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ORIGINAL RESEARCH

Assessing temporary traffic management measures on a motorway: Lane closures vs narrow lanes for connected and autonomous vehicles in roadworks

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Abstract

Connected and automated vehicles (CAVs) are being developed and designed to operate on existing roads. Their safe and efficient operation during roadworks, where traffic management measures are often introduced, is crucial. Two alternative measures are commonly applied during roadworks on motorways: (i) closing one or multiple lanes (ii) narrowing one or all lanes. The former can cause delays and increased emissions, while the latter can pose safety risks. This study uses a VISSIM-based traffic microsimulation to compare the effectiveness of these two strategies on traffic efficiency and safety, considering various market penetration rates (MPR) of CAVs. The model was calibrated and validated with the data collected from M1 motorway in the United Kingdom. Results show that average delays per vehicle-kilometre-travelled decreased from 102.7 to 2.5 s (with lane closure) and 23.6 to 0.6 s (with narrow lanes) with 0% and 100% CAV MPR, respectively. Moreover, safety in narrow lanes improved by 4.8 times compared to 1.5 times improvement in lane closure with a 100% CAV MPR; indicating that narrow lanes would result in better safety performance. These findings could assist transport authorities in designing temporary traffic management measure that results in better CAV performance when navigating through roadworks.

1 | INTRODUCTION

CAVs are expected to perform automated (driverless) driving with the ability to continuously communicate with the surrounding vehicles and infrastructure. According to connected places catapult, (2021) [1] it is forecasted that around 15–40% of new car sales would be automated vehicles in the UK. However, car manufacturers and software suppliers cannot fully deploy CAVs to the market on their own. Key stakeholders such as highway authorities need to upgrade their infrastructures to accommodate CAVs (such as lane markings and traffic management systems) with an enhancement of standards of road maintenance, to ensure that driverless vehicles can 'sense' the road environment accurately.

The increase in market penetration rate (MPR) of CAVs is expected to introduce infrastructure-related challenges. Policies are being developed by the UK government to prepare the strategic road network (SRN) for CAV operations to modernize the entire SRN [2]. Part of this modernization activity involves roadworks, which frequently take place along the road network. The occurrence of roadworks can have undesirable impacts for road users such as increased journey time, traffic congestion, and possibly impairing road safety. These impacts result from an alteration to the road layout during roadworks through narrowing the width of lanes or lane closure and reduction of speed limit in the roadworks zone from deploying temporary traffic management measures (TTMs) [3].

Lane closure (LC) and narrow lanes (NL) are common TTMs for roadworks [4]. When considering LC, the number of live lanes reduces, causing a significant reduction in the traffic capacity not only because of the TTM but also vehicles merging to through lanes [5]. The lead-in section of roadworks creates a bottleneck and vehicles are forced to merge to the live lane(s). Therefore, LC not only hampers traffic safety given the turbulent traffic flow, but also increases the travel time [6]. NLs as a TTM have recently become popular, especially in motorways because the overall road capacity is expected to be significantly higher than LCs [4].

In a bid to improve traffic performance and safety at roadworks, the deployment of intelligent transport systems (ITS) such as vehicular communication technology could be a potential solution [7]. The exchange of data from vehicle to vehicle (V2V) (providing information about the physical location, speed and other information of the preceding vehicle), vehicle to infrastructure (V2I) (providing information about traffic conditions ahead in addition to the recommended driving speed) and vehicle to devices (V2D) (providing an information package which provides accurate information about the modifications in the road environment) establishes a continuous real-time connectivity, maximizing safety and mobility benefits for road users [7].

Nevertheless, these improvements have not yet been fully quantified in the literature. An effective technique to evaluate CAV performances at a roadworks section can be conducted with the aid of traffic microsimulation models. Existing studies have reported that CAVs may improve overall traffic performance such as reducing unstable traffic flow, delays and improving capacity and safety [8]. However, most studies have carried out the simulation assessments in normal motorway settings and the traffic performance during roadworks has yet to be fully understood. In the foreseeable future, the introduction of CAVs and motorway upgrades would take place concurrently and the research problem naturally arises as to a question whether the CAVs are able to transverse through roadwork sections with TTMs (i.e. LC and NL) in place.

Consequently, this study evaluates both TTMs in a motorway scenario and quantifies the impacts of traffic efficiency and safety with different MPRs of CAVs. To achieve this goal, a microsimulation model of a section of M1 motorway in the UK was created using VISSIM with disaggregated traffic data collected from inductive loop detectors for model calibration. The simulation model was then validated by employing real-world data collected by an instrumented vehicle performing repeated trips along the studied network (M1 motorway Junctions 13 to 16). With different combinations of MPRs of CAVs, the safety impacts were extracted from the surrogate safety assessment model (SSAM) to evaluate the safety surrogate measure required. To the authors' knowledge, no research has attempted to quantify the impacts of traffic management measures on the traffic and safety performance with different MPRs of CAVs at roadworks.

As a result, this study critically addresses this existing gap in literature, concerning the operational challenges and safety implications of CAVs during roadworks, a context often characterized by the introduction of ad-hoc traffic management measures. Focusing on the commonly applied measures of lane closures and narrow lanes, the research employed a traffic microsimulation model developed for corridor-level assessments. Development, calibration and validation of this model utilizing data from the M1 motorway in the United Kingdom ensure a real-world basis for the study. The findings indicate substantial reductions in delays and enhanced safety metrics with narrow lanes, particularly at 100% CAV market penetration rates. The emphasis on real-world relevance, methodological contributions through the model, and clear, actionable findings contribute significantly to addressing the identified literature gap and offer valuable insights for transport authorities seeking to optimize CAV performance in roadwork scenarios.

2 | LITERATURE REVIEW

Roadworks compel all vehicles to navigate an altered road layout and lane configuration which poises challenge on the path planning of vehicles which are required to adapt their trajectories to travel reliably within the new road configurations. This might negatively affect traffic mobility and safety performances. This review examines how CAVs can improve the traffic performance in roadworks from mobility (capacity, demand, delay, and travel time) and safety (reducing accidents) perspectives.

2.1 | Mobility and safety concepts using CAVs

CAVs deployment can reduce the mean time headway 0.6 s as compared to 1.4 s for conventional vehicles [9], allowing better utilization of the motorway space. This is crucial at congested roadworks zones as it allows higher capacity on the road network and quicker queue dissipation. Rerouting also reduces the traffic demand at roadworks zone because it allows drivers to make timely decisions to change to multiple rerouting options and do not have to wait to detect a warning of roadworks zone upstream [10]. Moreover, due to the dynamic changes happening in roadworks zones, all vehicles frequently change their speed resulting in speed oscillations. Speed harmonization is key to counterbalance speed variability and it was also shown that even at low MPRs, CAV-powered speed harmonization is advantageous [11].

Due to the reduced traffic capacity in roadwork zones, vehicles frequently merge lanes to access the operational lanes. Diverse merging behaviours preceding the roadwork section disrupt traffic efficiency to various degrees and increase the probability of collisions. Rear-end collisions are the most common type of collision in the entire construction zone. Lane change and crossing collisions are also common, but their frequency increases in the transition zone. As a result, exploring the mobility and its impact on nearby vehicles are essential to maximize safety.

2.2 | CAV impact on traffic performance during roadworks

Roadwork zones tend to increase travel time, queue, accidents and dissatisfaction amongst road users [6, 10]. Utilizing the advanced vehicular communication technology, CAVs have the potential to improve traffic performance at roadworks by exchanging information of the traffic conditions ahead as well as recommending a driving speed in a timely manner to smoothen the traffic flow [10, 12].

Zou et al. [5] observed a reduction in average travel time with CAVs. For example, travel time reduces by 25%, 50%, and 90% at the CAV MPRs of 34.1%, 62.25%, and 100% respectively in a congested 2-to-1 lane roadworks area [5]. Abdulsattar et al., [7] examined the impact of CAVs at different traffic demand levels. The mean travel time was reduced by 40% and capacity increased by 65% at 2-to-1 roadworks with a flow rate of 3,000 vehicles/hour. However, the results were only significant at a high traffic flow rate. Ramezani & Benekohal, [13] tested the effectiveness of speed limits for CAVs in the proximity of roadworks areas. Their results show that by deploying speed management techniques with a CAV MPR of 80% or higher, delays were reduced by 13%, while the congestion period was reduced by 26.4% with a 100% MPR of CAVs. Moreover, Genders & Razavi, [14] appraised the safety advantages (using time-to-collision (TTC) as the safety surrogate measure (SSM)) when diverting CAVs to alternative routes in roadworks at different MPRs.

