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# How can on-street parking regulations affect traffic, safety, and the environment in a cooperative, connected, and automated era?

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**Abstract**

On-street parking is a commonly used form of parking facility as part of transportation infrastructure. However, the emergence of connected and autonomous vehicles (CAVs) is expected to significantly impact parking in the future. This study aims to investigate the impacts of on-street parking regulations for CAVs on the environment, safety and mobility in mixed traffic fleets. To achieve this goal, a calibrated and validated network model of the city of Leicester, UK, was selected to test the implementation of CAVs under various deployment scenarios. The results revealed that replacing on-street parking with driving lanes, cycle lanes, and public spaces can lead to better traffic performance. Specifically, there could be a 27–30% reduction in travel time, a 43–47% reduction in delays, more than 90% in emission reduction, and a 94% reduction in traffic crashes compared to the other tested measures. Conversely, replacing on-street parking with pick-up/drop-off stations may have a less significant impact due to increased stop-and-go events when vehicles pick-up and drop-off passengers, resulting in more interruptions in the flow and increased delays. The paper provides examples of interventions that can be implemented for on-street parking during a CCAM era, along with their expected impacts in order for regional decision-makers and local authorities to draw relative policies. By replacing on-street parking with more efficient traffic measures, cities can significantly improve mobility, reduce emissions, and enhance safety.

**Keywords** On-street parking, Parking regulation, Connected and autonomous vehicles, Traffic microsimulation, Impacts assessment

## 1 Introduction

Urban transportation is a cornerstone of modern societies, ensuring mobility and access to services and opportunities. Parking, a crucial component of this system, is increasingly becoming a challenge in major cities around the world. Vehicles typically start their search for parking as they approach their destinations, driving around until they find a location that meets specific driver requirements such as proximity to their endpoint, parking fees, and safety. While on-street parking can be convenient, it often presents challenges due to its unpredictable nature, which can result in unexpected driving manoeuvres.

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In the United Kingdom, drivers spend an average of 44 h a year looking for parking, resulting in a total expense of £733 per individual in terms of lost time, fuel consumption, and carbon emissions, which adds up to a total of £23.3 billion across the entire country [30]. Moreover, 69% of female drivers in the country report feeling stressed and getting into disputes with other motorists when they cannot find a suitable parking space, and 40% of UK residents have missed important events due to parking congestion [14].

In this backdrop, the development of Cooperative, Connected, and Automated Mobility (CCAM) services emerges as a promising solution. Building on advancements in computing and technology, CCAM is anticipated to bring transformative changes to the economy and society over the coming years. These innovations will enable the collection, exchange, and analysis of massive amounts of data, allowing for better decision-making at the individual, local, and city levels. The integration of such systems has the potential to significantly reduce the downsides of on-street parking, including traffic congestion, reduced road capacity, and the heightened risk of accidents.

A significant field within the CCAM services is the deployment of CAVs. CAVs can effectively reduce parking demands by allowing passengers to be dropped off at their desired locations and then proceed to serve another passenger or head to a more strategic parking or waiting area. Such efficiency makes a strong case for city planners and administrations to reconsider the traditional role of on-street parking spaces. Opportunities arise for these spaces to be converted into more beneficial utilities for the public—such as parks, pedestrian areas, or other public spaces.

In addition to addressing parking concerns, introducing CAVs presents the opportunity to improve road safety, reduce urban space requirements for roads and parking, and enhance the quality of liveable areas [23]. However, limited real-world data from CAVs operations at a network or corridor level makes understanding the effects of on-street parking regulations on a transport network challenging. As a result, recent studies have relied on traffic microsimulation platforms to address this issue. By using such tools, researchers can better understand how parking regulations for CAVs could affect the transportation network and make recommendations for future policy decisions and urban planning initiatives.

Grounded in this context, this study aims to investigate the various impacts of on-street parking regulations in the presence of mixed traffic fleets, including both human-driven vehicles (HDVs) and CAVs, at various market penetration rates (MPRs). The paper outlines the methodology and key findings of evaluating mobility, environment, and safety impacts regarding CAVs as reported in the framework of the EU H2020 LEVITATE-Societal level impacts of CCAM-project [35]. Understanding the relationship between CAVs and parking regulations, can pave the way for more sustainable, efficient, and harmonious urban transportation environments. This will ultimately result in an improvement to the quality of life in urban centres. The insights gained from this research could provide valuable guidance for policymakers, urban planners, and transportation professionals as they navigate the transition to a CCAM future.

