Safety impact of dedicated lanes for connected and autonomous vehicles – a traffic microsimulation study

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1. Introduction

Cooperative, connected and automated mobility (CCAM), in particular, the advancements of CAVs are expected to improve the driving experience, efficiency, and reduce vehicle emission, especially enhancing road safety by removing driver-related errors [1]. It has been recognised that there must be a transition phase in which human-driven vehicles, autonomous vehicles or connected and autonomous vehicles will be operating with mixed traffic for a long period (e.g., [2-6]). Hence, the operation of CAVs in a dedicated lane with an uncomplicated environment has been suggested by many researchers [3,7-8].

According to the ERTRAC Connected Automated Driving Roadmap [9], 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). 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. 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 optimise the traffic benefits of CAVs. This is especially true during the initial phase of AV implementation to limit the interactions between humans and AVs, which could be proven problematic.

Several studies attempted to predict the impacts of dedicated lanes using a traffic simulation approach [7,10-12]. Others focused on safety evaluation through safety surrogate measures. An evaluation of the Dedicated AV Lane literature showed that the impact of dedicated lanes on traffic and safety could vary based on the Market Penetration Rate (MPR) of AVs and the number of lanes (both dedicated and total number). Overall, these can significantly improve safety. In addition, it can be concluded that the performance of traffic increases with the dedicated lane in terms of VHT, VMT, speed, throughput, etc. [8,13]. Furthermore, the headway in the dedicated lanes is reduced, and that may result in a higher traffic flow [11,14]. However, the number of dedicated lanes can be decided based on the traffic demand.

In addition to other impact dimensions (e.g., mobility and environmental impacts), there is a lack of knowledge on the safety impacts of CAVs on dedicated lanes [10]. To quantify how dedicated lanes for CAVs 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 that are based on the scenario capture, development and specification of the models. In this regard, this study aims to perform a safety assessment of CAV dedicated lanes by analysing different configuration and placement strategies using the microsimulation method. While many studies rely only on traffic conflicts in evaluating the safety impact, this paper utilises a new approach to estimate the expected number of crashes through traffic conflicts identified through microsimulation.

2. Methodology

The evaluation of the safety impacts of the dedicated lane for CAVs in this study was undertaken using a calibrated and validated microsimulation model of 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 Surrogate Safety Assessment Model (SSAM) [15]. Traffic

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conflicts were then translated to estimate the number of crashes using a probabilistic methodology proposed by Tarko [16].

2.1. Simulation network

A calibrated and validated traffic microsimulation model of the Manchester sub-urban area (provided by Transport for Greater Manchester) was used to evaluate the impacts of new dedicated lanes for CAVs under realistic conditions. This model provides a good foundation for the experiment as it includes a motorway and a major arterial road (M602 and A6, respectively) (Figure 1).

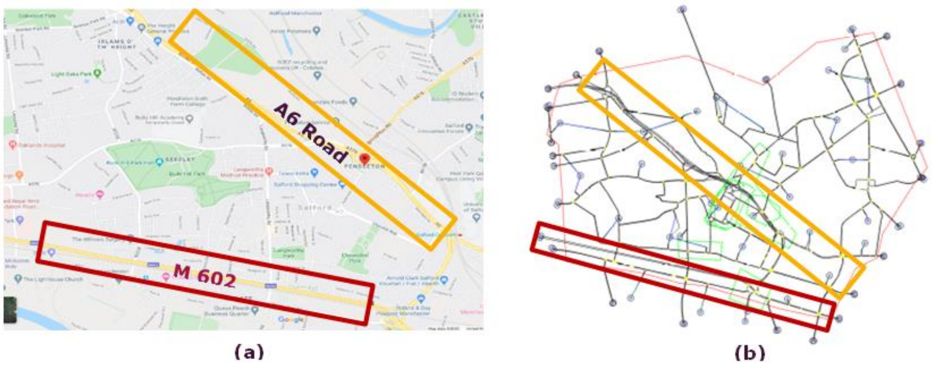

Figure 1: (a) The modelling area in the city of Manchester (b) and network in AIMSUN Next software

The placement of dedicated lane was investigated under various scenarios including:

- Baseline scenario – CAV implementation without a dedicated lane
- Motorways only – CAVs use a dedicated (innermost) lane in the motorway
- Motorway & A-roads – CAVs use a dedicated (innermost) lane in the motorway and the A-road
- A-roads left most lane – CAVs use a dedicated (innermost) lane in the A-road
- A-road right most lane – CAVs use a dedicated (outermost) lane in the A-road