Safety benefits are attained under moderate MPRs which early dynamic rerouting improved the network safety because the improved driving behaviour balance the additional trip distances. However, for high MPRs, the network safety decreased since longer trip distances were added to the network which increased the risk of safety hazards. Safety related to roadworks was also explored by Abdulsattar et al., [15]. At 10% MPR with medium and high traffic demand levels, safety was improved significantly and the probability of rear-end collisions were halved.

2.3 | TTM configurations' effect on traffic performance

Sophisticated TTM configurations are employed in the road network and each TTM provides a different impact on the traffic performance. The two main TTM schemes applied in roadworks are the use of NLs or LC.

It can be challenging for CAVs to adopt suitable speeds in a NL segment. Michalke et al., [16] developed a machine learning based road navigation system, specifically for driving through narrow roads. Similarly, Polack et al., [17] developed a control strategy to drive CAVs in a narrow space to guarantee the movement of vehicles in a confined space. Other studies have tried comparing the effects on human driver behaviour of driving in narrow and regular lanes [18]. In this study, human driver subjects were asked to travel in two different lanes of width 9 and 12 ft respectively. Results showed that there is no statistical difference between the driving behaviour in lanes with different widths. On the other hand, García & Camacho-Torregrosa, [19] showed that lane width can change the accuracy of the localization of CAVs. Singh & Islam, [20] evaluated the safety impacts of mixed traffic in roadworks with NLs configuration. Different road markings and signages were suggested for CAVs and conventional vehicles to enhance safety.

With regards to LC, CAVs can receive information from surrounding infrastructure and neighbouring vehicles about the new road layout and re-route accordingly. Banerjee et al., [21] found that early on signs of LC are very helpful for route decision. Hess et al. [22] modelled the lane change behaviour for a closed lane scenario using a driving simulator. Their results show an increase in delays and congestion since conventional vehicles are usually not aware of the LC and are forced to perform a mandatory lane change close to the closure point. This effect becomes more apparent under traffic congestion. Similarly, Mohammed et al., [23] developed a framework for cooperative driving of CAVs in a two-lane freeway with a LC. Two scenarios of LCs were investigated where drivers were informed about the LC in one scenario and non-informed in the other. It was found that the scenario where drivers were informed about the LC perform better and improved the traffic throughput. Agriesti et al., [24] explored the impact of LC on CAVs with different MPRs of CAVs. Average delay was reduced between 10–25% when the MPR increased from 10–100%.

In conclusion, a well-designed roadworks zone can provide both safe and uninterrupted driving to vehicles using the roadway and safe construction area to workers. However, current literature lacks comprehensive studies that compare and establish the optimal traffic management techniques (TTMs) for roadworks, i.e. lane closure or narrow lanes scenarios specifically considering CAVs. Therefore, this research develops a microsimulation simulation model using VISSIM to replicate roadworks with LC and NLs to effectively explore CAV behaviours at roadworks in a highway environment. A number of scenarios are developed for each TTM to determine their efficiency in terms of traffic performance and safety benefits with different MPRs of CAVs.

3 | METHODOLOGY

This section outlines the experimental framework which utilizes a simulation platform to investigate how CAVs navigate through roadworks. Subsequent parts of the section explain the simulate mixed scenario development in VISSIM with different CAV penetration rates, concepts of the microsimulation model and the procedures of model calibration are also discussed.

3.1 | Overall framework

The overall methodological framework to evaluate the impact of TTM schemes: NLs and LCs along roadworks for CAV operations is presented in Figure 1. The study begins by exploring different TTMs used for roadworks and developing such

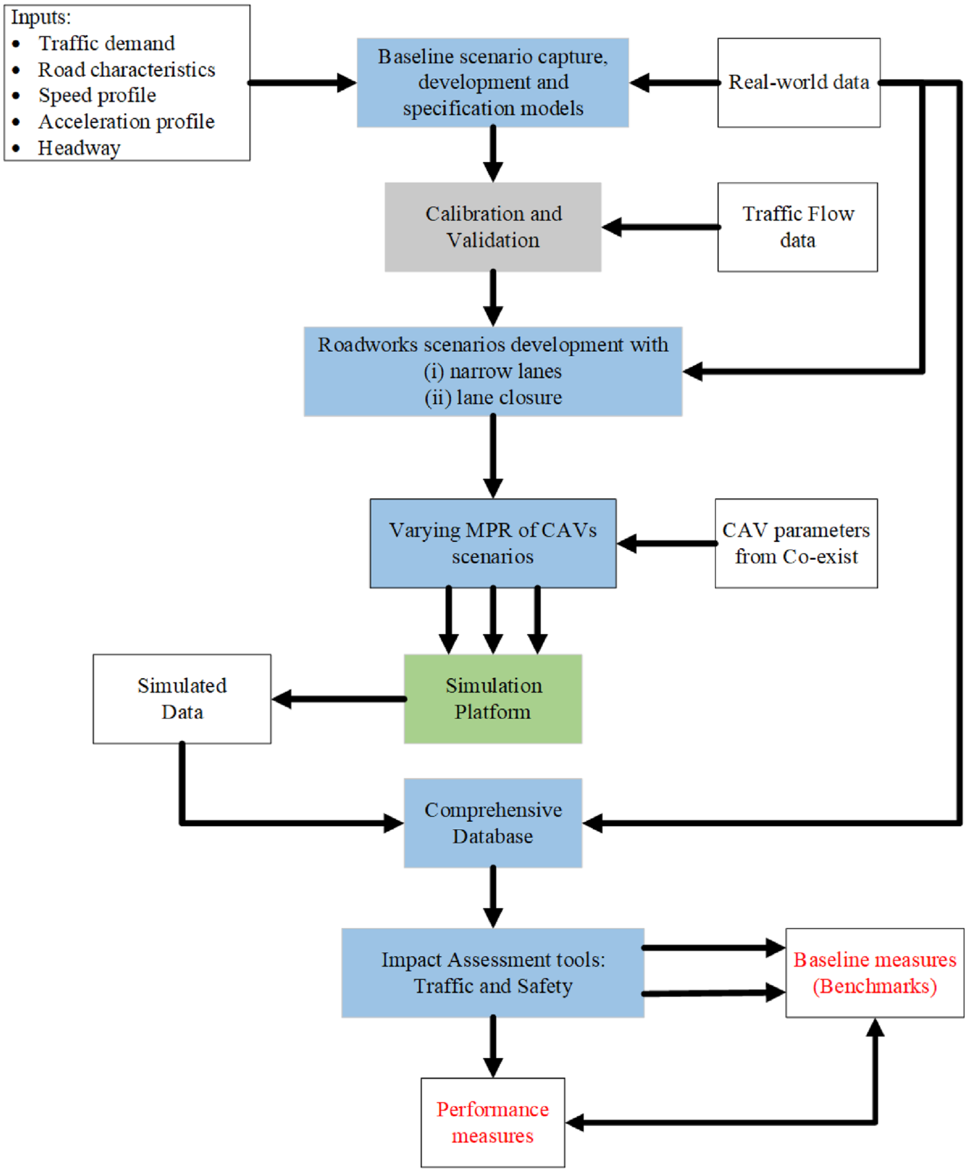

FIGURE 1 Overall framework of the study.

scenarios virtually in VISSIM. The surrounding traffic in the simulation model was inputted using disaggregated traffic data to ensure a realistic virtual representation of the road network. Different MPRs of CAVs were also tested in the simulation and the characteristics and behaviours of CAVs were modified in relation to the human driven vehicles. The calibrated and validated CAV behaviours were created in VISSIM based on the findings from an European project – Co-Exist [25]. For calibration and validation of the simulation model, each scenario was run 10 times to generate the traffic data such as traffic flow, density, speed, and trajectories. This was carried out to compare with real-world data to ensure realistic values from simulated data. By modifying the MPR of CAVs, conclusions about their impact on mobility and safety on the road network were derived.

3.2 | Scenario development

The topological configurations of the TTM scenarios used in this study were based on the traffic safety manual specification [26] and reflect real-world situations. The purpose of our analysis was to evaluate the impact of roadworks on CAVs and determine the TTM that can improve both traffic efficiency and safety. It's worth noting that the reduced speed limit in present simulated scenarios reflects real-world conditions. The simulation model captured the ability of drivers (or automated driving systems) to maintain speed and safe steering control in the narrowed lanes, along with other relevant parameters such as maximum allowed speed, headways, and gaps.

In designing LC scenario, a signage preceding the roadwork zone (100 m ahead of lane change zone [26]) was erected to

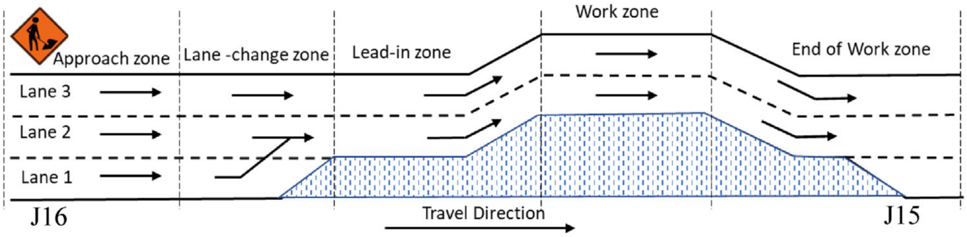

FIGURE 2 Development of lane closure (workzone) scenario [26].