## 2 Literature review

Earlier studies have projected the possible effects of on-street parking in the context of CCAM services on several aspects, such as mobility, environment, and safety. The subsequent paragraph summarises some of the research findings on these impact categories.

### 2.1 Impacts of on-street parking

Several studies have explored the relationship between on-street parking and traffic characteristics. Nahry et al. [41] examined this connection in Jakarta by analysing the parking turnover, parking index, flow-in, and flow-out. Their results suggested that parking turnover significantly impacts traffic delay, indicating that higher volume and parking turnover lead to longer delays. A similar finding was reported by Borovskoy and Yakovleva [8], who developed a dynamic simulation model using AIMSUN software and AutoCAD's Vehicle Tracking application to examine the impact of parking turnover on traffic delay. Their results indicated that an increase in on-street parking turnover leads to higher traffic delays. Sugiarto and Limanoond [55] analysed the effects of on-street parking manoeuvres on travel speed and capacity, particularly on urban artery roads in the city of Banda Aceh. Their traffic simulation results showed that on-street parking resulted in a 32% increase in average delay time and a 24% reduction in speed.

The impact of on-street parking on traffic performance can be significant and might lead to various problems for urban areas. Haider et al. [26] conducted a recent study on the effects of on-street parking in Chittagong City, Bangladesh, and found that it can result in road narrowing (47%), footpath crises (29%), noise and air pollution (23%), blocked shops (5%), and loss of time (30%). Guo et al. [24] applied the hazard-based duration model to investigate the factors influencing on-street parking-related travel time based on observations of 938 vehicles on two-lane, two-way streets. They found that on-street parking has a significant impact on travel time, with influential factors including the distribution of travel time, the effective lane width, and the frequency of parking/

unparking manoeuvres. Similarly, Lim et al. [37] used the analytical survey and experimental method in Metro Manila. They found that the manoeuvring of vehicles in and out of on-street parking spaces increased the travel time of moving vehicles. Putri and Prahara [47] utilised the Manual Kapasitas Jalan Indonesia (MKJI) 1997 and a linear regression model to study the travel time of vehicles in the study area and they reported that on-street parking has a strong influence on the travel time required to get through to the area.

Vehicles searching for an empty parking space may significantly lead to cruising and frequent stops, which increases $CO_2$ emissions [57]. Paidi et al. [43] carried out a recent study to estimate the excess $CO_2$ emissions from drivers searching for vacant parking spaces during peak and non-peak hours. The study revealed that cruising distance and time are predominantly influenced by the number of empty parking spaces available and the driver's location within the parking lot. As a result, higher levels of $CO_2$ emissions were emitted due to non-optimal cruising distances. According to a study conducted by Shoup [51] in Westwood Village, Los Angeles, it was found that the average time spent cruising to locate a curb space was approximately 3.3 min. This amounts to almost 950,000 million vehicle miles travelled (VMT) per year, resulting in an additional 47,000 gallons of gasoline consumed and emitting approximately 730 tonnes of $CO_2$.

Aside from the impact on mobility and environment, on-street parking affects safety. Firstly, it creates hazards and increases risks for vulnerable road users [6, 46]. The presence of parked vehicles on the road can contribute to heightened uncertainty, mental strain, and potential hazards, as they may obstruct the view of the road and make it more challenging to spot pedestrians who are crossing [17]. Several studies have suggested a strong correlation between child injuries on urban roads and on-street parking, as parked cars can decrease their visibility and limit their ability to discern an approaching vehicle [6, 16, 38, 48, 49]. The Department of Transport in Great Britain [15] issued a report that highlights the relationship between on-street parking and car-pedestrian injury accidents, with on-street parking contributing to 13–17% of such incidents. Additionally, statistics have been released showing that between 1990 and 2021, back-over incidents resulting from vehicles reversing out of parking spots led to the deaths of 1,502 children aged 14 and under in the United States [33].

