (around 8 % reduction in total conflicts) compared to the No CAV DL.

At higher market penetration, i.e., 20-40-40, a significant reduction in the number of conflicts compared to the baseline scenario (current situation, i.e., 100-0-0) could be seen (Fig. 8). A reduction between 53 % and 58 % in conflicts can be achieved for all scenarios. With CAV DL scenarios the reduction in conflicts at higher MPR could also be associated with traffic congestion caused by the CAV DL becoming busier, which might impact the number of vehicles entering the network and, thus, the number of conflicts. The results in Fig. 12 show that conflicts involving CAVs become more dominant through all examined scenarios. A significant number of these conflicts are formed between HDVs and 1st/2nd Gen CAVs. In other words, more conflicts have been generated for a heterogeneous mixed fleet condition. One of the most important potential reasons could be that inhomogeneous traffic arising due to differences in driving behaviour, for example, differences in driving styles (e.g., automated vehicles adopting shorter headways) and capabilities (e.g., human drivers' longer reaction times). This is in line with previous studies (e.g., Favarò et al., 2017; Yu et al.,2019; Shi et al., 2020).

4.3. *Estimation of crashes from conflicts*

In this study, an effort has been made to present the road safety impacts in terms of crashes or crash rates. Therefore, the estimated numbers of conflicts are converted into numbers of crashes using a probabilistic method proposed by Tarko (2018), as explained in section 3.4. Fig. 13 shows the total number of crashes (normalised per 1000 veh-km) calculated based on the approach mentioned above, considering different MPR of CAVs compared to the baseline scenario (current

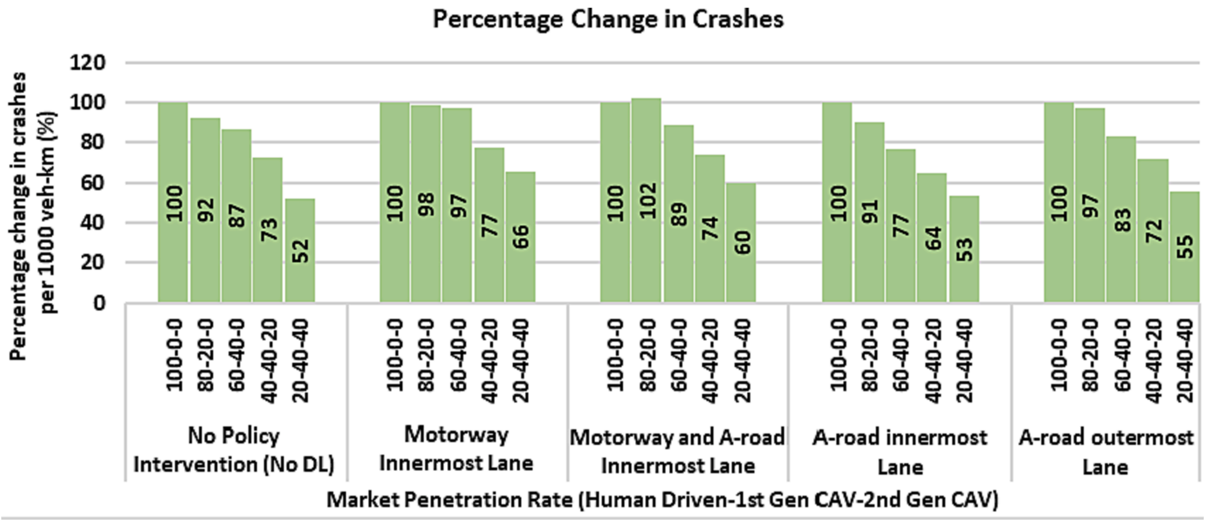


Fig. 13. Percentage of crashes per 1000 veh-km travelled based on varying MPR.

situation 100-0-0). The percentage reduction in crashes at full market penetration rate of CAVs is estimated between 34 % and 48 % for all tested scenarios.

Table 3 presents the percentage change in crashes after the intervention (implementation of dedicated lane) in comparison to the no policy intervention (no dedicated lane) scenario. The results indicate that various CAV penetration rates in different scenarios can result in up to 18 % more crashes than no policy intervention scenario. Additionally, a dedicated lane for automated vehicles loses its value at very high penetration rates and results in a slightly higher crash rate prediction than no dedicated lane scenario. However, when the vehicle fleets have nearly equal proportion (i.e., 60-40-0 or 40-40-20), a small benefit can be seen from dedicated lanes when implemented on A-level roads. With respect to CAV MPRs, potential disbenefits can be expected at low and high MPR scenarios due to unbalanced utilisation of the dedicated and non-dedicated lane, respectively. The safety benefits can be maximised (decreased around 12 %) around moderate penetration scenarios, such as at 40-40-20, under the provision of a single CAV dedicated lane, as evident from the results presented in Table 3.