2.2. CAV parameters and deployment scenarios

Within LEVITATE, two types of CAVs were considered: 1st Generation (Gen) CAVs and 2nd Gen CAVs. Both types are assumed to be fully automated vehicles with level 5 automation. 2nd generation CAVs were assumed to have improved driving characteristics and enhanced cognitive capabilities compared to the 1st generation CAVs. Both types are assumed to be fully automated vehicles with level 5 automation. The deployment of CAVs was tested from 0 to 100% MPR with 20% increments across the LEVITATE project as shown in Table 1. Dedicated lanes were provided with mixed fleets of 80-20-0, 60-40-0, 40-40-20, and 20-40-40 (human-driven vehicles-1st Gen CAVs- 2nd Gen CAVs) MPRs in the study (highlighted in Table 1). For each scenario, 10 replications with different random seeds were simulated. The CAV parameters used in this study were derived from the LEVITATE project [17].

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
	Passenger vehicles							
Human-Driven Vehicle	100%	80%	60%	40%	20%	0%	0%	0%
1st Gen CAV	0%	20%	40%	40%	40%	40%	20%	0%
2nd Gen CAV	0%	0%	0%	20%	40%	60%	80%	100%
	Freight vehicles							
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%

2.3. Quantifying the safety impacts

To quantify the potential safety impacts, the SSAM was applied to identify the traffic conflicts from vehicular trajectory data. In SSAM, conflicts are identified based on the specific thresholds for time-to-collision (TTC), post-encroachment time (PET) and the conflict angle. Based on the conflict angle, conflicts are classified into four manoeuvre types: rear-end, lane-change, crossing and unclassified [15]. Within LEVITATE, the TTC threshold was set to 1.5s for human-driven vehicles, 1.0s for 1st Gen CAVs, and 0.5s for 2nd Gen CAVs based on existing studies [18-20].

Within LEVITATE, the number of conflicts was converted to the number of crashes by applying a probabilistic method proposed by Tarko [16] due to the unavailability of suitable empirical crash data involving automated vehicles. The Lomax distributions used in the method proposed by Tarko [16] are based on the properties of the traffic conflict phenomenon. The Cumulative Distribution Function (CDF) of Tarko's method is given in the following equation:

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

θ and k are Lomax distribution parameters, x is the difference of threshold and observed TTC. Equation 1 is used to calculate the probabilities of crashes.

3. Analysis and results

3.1. Identified traffic conflicts

Forecast traffic conflicts are presented in Figure 2. The conflicts are normalised in terms of Vehicle Kilometres Travelled (VKT). The figures in a fleet composition refer to the percentage of human-driven vehicles, 1st Gen CAVs, and 2nd Gen CAVs, respectively, e.g., scenario 40-40-20 indicates 40% fleet of human-driven vehicles, 40% of 1st Gen CAVs and 20% of 2nd Gen CAVs.

The overall decreasing trend for all tested scenarios of conflicts with higher MPR of CAVs can be observed in Figure 2. However, the reduction rate varies between the scenarios. For example, the number of conflicts increases in lower MPRs, i.e., 80-20-0 for both ‘Motorway and A-Road’ and ‘A-Road outermost lane’ scenarios. At full market penetration, a significant reduction in the number of conflicts compared to the baseline scenario could be seen. A reduction between 53% to 58% in conflicts can be achieved for all scenarios.

The conflict results are further disaggregated into three types, i.e., rear-end, lane-change or crossing conflict. It can be seen that the rear-end type conflicts contribute to the majority of the conflicts across all scenarios.