### 2.2 Impacts of connected and automated vehicles (CAVs)

Several studies have indicated that the introduction of CAVs has the potential to reduce the amount of urban space required for roads and parking [5, 11, 18]. This could create more high-quality liveable space in cities, particularly in the case of shared autonomous vehicles (SAVs), which can serve multiple customers at different times and reduce the number of required parking spaces [42]. As a result, a significant number of existing parking spaces will gradually be removed, replaced or repurposed, for instance, as green or recreational areas [39, 61].

A recent study by Xia et al. [61] reviewed the current research on public parking spaces in urban areas under the scenario of SAVs, and reported that a considerable number of parking spaces would be renovated and repurposed for other uses in the SAV era. Zhang and Guhathakurta [62] studied the impact of SAVs on urban parking land use in Atlanta, Georgia, using a real-world transportation network that incorporated calibrated link-level travel speeds and a travel demand origin–destination matrix. The results revealed that nearly 5% of parking land could be reduced by the SAV system at a 5% MPR level. The results also indicated that each SAV could potentially free up over 20 parking spaces within the city. The International Transport Forum [31] conducted a report investigating the microsimulation of SAVs in Lisbon, Portugal, and found that both on-street and off-street parking spaces could be significantly reduced by about 84–94% under a fully SAV fleet scenario. Zhang et al. [63] also reported a reduction of over 90% in parking space requirements using an agent-based simulation model of the SAV system. The results indicate that the space saved from urban parking spaces could be converted into more sustainable designs, such as green, open, and human-oriented spaces. Silva et al. [52] used the scenario building method to investigate the transformation between SAVs and urban spaces in a case study in Budapest, Hungary. The results showed that almost 83% of the parking demand could be reduced, and the available urban spaces could be repurposed for other uses. The study also found that SAVs could significantly minimise air pollution caused by parking infrastructure, up to 45%.

Several publications have investigated the impacts of on-street parking policies in urban areas [9, 10, 50]. The researchers used data from ticket vending machines, floating car video films, and parking supply information to measure the scheme's impacts on throughput, parking duration, and fare collection before and after introducing the new parking policy. The new scheme extended the zone in the city with the highest price level (green zone) and the second-highest price level (red zone) and introduced this zone on main arterials in the inner city that were previously in the lowest price zone (blue). The policy made it easier to find available parking spaces in central locations, decreasing in search time and traffic.

Based on previous research, on-street parking can negatively impact traffic performance in urban areas. These impacts include reducing road capacity, causing congestion, increasing emissions, and posing safety hazards for road users. However, the introduction of CAVs has the potential to alleviate some of these negative impacts through appropriate on-street parking regulations and create new opportunities for high-quality and liveable areas in cities. In addition to reducing the need for public parking space, the introduction of CAVs is expected to mitigate safety hazards resulting from on-street parking manoeuvres and provide environmental benefits through suitable on-street parking management.

The importance of dynamic management and reuse of on-street parking spaces has been highlighted in recent studies. A recent report [7] emphasises the need for cities to transition to more sustainable and efficient ways of traveling, which includes dynamically managing and reusing on-street parking spaces. The study suggests reclaiming the kerb and repurposing it for other uses such as bike lanes, parklets, and pedestrian zones. Another study [29] takes into account factors such as road conditions, dynamic traffic changes, and the demand for parking space utilization to establish an index system for the dynamic management of parking space usage. The study suggests that understanding these factors can help in the effective management and reuse of on-street parking spaces.

## 3 Methodology

### 3.1 Network and model

This study utilised a traffic network model that had been calibrated and validated using AIMSUN Next microsimulation. The modelling area covered the Leicester city centre network provided by the Leicester City Council in the UK and spanned approximately 10.2 km$^2$, with 788 nodes (junctions), 1,988 sections (roads), and an OD matrix of 209×208 centroids. The traffic demand was comprised of 23,391 trips for passenger cars, 3141 trips for large goods vehicles (LGVs), and 16 trips for heavy goods vehicles (HGVs). As shown in Fig. 1a, the network presented here only covers the city centre region. To enhance the efficiency of the simulation, on-street parking in the city centre has been separated into 4 parking zones that include a total of 52 streets and 138 parking bays, as illustrated in Fig. 1b.