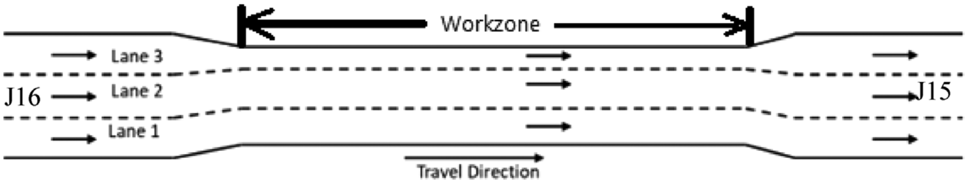

FIGURE 3 Development of NL scenario.

notify approaching vehicles. At the entry of LC zone, vehicles complete lane change manoeuvre from the closed lane to live lanes. This was followed by lead-in zone where vehicles are set to complete lane changes before the beginning of the work zone. Finally, the roadworks area ends until the last sign appears on the network. In the simulated LC scenario, Lane 1 was closed starting from J16 to J15 (Figure 2), and throughout the work zone the maximum allowable speed was reduced to 60 from 70 mph [26].

The NLs scenario was developed such that lanes width were reduced from 3.65 to 3.3 m for Lane 1 and 2 and to 2.75 m for Lane 3 (Figure 3) [26]. Lane 3 was the narrowest, and trucks cannot pass through this lane due to its reduced width. Hence, HGVs use the remaining two lanes for travel, ensuring their accommodation in the wider lanes designed to accommodate heavy goods vehicles. Similar to LC, vehicles in NLs can only drive at a maximum speed of 60mph with reference to the traffic safety manual [26]. The speed distribution in both scenarios were lowered by around 13%. This assumption is assigned based on [26] to adjust the maximum allowable speed as 60 mph.

3.3 | Simulation model

After developing the scenarios for simulation, the impact of CAVs the two TTMs in different MPR were analyzed using a simulation model in VISSIM. The car-following model, lane-change model, lateral control behaviour, cooperative lane change and safety rules, modelled in the present study are discussed in the subsequent sections.

3.3.1 | Car-following model

The car following feature is used to simulate the behaviour of vehicles as they follow other vehicles in traffic. A car-following model was assigned to each vehicle in the simulation. The car-following model determines how the vehicle adjusts its speed and position relative to the vehicle in front of it. These models are described using three major groups of parameters: desired speed, acceleration/deceleration, and safe following distance [27]. The simulator allows to change the intended speed distribution and desired acceleration/deceleration for drivers of different vehicle types. To produce traffic, the parameters were input into the VISSIM simulation model and make use of the Weideman-99 car's driving behaviour. This model is more suited to simulate traffic on motorways (i.e. the present study) which makes use of psycho-physical perception [27] given in Equation 1:

$$v_n(t+\Delta t) = \min \left\{ \begin{array}{c} u_n(t) + 3.6\left(\text{CC8} + \dfrac{\text{CC8} - \text{CC9}}{80} u_n(t)\right)\Delta t \\ 3.6\dfrac{(s_n(t) - \text{CC0} - L_{n-1})}{u_n(t)} \end{array}, u_\text{f} \right\} \tag{1}$$

where t is current time, Δt is the time step, $v_n(t+\Delta t)$ is the speed of the following vehicle in the next time step, s_n (t) is the space headway (head-to-head or bumper to bumper gap) between the AV and following vehicle, u_f is the free flow speed, u_n is the speed of following vehicle and L_{n-1} is the length of preceding vehicle. The car-following parameters appeared in the right-hand side of Equation (1) were adapted to represent CAVs behaviours and are presented in Table 1.

3.3.2 | Lane change model

VISSIM's lane-changing model is based on a model proposed by Willmann and Sparmann is a rule-based approach in which lane-changing behaviour is classified as either lane shift to a faster or a slower lane [27–29]. Lane changing in VISSIM is

TABLE 1 Calibrated set of car-following parameters.

Car following parameters				
Parameters	**Short name: description**	**CAVs (default)**	**Conventional car**	**Applications**
CC0	Standstill distance: distance between leader and follower vehicle when they are not moving	1 m	1.5 (m)	Safety distance
CC1	Headway time: time gap between leader and follower vehicle when they are moving	0.6 s	Cumulative distribution observed from field*	Safety distance
CC2	Following variation: additional safety distance	0.00 m	4 (m)	Maximum following distance
CC3	Threshold for entering following: time (s) required to start vehicle deceleration to reach the required safety distance	−6 (s)	−8 (s)	Threshold to reach in safety distance
CC4	Negative following threshold: controls a negative speed variation between the following process.	−0.1	−0.35	Decreasing speed difference; maximum following distance
CC5	Positive following threshold: controls a positive speed variation between the following process.	0.1	0.35	Increasing speed difference
CC6	Speed dependency of oscillation: impact of distance on speed oscillation	0	11.44	Decreasing speed difference; increasing speed difference
CC7	Oscillation Acceleration: minimum acceleration/deceleration during the following process.	0.1 m/s^2	0.25 m/s^2	Following process
CC8	Standstill acceleration: required acceleration when starting the vehicle	4 m/s^2	3.5 m/s^2	Starting the vehicle
CC9	Acceleration at 80 km/h	2 m/s^2	1.5 m/s^2	Acceleration beyond 80 km/h

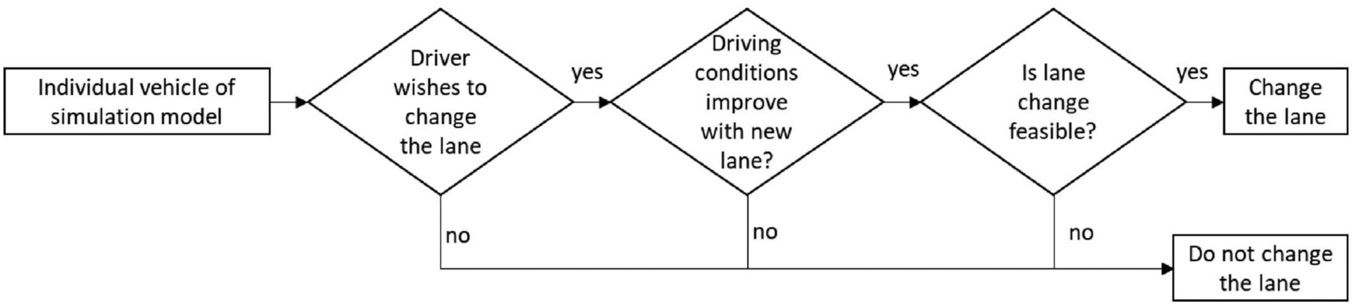

FIGURE 4 Lane change algorithm in VISSIM.

performed in a sequential rule-based manner. The model first assessed the motive of lane changing, then evaluated if the conditions of driving would improve, and the feasibility of lane change manoeuvres (Figure 4).

In the LC scenario, a mandatory lane change is required prior to entering the construction zone. However, in the case of NL, the necessity to change lanes depends on their driving preferences and other safety concerns (e.g. gap, acceleration, deceleration, waiting time, safety distance). For this manoeuvre, conventional vehicles could only interact with four vehicles simultaneously. However, CAVs could observe a maximum of ten objects (including vehicles and infrastructure—Vissim default for AVs) while they could interact with eight vehicles simultaneously to modify their behaviour. In addition, "cooperative lane change" was added to the simulation. This is a binary parameter called which by default is disabled in Vissim. Vissim recommends this feature to be turned on while simulating the AVs [25, 30]. This feature enables vehicles to recognize opportunities to aid other cars in performing lane changes, by providing space for them to merge into the adjacent lane. In our study, we activated this feature to enable the CAVs to cooperate with other vehicles on the road.

When a CAV approaches a lane closure, it first checks whether there is space in the adjacent lane to safely perform a lane change. If there is insufficient space, the CAV waits for other vehicles to provide a gap before initiating the lane change. The cooperative lane change parameter in Vissim enables CAVs to communicate with other vehicles and request space to perform a lane change, thereby reducing the overall delay caused by the lane closure.