Furthermore, the increment in the crashes on the Motorway can also be observed in Fig. 9. This happens due to higher speed limits of vehicles allowed on the Motorway, compared to A-roads (SWOV, 2004; Aarts and Van Schagen, 2006). It is important to note that the crashes were reduced with the increment of CAVs MPR.

In order to obtain more insight into the impacts of CAVs, delay time and travel time were also investigated in the study. It was found that delays and travel time (Fig. 14) improve significantly with the 40-40-20 MPR. Delays and travel time were reduced up to 12 and 2.4 % respectively with this MPR.

5. Discussion

In this study, the safety impacts of dedicated lanes for CAVs with various configurations have been investigated and discussed. The investigation was conducted using a microsimulation framework (AIMSUN Next) and integrating it with the SSAM. The investigation was performed on a Motorway (M−6) and a major arterial (A level road) in a sub-urban area within Manchester. Several configurations of CAVs dedicated lanes on these two roadways were tested with varying MPR of CAVs. To identify an event as a conflict, different TTC thresholds were used for HDVs, 1st and 2nd Gen CAVs, based on the findings of existing literature. The identified conflicts were translated to crashes by using a probabilistic method proposed by Tarko (2018).

Overall, the results (Fig. 13) showed a decrease in crashes with increasing MPR of CAVs under all tested configurations of CAVs. This finding is consistent with previous studies (e.g., Papadoulis et al., 2019; Morando et al., 2018; Virdi et al., 2019). However, with respect to no policy intervention (without dedicated lanes for CAVs), only the A road innermost scenario showed a reduction in crashes among all the other tested configurations. The results also revealed that dedicated lanes are expected to increase the number of crashes per km travelled compared to the baseline scenario (current situation without a dedicated lane) at low and high MPR levels. This can be explained by high traffic volumes in respective lanes for non-automated vehicles and lanes for automated vehicles. When the vehicle fleets are more equally split, a small benefit can be seen from dedicated lanes when implemented on A-level roads.

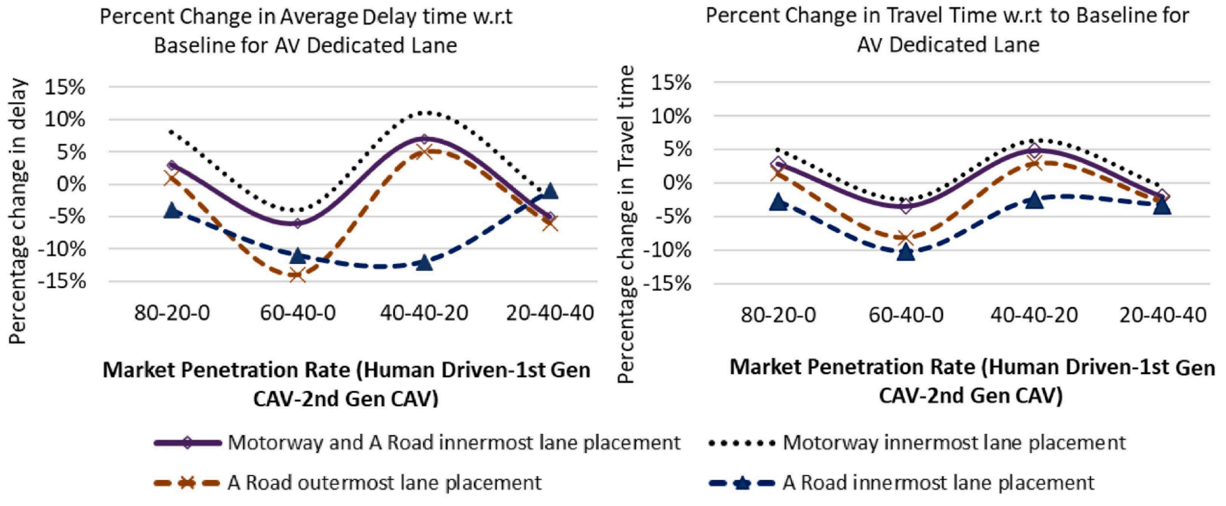
Table 3
Total change in crashes per vehicle-kilometre travelled with regard to NO Policy Intervention (NO DL).