Within this SUC, six scenarios were studied using microscopic simulation:

- No policy intervention scenario—CAV fleet penetration increases without replacing on-street parking intervention.
- Removing half of the on-street parking spaces—reducing parking capacity. After removing half of the parking spaces in each of the four parking zones, the on-street parking spaces have been reduced from 138 to 79 parking bays.
- Replacing all on-street parking spaces with driving lanes (Fig. 2).
- Replacing all on-street parking spaces with cycling lanes (Fig. 2). Cycling behaviour was not simulated in the modelling.
- Replacing on-street parking spaces with pick-up and/or drop-off points (Fig. 3). The scenario is based on the assumption that the AVs are SAVs. As a result, once the vehicle has picked up or dropped off the passenger, it will leave the study area to return home or serve another customer.
- Replacing on-street parking spaces with public spaces, e.g., green and recreational spaces (Fig. 2).

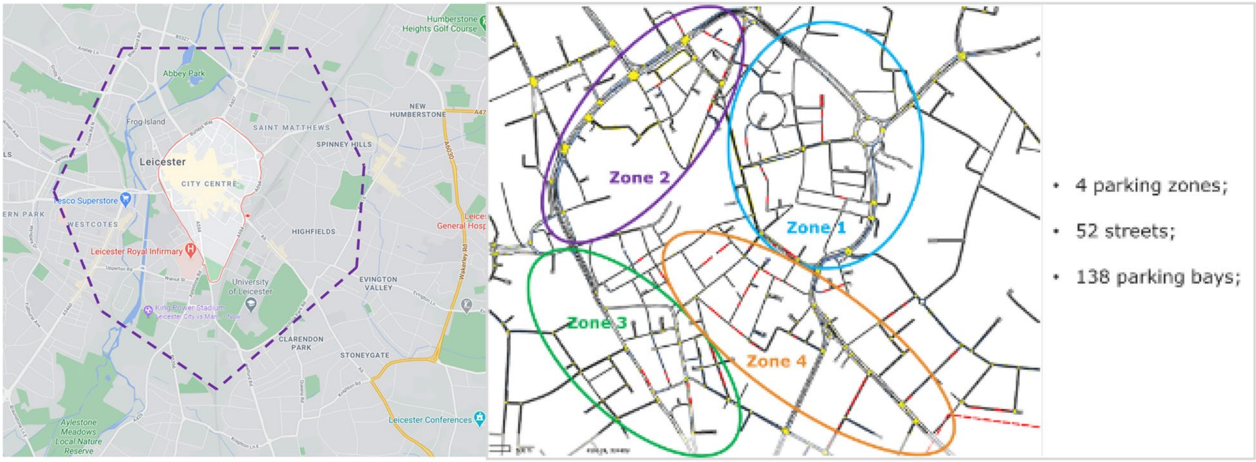