3.3.3 | Lateral control behaviour

This module within VISSIM is designed to replicate the behaviour of vehicles when they need to change lanes. It distinguishes between two types of lane changes: Necessary lane changes, where a lane change is essential for the vehicle's intended path, and free lane changes, where a lane change is discretionary based on the driver's decision-making [31]. This feature leverages a dynamic link library (DLL) to receive information about the present state of the vehicle and its surroundings. Based on this information, the DLL calculates the vehicle's acceleration/deceleration and lateral behaviour, primarily for lane changes. The updated vehicle state is then transmitted back to Vissim, which allows for a seamless integration of the simulation. This feature is similar to a previous study [32] and provides a realistic virtual traffic environment, which facilitates the simulation of automated vehicle control algorithms, sensors, and communication protocols with a high degree of detail. It also takes into account various factors that influence the lateral behaviour of the vehicle, such as road geometry, traffic flow, and vehicle dynamics. For example, it considers narrow lanes and adjusts the vehicle's behaviour accordingly. By incorporating these factors, the lateral control feature can accurately simulate the behaviour of different types of automated vehicles in a wide range of traffic scenarios. This makes it possible to test and evaluate different scenarios, such as varying traffic flow and road geometry, under controlled conditions, without putting actual vehicles or drivers at risk.

3.3.4 | Cooperative lane change

Vissim has a feature called cooperative lane change (CLC) that is by default disabled. Upon activation, it enables automobiles to recognize and generate gaps for adjacent vehicles to switch lanes. This option introduces an element of cooperative behaviour among vehicles. If a vehicle observes that a leading vehicle on the adjacent lane wants to change to its lane, it will try to change lanes itself to the next lane to facilitate lane changing for the leading vehicle. This cooperative mechanism is instrumental in mimicking real-world scenarios where vehicles collaborate to optimize traffic flow and accommodate lane changes seamlessly. [33]. The impact of CLC on link speeds and densities is more significant than its impact on vehicular throughput. Enabling CLC in regions with high merging and weaving traffic patterns has the potential to enhance motorway operations and mitigate impractical waiting periods for merging automobiles. The impact of CLC can be observed in the upstream direction due to the heightened frequency of lane changes, which can lead to turbulence in the flow of traffic.

3.3.5 | Safety

Safety was dependent on the headways (standstill and time) and speeds of the vehicle. Safety distance required for the movement of vehicles without a collision was calculated with the help of the following Equation 2 [34]:

$$\text{Safety distance} = CC0 + CC1 \times v \tag{2}$$

where CC0, CC1 are detailed in Table 1 and 'v' is the speed of vehicle. In the simulation, vehicles maintain this safety gap. CAVs were able to maintain less time and standstill headways (0.6 s and 1 m respectively [25]) compared to conventional vehicles (field observed distribution and 1.5 m respectively).

VISSIM is not able to produce safety results (crashes) directly. Hence, surrogate safety measures (conflicts, steering angle, speeds) were used to estimate conflicts between vehicles using SSAM [35, 36]. The simulation model examines three types of conflicts which are common in roadworks: rear end, crossing, and lane change conflict. These conflicts were calculated based on the angle of interaction between vehicles, their relative speed and the gap between consecutive vehicles. It is also important to note that all simulation software, including VISSIM, may not capture some random or illegal driving manoeuvres that could result in differences between simulation and real-world conflict metrics. Nevertheless, these models are widely accepted in academic research as the calibration process yields results that fall within an acceptable range of 20% [37, 38].

The safety measures associated with narrow lanes were analyzed for further insights to explore CAV behaviour in roadworks. The behaviour of vehicles in VISSIM is influenced by changes in lane width [39] which allows simulating the effect of narrow lanes on vehicle behaviour and analyzing the resulting implications for safety. These considerations aim to provide a more accurate representation of real-world conditions and a nuanced assessment of the safety implications of narrow lanes.

To model the behaviour of CAVs, several parameters were modified including standstill distance, headway time, following variation, negative and positive following thresholds, speeds, and accelerations compared to conventional vehicles. Additionally, automated vehicles are expected to be equipped with advanced communication technologies and can interact with more objects (such as other vehicles and infrastructure) than human driven vehicles. Therefore, the number of objects CAVs can observe in the simulation model was also updated in the simulation model. To enhance the coordination of CAVs during lane changes, the cooperative lane change feature was enabled in the simulation. This feature allows CAVs to effectively check for and provide sufficient gaps for vehicles attempting to change lanes. By actively interacting with nearby vehicles and strategically waiting at their position, AVs are able to ensure that the necessary gaps are provided to any vehicles in need.

To assess the impact of various roadwork scenarios on traffic flow and safety, a simulation model was developed and calibrated using a standard road segment. The calibration parameters were chosen to enable the simulation to accurately represent a variety of roadworks scenarios. As a result, it was not necessary to independently model driver behaviour for the lane closure and narrow lane scenarios. In accordance with the [26] guidelines, the maximum speed allowed for vehicles traveling through roadworks is 60 mph. In the Vissim simulation, vehicles adjust their speed based on the traffic and road

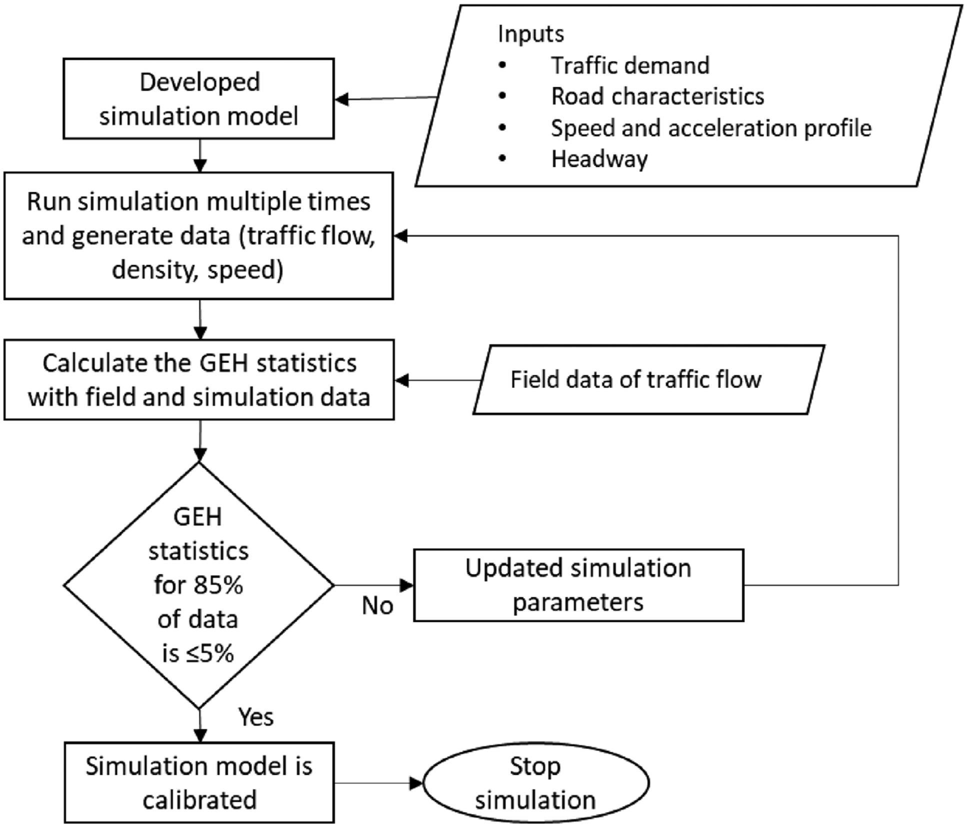

FIGURE 5 The calibration process.

conditions surrounding them. If the road is clear and traffic is light, vehicles are able to travel at the maximum allowable speed.

3.4 | Calibration of the simulation model

To ensure a simulation model mimics real-world traffic conditions, it must be calibrated in both the map geometry and the traffic representation. Calibration improves the model's representation of reality by changing simulation settings. To avoid incorrect evaluation results, the disparity between observed and simulated data must be minimized and therefore, model needs to be calibrated. To construct a realistic geometry, the simulation model was constructed over a Bing map. During the development of the simulation model, the lane changing behaviour of vehicles was established at a distance of 400 m based on the findings from prior research [40–42]. This indicates that a car has 400 m to change a lane before it is closed for vehicles.

Figure 5 depicts a general structure for the calibration procedure. Traffic flow, speed, and headway measurements were derived from real-world data, and given as input to the simulation model. In order to compare simulation results with real-world data (from inductive loop), it was necessary to conduct multiple simulations to estimate an error by GEH statistics as proposed by Dowling et al., [35]. If the error is within the permitted range (≤5% for ≥85% times Dowling et al., [35]), it would imply that the simulation model has been correctly calibrated. In this case, calibration and validation procedures were repeated until the disparities between simulated and observed values are within acceptable ranges.