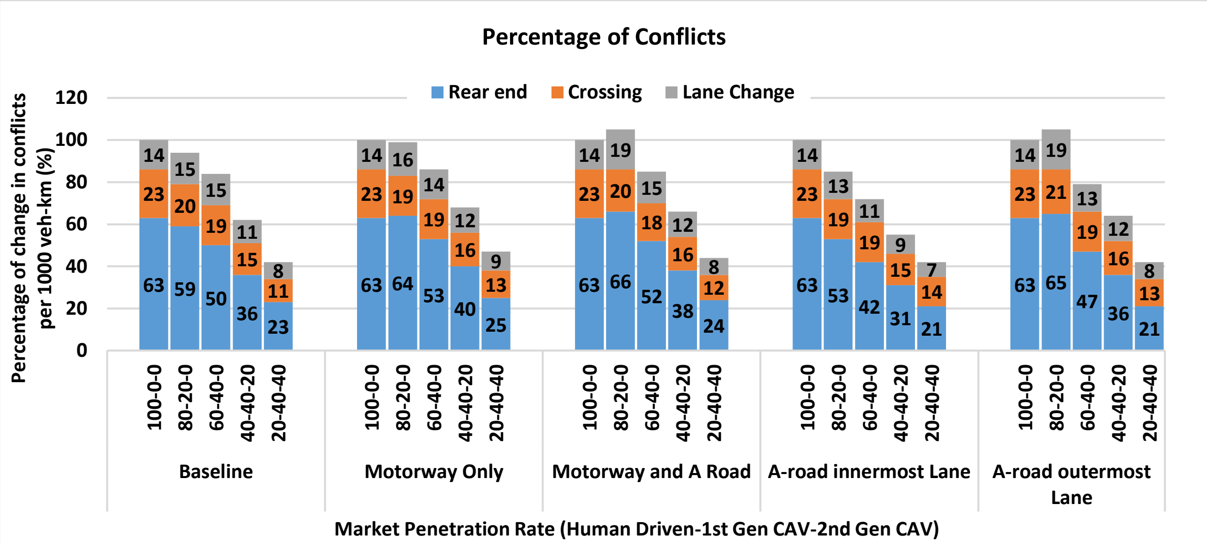

Figure 2: Percentage of conflicts per 1000 veh-km travelled based on conflicts type

3.2. 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 [16] as explained in section 2.3. Figure 3 shows the total number of crashes (normalised per 1000 veh-km) calculated based on the approach mentioned above with varying MPR of CAVs. The percentage reduction in crashes at the full market penetration rate of CAVs is estimated between 34% and 48% for all tested scenarios. In each case, the reduction in crashes was less than conflicts suggesting that research that only measures conflicts may overstate safety benefits.

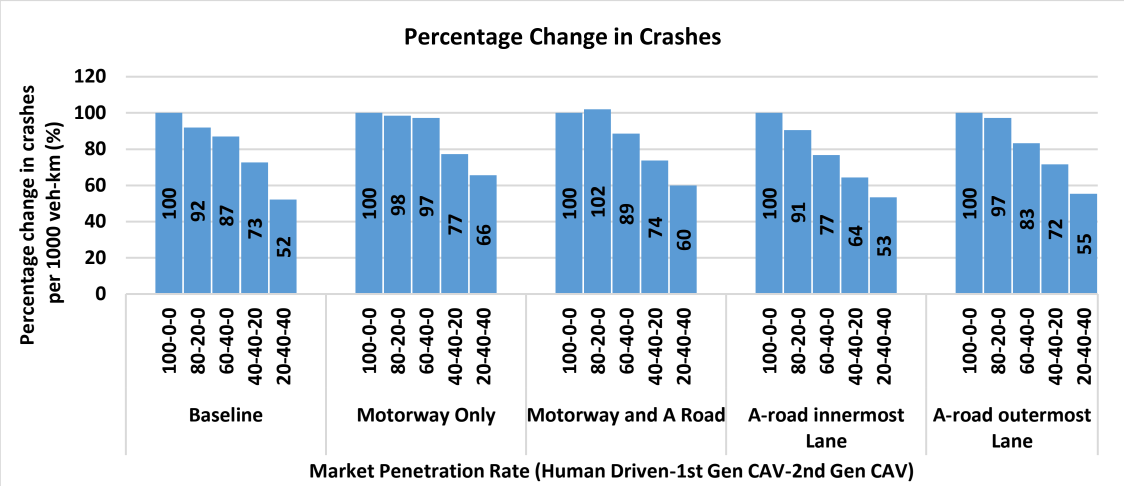

Figure 3: Percentage of crashes per 1000 veh-km travelled based on varying MPR

4. Conclusions

In this study, the safety impacts of dedicated lanes for CAVs with various configurations have been investigated. To identify an event as a conflict, different TTC thresholds were used for human-driven vehicles, 1st and 2nd Gen CAVs, based on the findings of existing literature. The identified conflicts were translated into crashes by using a probabilistic method proposed by Tarko [16]. Overall, the results showed a decrease in crashes with increasing MPR of CAVs under all tested configurations of CAVs. The results also revealed that dedicated lanes are expected to increase the number of crashes per km travelled compared to the baseline scenario (no 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.

The introduction of specific measures such as those proposed in this study (i.e., dedicated lane) can cause additional impacts on the general effects of CAVs. A critical advantage of a dedicated lane is that human drivers are separated from automated vehicles, as this reduces human error while driving as well as the interaction between human drivers and autonomous vehicles.

This paper provides, for the first time, a comprehensive evaluation of the safety impact of dedicated lanes for CAVs. While many studies rely only on traffic conflicts in evaluating the safety impact of any CCAM, this paper also uses traffic crashes generated from the TTC distributions. It is interesting to note that the results for traffic conflicts are slightly different than those for traffic crashes. The findings of this paper would be useful in developing a policy support tool for evaluating the safety impact of dedicated lanes for CAVs. Future research should be directed on addressing the existing methodological limitations and biases, as well as calibration of models to adequately incorporate conflict characteristics of CAVs.

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