**Fig. 1** **a** The Leicester city centre network and **b** on-street parking zones in AIMSUN software

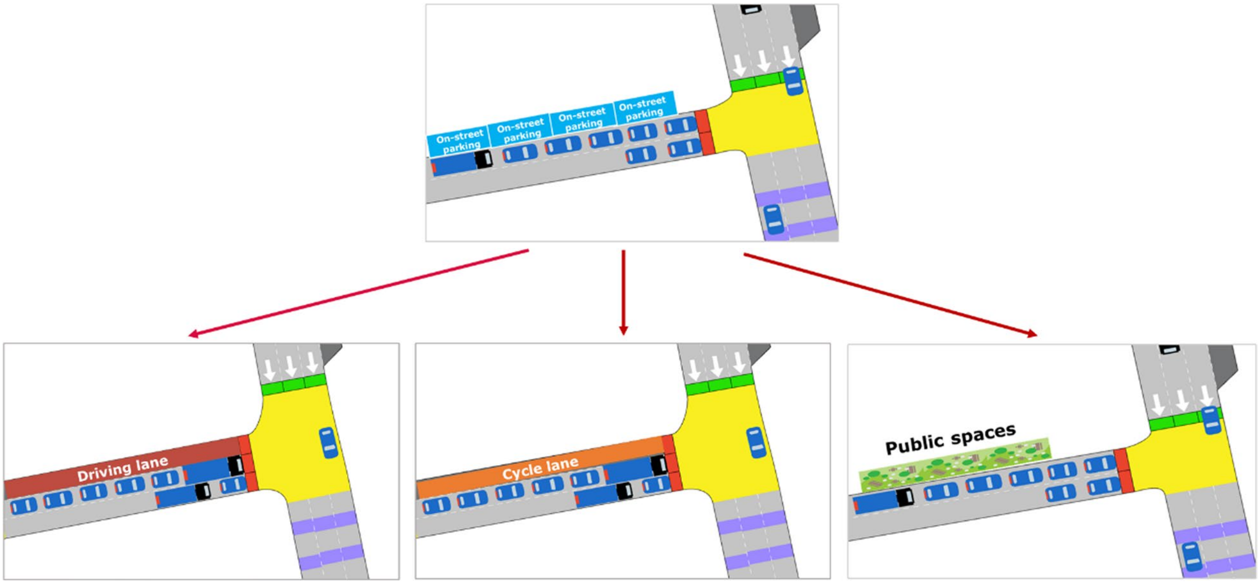


**Fig. 2** Replacing on-street parking with driving lanes, cycle lanes and public spaces

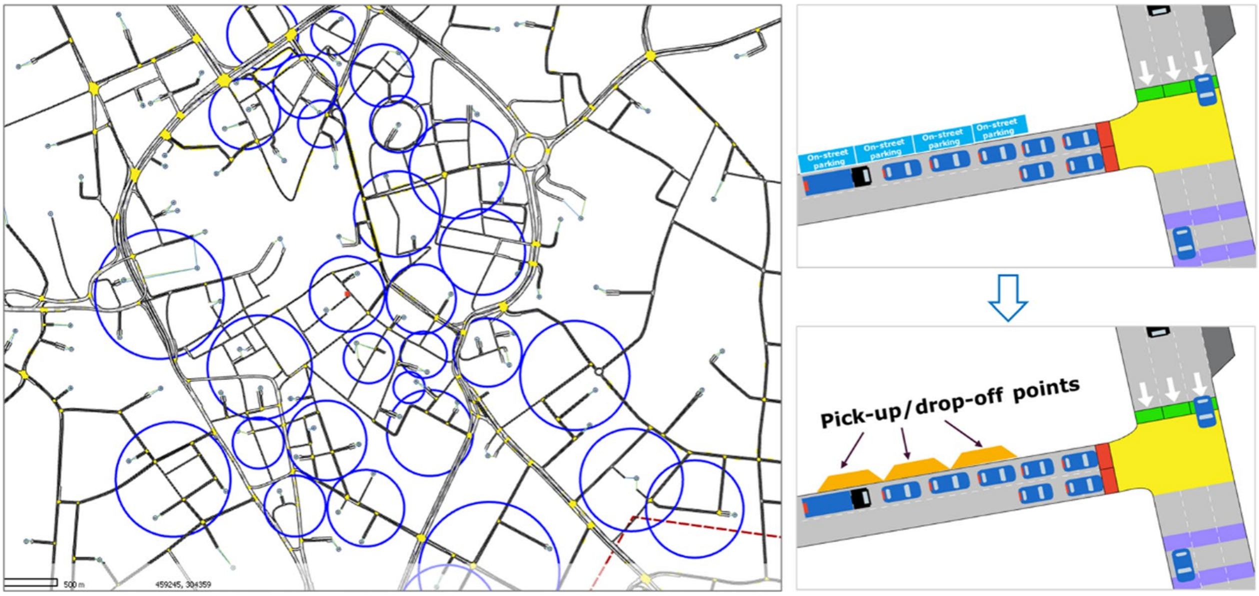


**Fig. 3** Replacing on-street parking with pick-up and/or drop-off points

The following assumptions and limitations exist in this study implementation:

- All CAVs are assumed to be electric vehicles (EVs), and HDVs are assumed to be non-electric vehicles;
- Simulations are conducted during lunchtime rush hour, which is considered as the most critical period for this study;
- No residential parking is considered in the model;
- No changes have been considered in the number of locations for disabled on-street parking bays;
- The pick-up/drop-off scenario was assumed to follow the SAVs concept;
- Due to software limitation and a lack of model calibration, cyclists are not modelled in replacing on-street parking spaces with cycling lanes scenario.