To quantify the model calibration performances, GEH statistic is used [35]. GEH is defined as follows (Equation 3):

$$\mathrm{GEH} = \sqrt{\frac{2(M-C)^2}{M+C}} \tag{3}$$

where M is the simulated values and C is real-world values of traffic flow at different time intervals. FHWA rules state that outputs such as traffic flow and journey time are acceptable if the GEH is less than 5% for more than 85% of the observed pairings [35]. Table 1 gives the calibrated set of parameters of conventional vehicles gathered from the field. Due to the lack of practical data on CAVs, the research utilized parameters for CAVs from a prior study conducted by [25]. These parameters, specifically designed for application in European cities, were developed under the Horizon 2020 Project known as co-exist. This project aimed to prepare for a transition phase where automated and conventional vehicles would coexist on city roads [25]. As these were calibrated and validated values, this study adopted these values as realistic driving parameters

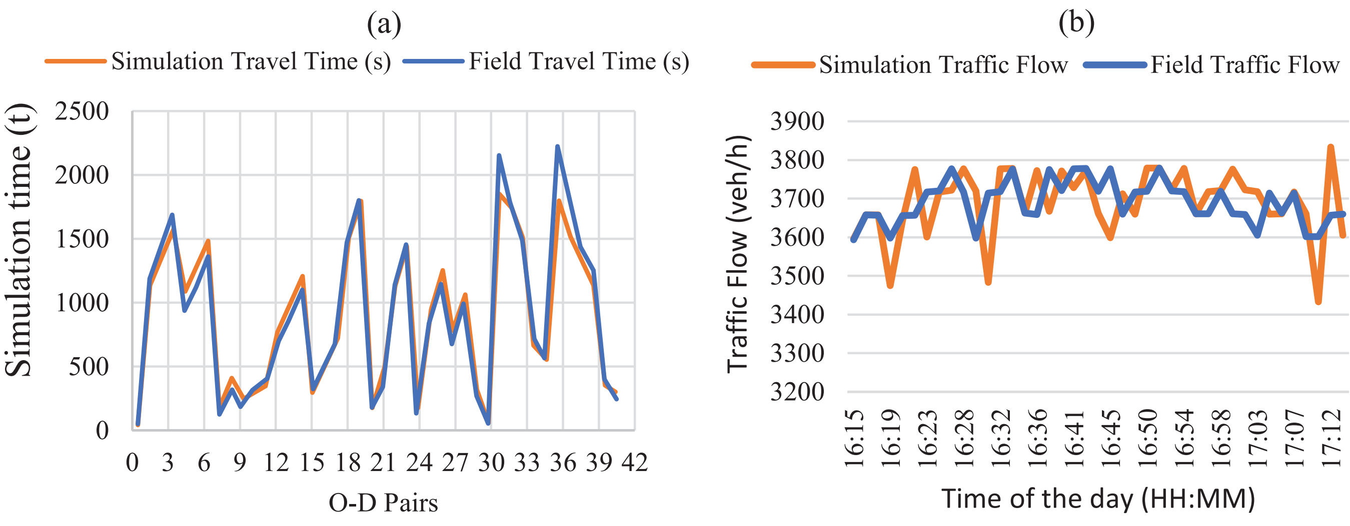

FIGURE 6 (a) shows the travel time calibration of mainline roadway (estimated vs simulated) and (b) observed vs simulated traffic flow of the mainline.

The parameters from Sukennik, [25] offer a solid foundation due to their prior calibration and validation in real-world conditions. While roadwork-related conditions are unique, the fundamental driving characteristics captured by these parameters can be considered transferable and adaptable to various urban traffic configurations, including scenarios involving mixed traffic, lane closure, and lane narrowing. In the absence of a dedicated dataset specific for roadwork-related CAV parameters, the adoption of well-calibrated and validated parameters from a reputable study becomes an acceptable approach. This not only ensures a realistic representation of CAV behaviour but also aligns with established practices in traffic simulation research, where existing parameters are often used as a starting point for studies in specialized domains.

For further information about the application of these parameters in an equation for the calibration of a simulation model has been discussed thoroughly in the study by Chaudhari et al., [43].

3.5 | Data

Before the coronavirus outbreak, traffic data from MIDAS (motorway incident detection and automatic signalling) using inductive loop detectors on the UK M1 between junctions 13 and 16 were collected from January 2018 to March 2020. This includes a stretch of 30 km of 3-lane highway. Along the segment, there are 74 loop detectors (28 northbound; 27 southbound; 9 on slip roads northbound; 10 slip roads southbound). The loop detectors use radar technology and magneto-resistive wireless sensors to measure direct values of speed, occupancy, flow, and headway every minute per lane [44, 45]. The microsimulation was developed using the real-world network using evening peak hour (16:15 to 17:15) traffic data as an input. After cleaning, aggregated data was utilized to produce minute-level data for flow, HGV %, average speed and headway within lanes, and average speed, headway, and speed standard deviation between lanes.

3.6 | Limitations of the data

Data quality can hinder a simulation model's performance. Starting in 2018, the smart motorway project closes parts of the motorway network. As a result, some loop detectors have no traffic data for the entire year. Traffic data were collected in 2019 and early 2020 to reduce traffic parameter volatility. Another loop detector issue is 'no-flow' when no vehicles appeared in the past minute.

3.7 | Calibration of the model

Both evening peak and evening off-peak time periods were used for model calibration and validation in this study. Actual journey times are calculated using Google Maps distances and average speeds in the research network consisting of 42 OD pairs. Simulated journey times were obtained directly from VISSIM. The variance between simulated and observed travel times for the specified routes were within the permitted range. As a result, the default driving behaviour settings in VISSIM were used without any additional alterations. The GEH statistic of travel times indicate that simulation model generates travel times at a sufficient level with 88% of accuracy. Figure 6 shows the time series distribution of field observed versus simulated travel times and flows of the mainline segment of motorway M1. It can be stated that the simulation model outputs illustrate similar pattern with the estimated (simulated) travel time. The traffic flow in the Figure 6(b) seem to be deviated from each other. However, a statistical test (Man–Whitney) shows that the mean results have no significant difference.

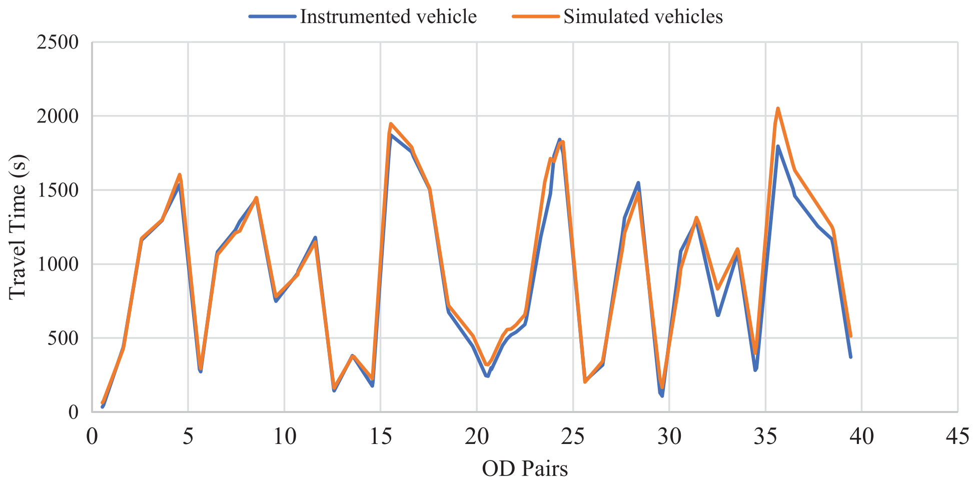

FIGURE 7 Comparison of travel time from the instrumented vehicle and the simulation model (26th May 2021).

3.8 | Validation of the simulation model

To validate the simulation model, an instrumented vehicle was driven between J13 and J16 of M1 motorway multiple times to collect real-world data. The instrumented vehicle was equipped with a GARMIN GNSS-DR device which was able to acquire highly disaggregated speed and vehicle position data at frequency of 1 Hz. Both speed and journey times of the real-world data were compared to data from the simulation model to investigate whether the traffic simulation accurately matches real-world driving situations.

To further verify the simulation model, the non-parametric Mann–Whitney test is used. Based on the trip conducted on the 26th of May 2021 during the evening peak hour, results indicated that the independent samples of simulated and ground-truth speed profiles were from the same distribution as the *p*-value of the southbound was found to be 0.51, and the northbound was 0.11 indicating that there is evidence that the simulated model represents the expected traffic operations and vehicle behaviour of real-world evening peak hour of 16:15 to 17:15 accurately. As a result, it can be noted that the simulation model successfully replicates the actual traffic conditions of the studied network. In addition to speed profiles, journey times representing a number of origin-destination (OD) pairs were also examined. In the simulation, each OD pair represents a specific traffic flow input and output point. The origin points are where the vehicles are generated and enter the simulation on a particular link (road) and at specific times, based on the traffic flow data collected in the field. The destination points represent where the vehicles in each traffic flow reach their final destination and are removed from the simulation. The connection lines between the OD pairs on Figure 7 are used to show the trend of the simulation results for travel times between these origin and destination points. The travel times for individual OD pairs can vary significantly, depending on factors such as the distance between the origin and destination points, the level of congestion on the link, and the speed of vehicles. The *p*-value of the Mann–Whitney U test was found to be 0.70 meaning that the simulating traffic conditions, and the actual road conditions are similar. The purpose of Figure 7 is to visually compare simulation results and probe data for each OD pair. It is important to note that data from several probe trips were utilized to ensure the robustness of our findings, but only one sample is presented.