Penetration Rate	Motorway and A Road innermost lane placement	Motorway innermost lane placement	A Road outermost lane placement	A Road innermost lane placement
100-0-0	0 %	0 %	0 %	0 %
80-20-0	5 %	5 %	3 %	−5%
60-40-0	3 %	9 %	−3%	−5%
40-40-20	−3%	4 %	−5%	−12 %
20-40-40	11 %	18 %	−1%	−3%

The introduction of specific measures, such as the dedicated lane proposed in this study, can have additional impacts on the overall effectiveness of CAVs. One critical advantage of a dedicated lane is its ability to separate human drivers from automated vehicles, which, in turn, reduces the interactions between them. This separation reduces human drivers on the road and leads to minimise the potential for human error while driving, thus improving the overall safety and efficiency of the transportation system. The ‘no policy intervention’ scenario represents CAV implementation without a dedicated lane, has shown that the expected number of crashes could increase when human drivers are mixed with automated vehicles. This is due to potential behavioural differences and capabilities between human drivers and CAVs. This finding seems to support the study by Sinha et al. (2020) that showed that the introduction of CAVs does not result in the expected reduction in crash severity and rates involving HDVs. Dedicated lanes separate CAVs from human-driven cars and limit the interactions between them, which is expected to increase road safety. It should be noted here that there have been studies that have examined drivers’ adaptation behaviour when interacting with connected and automated vehicle (CAV) technologies while driving on actual roads. These studies have furthered our understanding of the positive and negative safety consequences of those advanced technologies. Soni et al., 2022 found that human drivers on a straight road adopted significantly smaller critical gaps when interacting with an approaching autonomous vehicle as compared to when interacting with an approaching human-driven vehicle. Another study by Li et al. (2023) proposed a modelling method to analyse the operating mechanism of mixed traffic flows of human-driving vehicles (HDVs) and CAVs, considering HDV drivers’ cognitive behavioural characteristics and HDV-CAV interaction effects. Future research could continue to explore the impact of short and long-term behavioural adaptations of human drivers when interacting with CAVs to maximise positive impacts of their implementation.

In addition, when an existing lane (usually accessible for all traffic) is converted to a dedicated CAV lane, all non-CAV traffic will have to distribute over the remaining lanes. When CAV penetration rates are low, non-dedicated lanes will get busier, which might result in more conflicts and accidents in these lanes. When CAV penetration rates are high, the problem likely shifts to the dedicated lane. Moreover, the combination of 40-40-20 could be the optimum MPR for CAVs to provide dedicated lanes to achieve the best safety benefits from the simulation results. Further, it was discovered that the 40-40-20 MPR considerably reduces delays and travel time. With the help of this MPR, delays and travel time was decreased by up to 12 and 2.4 %, respectively. Other studies also report similar percentages of CAVs (between 40 and 60 %) to get a maximum advantage ()(Abdel-Aty et al., 2020). Findings from Abdel-Aty et al. (2020) suggested that a dedicated CAV lane was recommended when the MPR% is between 10 % and 30 %. Furthermore, dedicated lanes could increase the complexity of merging and exiting situations. As mentioned above, dedicated lanes might result in increased traffic volumes in some lanes. For example, when the outermost lane is a dedicated CAV lane and CAV penetration rates are high, merging onto the highway or exiting the highway can become more difficult for the remaining traffic.

Furthermore, dedicated lanes could help address the additional crash risks that come from inhomogeneous traffic due to reducing interactions between HDVs and automated vehicles. A similar statement was also found in Hamad and Alozi (2022), which indicated that optimised dedicated lanes could minimise the risk of collisions due to imposed driving behaviours variations between HDVs and CAVs. However, congestion may worsen on one of the dedicated lanes, depending on how the fleet’s automated and HDVs are distributed. For example, when CAV penetration rates are low, human-driven lanes are expected to become more congested, potentially leading to more conflicts and crashes. When



(a) (b)

Fig. 14. Percentage changes of delays and travel times based on varying MPR.

CAV penetration is high, the problem will likely to shift to the dedicated lane. Therefore, the optimised strategies of MPR and configuration of CAV dedicated lane could be crucial. Careful consideration should be given to ensure fair and inclusive transportation solutions that minimise collision risks while optimising traffic flow, especially during the initial stages of low CAV market penetration. The aim is to develop comprehensive recommendations that address both the potential benefits of dedicated lanes for CAVs and the equitable distribution of resources and infrastructure.

There are a number of limitations identified in the study. SSAM only detect the conflicts between vehicles, and not those involving pedestrians or cyclists. In addition, more knowledge is needed on understanding the relationship between surrogate safety measures and actual crashes. Furthermore, the analysis of TTC distribution revealed a high number of events falling at very low TTC values, which was interpreted as data noise because simulation software is not designed for crash events. Nonetheless, the results in terms of percentage change between scenarios and the impact of different network characteristics and fleet composition provides a useful insight into the safety impacts of CAVs.