### 3.2 Modelling on-street parking manoeuvres

This study uses the periodic section incident function to simulate on-street parking manoeuvres, as shown in Fig. 4a. This function was implemented in the simulation as a traffic incident, resulting in a lane blockage for a certain period [3]. Random incidents were generated and placed throughout the area, including streets and parking bays, at regular time intervals (e.g., 3, 5, 8, 13, 17, 22, 27, and 31 min), depending on the length of the parking bay. The duration of on-street parking manoeuvres, or blockage time, was assumed to be 30 s with a 20-s deviation, and both the manoeuvre duration and obstruction frequency were based on previous literature [8, 12, 45]. Figure 4b, c provide examples of the periodic section incident representing on-street parking on a single-lane and multi-lane road using the AIMSUN Next simulation platform. Figure 4b demonstrates on-street parking happening on a single lane, blocking traffic for a specific time. Figure 4c shows the incident on a multi-lane road, where the following vehicle changes lanes due to the leading vehicle making an on-street parking manoeuvre.

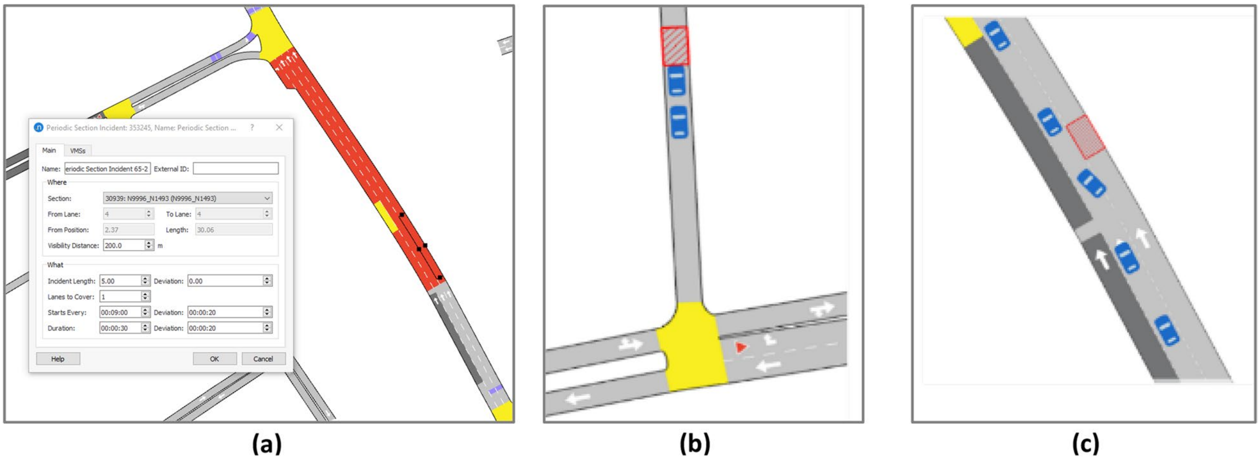
### 3.3 CAV parameters and deployment scenarios

In this study, two types of CAVs were analysed: 1st Generation (Gen) CAVs and 2nd Gen CAVs. Both types were assumed to be fully AVs with a level 5 autonomy. The modelling of these two types was based on the assumption that technology would continue to advance over time, resulting in 2nd Gen CAVs having improved sensing and scenario identification capabilities, decision-making, driving characteristics, and incident anticipation, among other things. The following are the general assumptions regarding the characteristics of CAVs that were utilised in this study:

- 1st Gen: limited sensing and data processing capabilities, long headways, early anticipation of lane changes than HDVs and longer time in give way situations.
- 2nd Gen: advanced sensing and data processing capabilities, data fusion usage, small headways, early anticipation of lane changes than HDVs and less time in give way situations.