The GEH Statistic was used to enhance the realistic representation of the simulation model. According to the guidelines published by FHWA [35], GEH values should be lower than 5 for at least 85% of the observed pairs. The average GEH values for the southbound and northbound were found to be 0.49 and 2.32 implying that the simulated model has the capability to generate realistic traffic conditions. Figure 7 displays the graphical demonstration of the simulated travel time outputs over the ground-truth travel time data, with a high degree of similarity being visible. This indicates that the simulation model has the capability of capturing real-world traffic representation in a virtual platform.

In light of this information and analyses, it can be stated with a high level of confidence that the real-world traffic conditions and vehicle behaviours were simulated accurately within the microsimulation platform of VISSIM, therefore, the outputs of the microsimulation scenarios would provide realistic results.

4 | RESULTS

TTM roadworks scenarios were developed in the simulation model and sensitivity analyses were conducted. The findings were evaluated through key performance indicators (KPIs) covering traffic conflicts and delays. The potential benefits of CAVs in improving traffic performance and safety because of work zone impacts were analyzed mainly with two aspects: (i) reduction in delay with improved capacity and (ii) low risk of collision and TTC. The impacts of multiple MPR of CAVs for each scenario were also investigated. Each scenario was simulated 10 times by utilizing different random seeds to generate different traffic dynamics surrounding CAVs. Parameters such as road

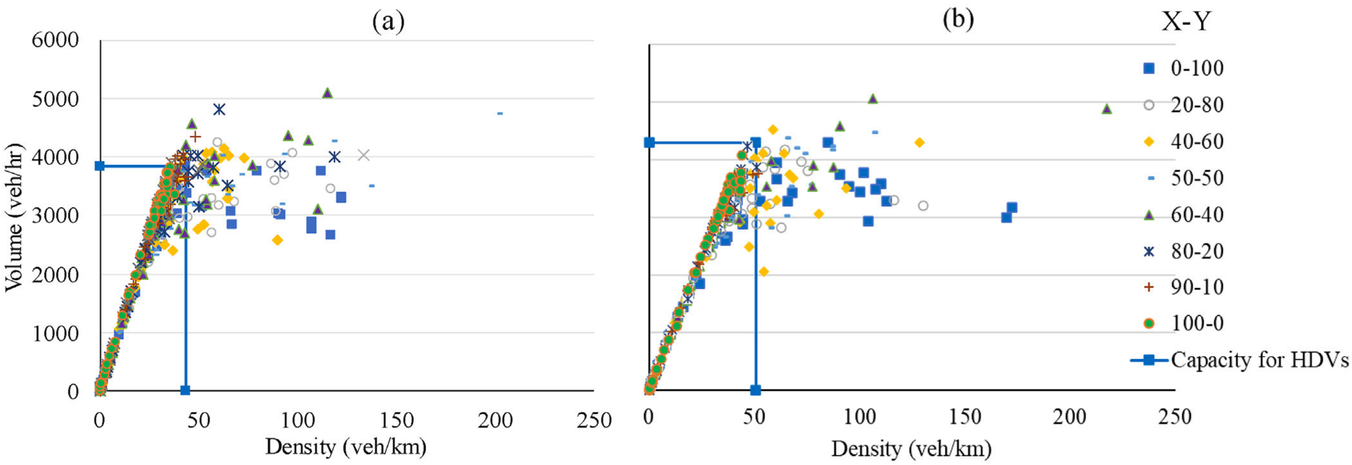

FIGURE 8 Fundamental diagrams of (a) lane closure and (b) narrow lanes (CAVs *X*% -and conventional vehicle *Y*%).

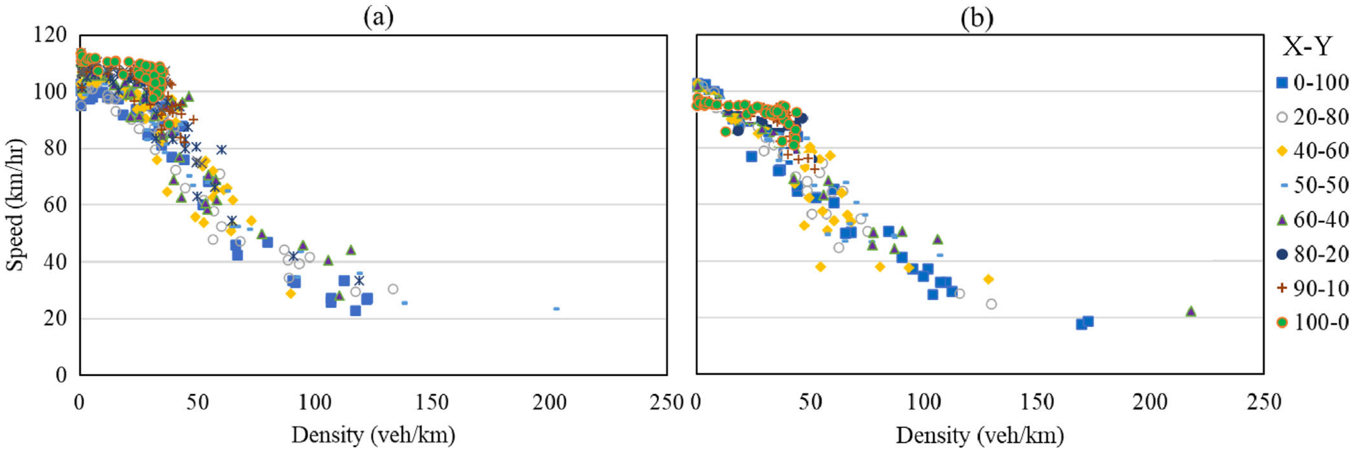

FIGURE 9 Density-speed diagrams of (a) lane closure and (b) narrow lanes (CAVs *X*% -and conventional vehicle *Y*%).

design, driving manoeuvres and behaviour of the CAV were kept constant.

4.1 | Traffic states in different MPRs in roadworks

A macroscopic fundamental diagram of traffic flow theory is the inverted U-shaped density-flow curve. At low traffic densities, there are not sufficient vehicles on the road so there is enough space for all vehicles to travel at their free-flow speed. This state of traffic can be seen on the left-hand side (of the capacity) of Figure 8(a),(b). As the density starts to increase, the speed starts decreasing. This continues increasing until the capacity of the road has reached saturation causing the traffic flow to start reducing (i.e. forming congestion). From Figure 8(a),(b) it can be observed that with no CAVs for both TTM schemes, the traffic tends to reach the congestion state (blue points in Figure 8). On the other hand, as soon as CAVs are introduced into the model, the congestion part of the graphs diminishes. This implies that the traffic flow would increase as the MPR of CAVs increases, leading to a higher capacity. The traffic states (congested and free flow) were tested extensively in simulation with different MPRs and traffic compositions. Macroscopic fundamental diagrams were created for each of the compositions as shown in Figures 8 and 9.

Figure 8(a),(b), show that as the market penetration rate of CAVs increases, the capacity for vehicles to travel also increases. At 80% market penetration rate, the vehicles are able to reach a capacity of 6000 vehicles per hour. However, beyond this point, the free flow side of the graphs is visible, indicating the potential for even greater capacity. Moreover, the capacity for conventional vehicles in lane closure (3800 vehicles per hour) and narrow lane (4300 vehicles per hour) scenarios is also depicted by straight lines on the plots, showing that CAVs have the potential to greatly enhance link capacity compared to traditional vehicles.