One significant knowledge gap exists regarding how CAVs will drive in traffic and interact with other road users. Since there is no definitive data on CAV behaviour, these parameters and functions must be estimated or assumed. Within this study, the assumptions regarding CAV parameters and their values were derived from a comprehensive literature review, encompassing both empirical and simulation-based studies, as well as discussions held with experts. Some guidance on behaviours was also obtained from studies on Adaptive Cruise Control (ACC) and Cooperative Adaptive Cruise Control (CACC) systems.

The study focused on key driving parameters, considering various presumed and expected characteristics of CAVs, such as improved sensing and cognitive abilities, enhanced situational awareness, and the integration of Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication. As a result, future connected and automated vehicles are expected to exhibit more efficient and safer operations on the road than human-driven vehicles due to better decision-making, heightened anticipation of upcoming lane changes, and increased awareness of incidents ahead. Regarding the choice of parameters in the current study, this translated to assigning appropriate values for reaction times, acceleration, and deceleration, among other factors. These parameter values were carefully selected to accurately represent the behaviour of CAVs in various traffic scenarios. For instance, the study highlighted that 2nd Gen CAVs exhibit advanced decision-making capabilities, utilising connectivity to a greater extent compared to 1st Gen CAVs, as discussed in the methodology section. The results presented in the study reflect how CAVs with these characteristics and behaviours would operate and, consequently, impact the transport system. The significance of choosing suitable parameter values lies in ensuring the reliability and validity of the simulation results, ultimately providing valuable insights for planners, policymakers, and vehicle manufacturers in the field of transportation and autonomous vehicle technology.

It should be stressed that the implications on vehicle kilometres travelled are used as a fixed input for estimating the overall road safety impacts and are beyond the scope of this study. However, these estimations are also based on assumptions. When estimating the overall road safety impacts, additional indirect effects are not taken into account.

It is also important to note that due to the unavailability of real-world data, the calibration of the simulation and SSAM models is primarily based on the existing knowledge through early automated vehicular systems. A recent study on surrogate safety measures and their applicability in CAV safety performance evaluation by Wang et al. (2021) highlighted that, most previous CAV safety studies assume conventional surrogate safety measures to be reasonable and transferable to the traffic environment with CAVs, the validation of surrogate safety measures must be examined and compared when field data becomes available. The implementation of CAVs should ideally lead to the prevention of all crashes involving human errors, particularly at a higher to full penetration rate. However, as indicated by the analysis results and also reported by several other studies (Shi et al., 2020; Yu et al., 2019; Tibljaš et al., 2018; Favarò et al., 2017; Petrović et al., 2019), the early and interim phases of implementation could be challenging for improvement in safety and therefore require substantial research and testing for safe operations.

6. Conclusions

In this paper, a comprehensive methodology was developed to evaluate the network-level safety impacts of CAVs operating on a dedicated lane. Given that real-world CAV operational data are not yet available, the use of traffic microsimulation models has been utilised in estimating such impacts. The result indicates that crashes and crash rates generally decrease with the increase in connected and autonomous vehicles in the network. In addition, a dedicated lane provided the highest safety benefits (i.e., a 12 % reduction in traffic crashes) when the combination of mixed traffic is: 40 % human-driven vehicles, 40 % 1st generation AVs and 20 % 2nd generation AVs. The optimum range of

MPRs is different depending on the road type and lane replacement. Undoubtedly, the implementation of dedicated lanes should be accompanied by appropriate design, planning and measures to ensure the highest efficiency, functionality, and safety benefits in the wider transport system.

The findings of this study provide significant insights into the safety impacts of dedicated lanes for CAVs and can act as very useful inputs for the development of a policy support tool for local authorities and practitioners. Future research should be directed toward addressing the existing methodological limitations and biases, as well as calibration of models to adequately incorporate conflict characteristics of CAVs.

7. Author contributes

Following contributions to the work have been confirmed by the authors: Study conception and design: Sha H., Singh M., Quddus M.; Literature review: Sha H.; Singh M., Haouari R., Papazikou E., Quigley C.; Microsimulation and SSAM analysis: Sha H., Singh M., Haouari R.; Analysis and interpretation of results: Sha H., Singh M., Haouari R., Papazikou E., Quddus M.; Draft manuscript preparation: Sha H., Singh M., Haouari R., Papazikou E., Quigley C., Chaudhry A.; Review of the paper: Sha H., Haouari R., Singh M., Papazikou E., Quddus M., Quigley C., Chaudhry A., Thomas P., Weijermars W., Morris A. All authors reviewed the results and approved the final version of the manuscript.

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

The authors do not have permission to share data.

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