The driving logic in Aimsun Next is primarily derived from the Gipps model [21, 22]. To facilitate HDVs and CAVs behaviours, various parameters of the driving logic were adjusted, including reaction time, time gap, acceleration and deceleration characteristics, and parameters associated with lane changing and overtaking behaviour. The automation of freight vehicles was also considered in this study. However, due to limited knowledge of the automation of freight vehicles, only a few parameters were adjusted to simulate the behaviours of freight CAVs in a manner similar to 1st Generation CAVs. The default Aimsun Next parameters were employed to implement public transport vehicles. Table 1 presents the key parameters that were modified to model the driving behaviours of HDVs and CAVs in the study. More information on the parametric assumptions and values of the key parameters can be found in a study by Chaudhry et al. [13].

The deployment of CAV was tested in increments of 20% from 0 to 100% MPR, as shown in Table 2. The figures in a fleet composition refer to the percentage of HDVs, 1st Gen CAVs, and 2nd Gen CAVs. Each scenario was simulated for a duration of one hour (during the lunchtime rush hour of 12:00–13:00) with a warm-up period of 20 min. To replicate the stochastic nature of traffic characteristics, 10 replications with different



Name: eriodic Section Incident 65-2
External ID:
Section: 30939: N9996_N1493 (N9996_N1493)
From Lane: 4
To Lane: 4
From Position: 2.37
Length: 30.06
Visibility Distance: 200.0 m
Incident Length: 5.00
Deviation: 0.00
Lanes to Cover: 1
Starts Every: 00:09:00
Deviation: 00:00:20
Duration: 00:00:30
Deviation: 00:00:20

**Fig. 4** Screenshot of periodic section incident in AIMSUN Next (**a**), and periodic section incident on a single lane and multi-lane road (**b, c**)

**Table 1** HDV and CAV parameters

| **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 s | 0.9 s | 0.4 s |
| Max. acceleration (m/s$^2$) | Maximum acceleration that a vehicle can achieve under any circumstances | 5 (3, 0.2, 7)<br>Mean (min, dev, max) | 4.5 (3.5, 0.1, 5.5)<br>Mean (min, dev, max) | 3.5 (2.5, 0.1, 4.5)<br>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)<br>Mean (min, dev, max) | 4 (3.5, 0.13, 4.5)<br>Mean (min, dev, max) | 3 (2.5, 0.13, 3.5)<br>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)<br>Mean (min, dev, max) | 7 (6.5, 0.25, 7.5)<br>Mean (min, dev, max) | 9 (8.5, 0.25, 9.5)<br>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)<br>Mean (min, dev, max) | 1 (0.8, 0.1, 1.2)<br>Mean (min, dev, max) | 1 (0.8, 0.1, 1.2)<br>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% |

**Table 2** CAV deployment scenarios

| **Type of vehicle** | **CAV deployment scenarios** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **100-0-0 (%)** | **80-20-0 (%)** | **60-40-0 (%)** | **40-40-20 (%)** | **20-40-40 (%)** | **0-40-60 (%)** | **0-20-80 (%)** | **0-0-100 (%)** |
| *Passenger cars* | | | | | | | | |
| 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 |
| *Light goods vehicles* | | | | | | | | |
| Human-driven LGV | 100 | 80 | 40 | 0 | 0 | 0 | 0 | 0 |
| LGV-CAV | 0 | 20 | 60 | 100 | 100 | 100 | 100 | 100 |
| *Heavy goods vehicles* | | | | | | | | |
| Human-driven HGV | 100 | 80 | 40 | 0 | 0 | 0 | 0 | 0 |
| HGV-CAV | 0 | 20 | 60 | 100 | 100 | 100 | 100 | 100 |

random seeds were simulated for each scenario. The simulation time step was 0.1 s.

### 3.4 Surrogate safety assessment model (SSAM)

In order to measure the potential safety impacts, vehicular trajectory data was analysed using the Surrogate Safety Assessment Model (SSAM), which is an application designed for safety evaluation by the Federal Highway Administration (FHWA) of the United States. Traffic conflicts were identified by applying specific thresholds for time-to-collision (TTC), post-encroachment time (PET), and conflict angle. The default values for TTC and PET, 1.5 and 5.0 s respectively, were suggested by previous studies [19, 20], and Low TTC and PET values indicate a high severity level of expected crashes [25]. Despite being considered a useful tool, there are several limitations of SSAM that should be taken into account when assessing road safety, such as the potential for misclassifying a safe interaction as a conflict due to small headways between CAVs [58]. Therefore, different TTC threshold values for each vehicle type were considered based on the literature [40, 53, 58]. HDVs were set to a TTC threshold of 1.5 s, 1st Gen CAVs were set to 1.0 s, and 2nd Gen CAVs were set to 0.5 s. The potential conflicts were then converted to crashes using a probabilistic approach proposed in a study by Tarko [56]. This technique utilises TTC distribution to predict the expected number of crashes by validating the Lomax distribution for estimating the likelihood of an observed conflict resulting in a crash within the reported time period [56]. Figure 5 shows an overview of the methodology for safety assessment in the study.