4.2 | Delays

Roadworks reduces the capacity of a road, which can lead to increases in journey times resulting in delays. Delay in this simulation was estimated as the total delays occurred throughout the

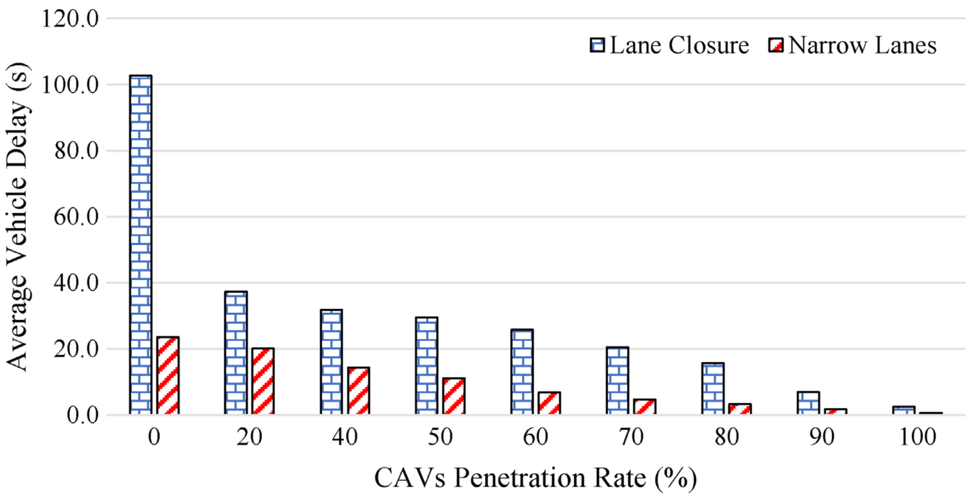

FIGURE 10 Average vehicle delay results of lane closure and narrow lanes.

segment between J16 and J15 divided by the number of vehicles that pass through that certain segment (i.e. delay per vehicle). Figure 10 shows how different traffic compositions affect the average vehicle delay.

The delay is highest (LC: 102.7 s, NLs: 23.6 s at 0% CAV MPR) when the traffic is composed of conventional vehicles (90% cars, 10% HGVs). The higher delays observed in the lane closure scenario compared to the narrow lanes scenario may be attributed to the fact that vehicles are not aware of the lane closure until they are within the proximity. As a result, they tend to change lanes when they are near to the closure, leading them to wait for a suitable gap and causing a delay. On the other hand, in the narrow lanes scenario, all the lanes are maintained, and vehicles are not required to change lanes. This allows them to continue in their lane and reduce the delay compared to the lane closure scenario.

In the case where all vehicles are CAVs (i.e. 100% CAVs), the lowest average vehicle delay was obtained (LC: 2.5 s, NLs: 0.6 s). Interestingly, the delay reduction due to CAVs is more significant in the lane closure scenario than in the narrow lane scenario. This could be because CAVs have access to more information and can plan their movements more efficiently. They can also communicate with each other to coordinate their movements, leading to smoother traffic flow and less delay. As a result, the situation in the lane closure scenario is improved and becomes closer to the narrow lanes scenario when CAVs are included in the traffic. Another important component to notice is that the delays are significantly lower when using NLs as the TTM scheme. This is noticeable, especially with a 0% CAV MPR where the delays in LC are 4.35 times higher. This could be attributed to the additional lane increasing the capacity of the road network.

4.3 | Safety

Since there is no collision in a traffic microsimulation, SSMs were employed to detect traffic conflicts. A traffic conflict is a traffic event involving the interaction of two or more road users, where one or both road users need to take evasive action, such as braking or swerving to avoid a collision [46]. The most widely used metric to identify traffic conflicts is TTC [47]. This measure is defined as the remaining time before an impact takes place between two road users unless an event to change their trajectories and speed occurs, such as braking or a change in steering angle. Its equation is given as (Equation 4):

$$\mathrm{TTC} = \frac{\mathrm{s}}{v_{\text{ego-vehicle}} - v_{\text{leading}}} \; \forall \, v_{\text{ego-vehicle}} > v_{\text{leading}} \tag{4}$$

where $v_{\text{ego-vehicle}}$ is the speed of a CAV, v_{leading} is the speed of the leading vehicle, and s is the distance between preceding vehicle and the CAV. A TTC of 1.5 s is a widely adopted threshold in the literature as a safety surrogate measure [47–51] and is used as a benchmark for comparison purposes. Similarly, to evaluate the safety of CAVs in this context, (TTC) metric was also adopted with a threshold of 1.5 s. This threshold is widely used in safety assessments of automated driving systems [52, 53]. In this research, it was used to determine the percentage increase in the number of traffic conflicts in relation to the baseline scenario (i.e. no roadworks) [47]. As shown in Figure 11, the number of conflicts change with the change of MPRs of CAVs as expected. Results, however, show that there are no conflicts due to crossing (i.e. overtaking). This could be due to LC as there was not enough lateral space for vehicles to perform an overtaking manoeuvre. When considering LC, with a 0% MPR of CAVs, the rear-end conflicts are significantly higher than lane-change conflicts (three times approximately). However, as the MPR increases conflict frequency gradually decreases. When considering NLs, it can be observed that the overall conflicts are reduced compared to the LC. The highest conflicts were observed with the 50% MPR of CAVs. After 50% MPR, the conflicts started to reduce, and the least conflicts were observed at the 100% CAVs MPR.

The findings in this research are consistent with other studies that have investigated similar issues in the past [32, 54].

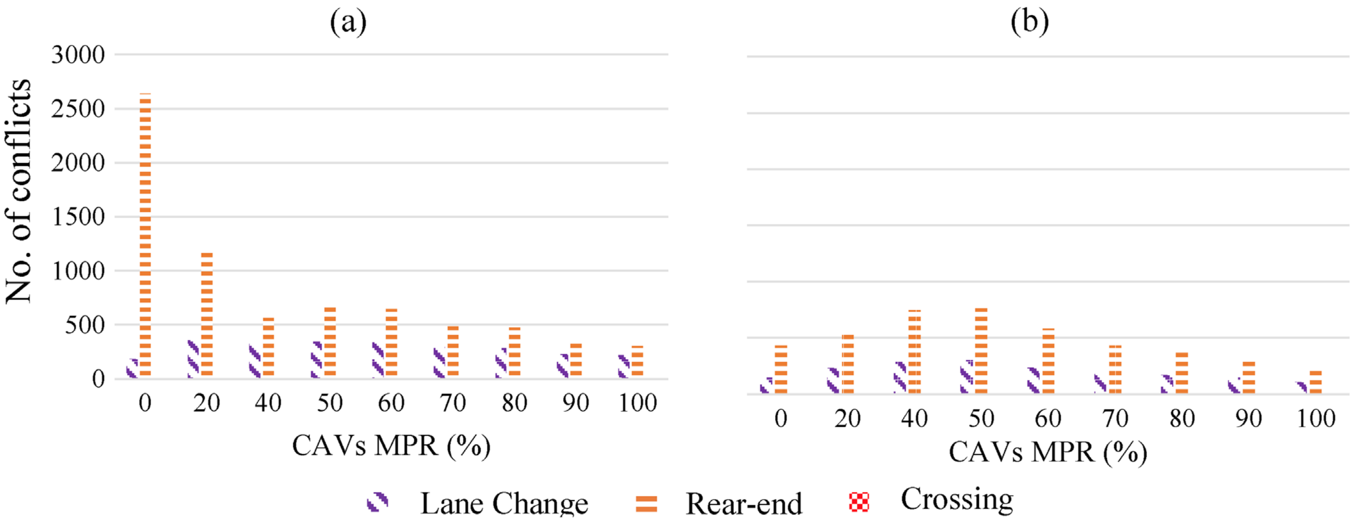

FIGURE 11 Number of conflicts for (a) lane closure and (b) narrow lanes TTM against MP.

Conflicts tend to peak when the percentage of MPR reaches around 50% due to the presence of mixed traffic given the increased frequency of mixed traffic interactions between CAVs and traditional vehicles. At low MPR, mixed traffic interactions are relatively infrequent, and traditional vehicles can adapt to the presence of CAVs. However, as the MPR of CAVs increases, the frequency of mixed traffic also increases interactions, which leads to conflicts due to differences in driving behaviours. After 50%, the frequency of mixed traffic interactions begins to decrease as more CAVs are deployed on the road and they can better communicate with each other and with traffic infrastructure.

5 | DISCUSSION

In preparation for the era of CAVs, highway infrastructure requires upgrades to facilitate CAV operation to minimize the possibility of disengagements. In the interim period, numerous roadworks are taking place in preparation for CAVs and intelligent mobility [10]. Currently, the impacts of roadworks with mixed traffic (i.e. conventional vehicles and different MPR of CAVs) are still unknown. Moreover, no standard operating procedures are currently in place for how CAVs should interpret and navigate the dynamic situations within the roadworks. Therefore, there is a need for developing dynamic frameworks to understand CAV navigation within roadworks. In particular, more research has to be dedicated to understanding the interaction between CAVs, their systems, and conventional vehicles at roadworks [10]. As a result, in this study, a microsimulation model was developed to examine the impact of traffic performance and safety in two TTM schemes for roadworks (NLs and LC) with different MPR of CAVs.

To quantify the impacts of traffic management measures on the traffic performance during roadworks, objectives such as mobility and safety are two main key performance indicators to be assessed. However, these two objectives often trade off with each other and it can be complicated to achieve the pareto equilibrium [10]. This research has shown that NLs outperform LCs across a range of KPIs including safety, delays, and capability at all levels of CAV penetration. However, the difference in performance becomes more marked at higher CAV MPRs. For example, road capacity for the case of 100% conventional vehicle is at around 3,800 (for LC) and 4,300 (for NLs). If these vehicles were gradually replaced with CAVs, the optimal capacity was not reached indicating that more CAVs could be introduced before any congestion occurs. This is correct for both TTM schemes, implying that the introduction of CAVs has the potential to enhance link capacity. Therefore, given the difference in performance roadway contractors should embed a presumption in favour of the employment of NLs. Any deviation from this should be justifiable on the basis of specific concerns or risks within the specific work zone.

Between the two TTMs, roadworks with NLs provided more safety benefits than roadworks with a closed lane. This is because NLs are associated with an initial increase in level of traffic conflicts up until 50% CAV proportion in the traffic, after which conflicts begin to decrease. Throughout the simulation runs, the amount of recorded rear-end conflicts are significantly outnumbered lane-change conflicts in both TTM schemes. This is comparable to results in the literature [55–57].

The calibrated and validated CAV behaviours were created in VISSIM based on the findings from a European project – Co-Exist [25]. The Co-Exist project involved an extensive calibration and validation process for the Vissim model, conducted across various test sites and conditions in Europe for CAVs. Using the outcomes of this rigorous calibration process, the calibrated model values were adopted to simulate conditions relevant to current analysis. The calibration of human driven vehicles was done as discussed in Section 3.7.

The present study evaluates the trade-off between safety and efficiency in a dynamic work zone. The methodology remains consistent and transferable, even though outcomes are specific to the modelled section of the M1 motorway. The simulation model needs to be adapted for a new work zone, considering changes in geometry, dimensions, traffic volumes, and other relevant characteristics of the specific location. VISSIM captures intricate vehicle interactions, enabling an evaluation of how changes to work zone geometry and traffic management measures influence individual vehicle movements. The adaptability of the approach makes it applicable to diverse locations, allowing for a tailored assessment that considers the unique attributes of each work zone. The methodology also includes a comprehensive impact analysis, simulating various scenarios representing different work zone configurations. Furthermore, changes to lane closures and geometrical layouts, providing insights into diverse outcomes concerning safety and efficiency metrics, are included. A robust set of performance metrics is defined and measured, including parameters such as travel time, delay, and safety-related indicators like conflicts.

The reliability of the simulation outcomes is validated against real-world data obtained from comparable work zones. Calibration against observed data ensures that the simulation model accurately reflects actual traffic behaviours, enhancing the credibility of the findings. As a result, the approach provides insights specific to the modelled M1 motorway section. It establishes a methodological foundation that can be flexibly applied to evaluate the trade-off between safety and efficiency in new work zones, contributing to a broader understanding of dynamic traffic management strategies.

This study employed the combination of microsimulation and sub-microscopic simulation software (i.e. VISSIM and PreScan) to investigate how CAVs the behave on road networks under roadworks. The accuracy and completeness of the results might not perfectly reflect the real-world situation given the software relied on assumptions and traditional car following and lane changing models. The traditional simulation assumptions may not fully capture the complex and dynamic nature of AVs. To mitigate this limitation, the parameters of the models have been customized to better reflect AV behaviour. It is also important to note that simulation softwares may not fully capture the stochastic illegal driving manoeuvres that could result in under-representation of conflicts between simulation and real-world. This study's limitation is the potential impact of vehicles disappearing or queuing due to failed lane changes in Vissim. However, the authors have taken mitigation issue by reducing the number of junctions and using single links for most of the roads. In cases where connectors were necessary, lane change parameters were adjusted to achieve a more realistic scenario and minimize the occurrence of vehicles queuing or disappearing from the network without following their intended route.

6 | CONCLUSION

CAVs may face significant challenges while navigating through roadworks as the operational environment is organically changing. A traffic microsimulation model representing a section of motorway was developed, calibrated, and validated at the base case traffic scenario and it was then employed to estimate the traffic and safety impacts while the market penetration levels of CAV were gradually increased. The findings indicate that NLs achieve better safety and traffic efficiency benefits than LCs. In terms of the traffic efficiency benefits, average delay was lower for NLs because of removing the need for mandatory lane change manoeuvre when entering the lead in zone for LCs. In all situations, the capacity was enhanced as the proportion of CAVs grew, particularly in NLs. Similarly, the safety benefits of NLs are more significant than LC, due to an extensive number of adjustments required for CAVs when entering LC zones.

In conclusion, our study not only advances the understanding of CAV operations during roadworks but also offers actionable findings that can inform the design of traffic management measures for optimal CAV performance. The findings of this paper could provide useful insights to network operators about traffic conditions and road safety after the implementation of CAVs. For CAV manufacturers, the result can benefit in the planning algorithms in developing an in-vehicle 'roadworks assist' system. Highway authorities can also benefit from the study to determine how infrastructures, especially roadworks, can be compatible with the introduction of CAVs and which TTM to employ.

The significant contributions of this study include:

(1) **Developing a traffic microsimulation model of a motorway segment for CAVs**: The paper develops and customize a traffic microsimulation model for simulating CAVs on a section of a motorway. This model serves as a comprehensive tool for assessing both traffic and safety impacts resulting from the presence of CAVs in roadwork scenarios. The robustness of the model is reinforced through thorough calibration and validation processes using real-world traffic data.
(2) **Integrating of real-world roadworks scenarios**: An essential contribution lies in the incorporation of roadworks scenarios with two traffic management measures into the simulation model. Such an integration enhances the study's validity and reliability, ensuring a more accurate representation of the challenges posed by CAVs in practical roadwork conditions.
(3) **Developing of a modelling framework**: The study introduces a new modelling framework tailored for evaluating CAV performance in roadworks. Specifically designed to assess two primary temporary traffic management measures—lane closures and narrow lanes—this framework stands out as a valuable tool for road operators. Its application extends beyond the study, offering practical insights for effective decision-making in managing CAVs within roadwork environments.

In terms of model validation, the speed results are only validated using data from multiple runs of the same vehicle, rather than from multiple vehicles directly. Aside from the model development, the transferability of the modelling result is applicable to similar road types. Whenever, in future, CAVs would be available, the heterogenous traffic conditions can be utilized for the simulation validation and the performance can be improved further. More suitable thresholds of TTC and PET for AVs can be adopted after the deployment of the CAVs.

The incorporation of these factors (i.e. narrow lanes and road closure) allowed this study to go beyond a simplistic analysis while providing a more accurate representation of real-world conditions to develop a more comprehensive understanding of the safety considerations related to these factors in roadworks. This approach enables a deeper understanding of the complex dynamics between CAVs and the roadwork environment, considering the subtle variations and interactions that can arise due to changes in lane width and lane closures. It is important to note that, this study took into consideration the increased difficulty of steering control in the narrowed lanes by modifying the parameters of the driver model in VISSIM to reflect the behaviour of CAVs. In this way, the simulation model was able to capture the ability of drivers or automated driving systems to maintain safe steering control and speed in the narrowed lanes. As a result, the findings contribute to a nuanced assessment of the potential impacts and help inform decision-making processes and future research in this area.

Despite this study comprehensively modelled the mobility and safety effects of CAVs along roadworks, this study does not come without any limitations. When calibrating and validating the microsimulation model, only homogenous traffic conditions were considered in the study. Moreover, the simulation did not include HGVs when modelling 100% CAVs due to the unknown automated parameters for HGVs. This was because the automated parameters for HGVs were unknown, and the study aimed to reflect real-world scenarios with the introduction of CAVs.

Future research should aim to address this limitation by incorporating HGVs into the simulation models and investigating their impact on traffic flow and safety. In terms of future research, a valuable avenue to explore further is the use of heat maps to compare detector data and simulation predictions for the full corridor in terms of occupancy, speed, or traffic flow. Such an approach could provide valuable insights and enhance our understanding of traffic patterns in the studied corridor. Further, it is planned to consider the impact of cooperative adaptive cruise control (CACC) on traffic flow and safety, using the CACC model available in VISSIM to simulate the behaviour of CACC-equipped vehicles.

AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: Study conception and design: Mohit Kumar Singh, Nicolette Formosa, M. Quddus, and Cheuk Ki Man. Data collection: Nicolette Formosa, Cheuk Ki Man, and Mohammed Quddus. Analysis and interpretation of results: Mohit Kumar Singh, Nicolette Formosa, Mohammed Quddus, Craig Morton, and Cheuk Ki Man. Draft manuscript preparation: Mohit Kumar Singh, Nicolette Formosa, Mohammed Quddus, Cheuk Ki Man, Cansu Bahar Masera, and Craig Morton. All authors reviewed the results and approved the final version of the manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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