## 4 Results and discussion

This study analysed three aspects of the impacts of on-street regulations using microscopic simulation and SSAM analysis: (i). mobility impacts, which include travel time, delay time, average speed, and distance travelled; (ii). environmental impacts, including the emission of carbon dioxide ($CO_2$), nitrogen oxides (NOx) and particulate matter (PM); (iii). safety impacts, such as conflicts and crashes.

### 4.1 Mobility

In this study, on-street parking spaces have been replaced with a range of interventions. Overall, travel time and delay time decrease as MPR of CAVs increases. This trend was observed in all tested interventions, as depicted in Fig. 6. In other words, higher CAV MPRs result in less journey time and reduced delay. This aligns with the findings of previous studies, which indicate that AVs can maintain a consistent speed and enable vehicles to accept shorter headways, thereby enhancing traffic flow performance [4, 36, 54].

Figure 6 illustrates the impact of each of the individual interventions on delay time (Fig. 6a) and travel time (Fig. 6b), presented as a percentage change in comparison to the corresponding values in the current situation (100-0-0 with no policy intervention). The results indicate that replacing on-street parking with driving lanes, cycle lanes, and public spaces significantly reduces travel time and delay compared to the baseline scenario (current situation i.e., 100-0-0 with no policy intervention), achieving reductions of between 27 and 30% in travel time and 43% and 47% in delay for these three interventions, respectively.

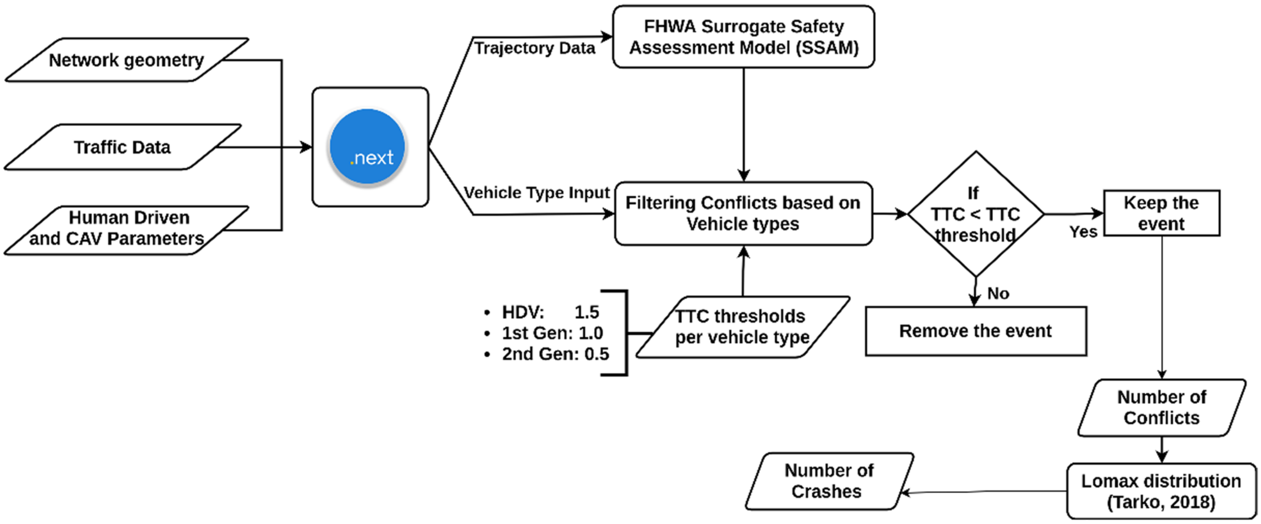


**Fig. 5** Safety assessment methodology

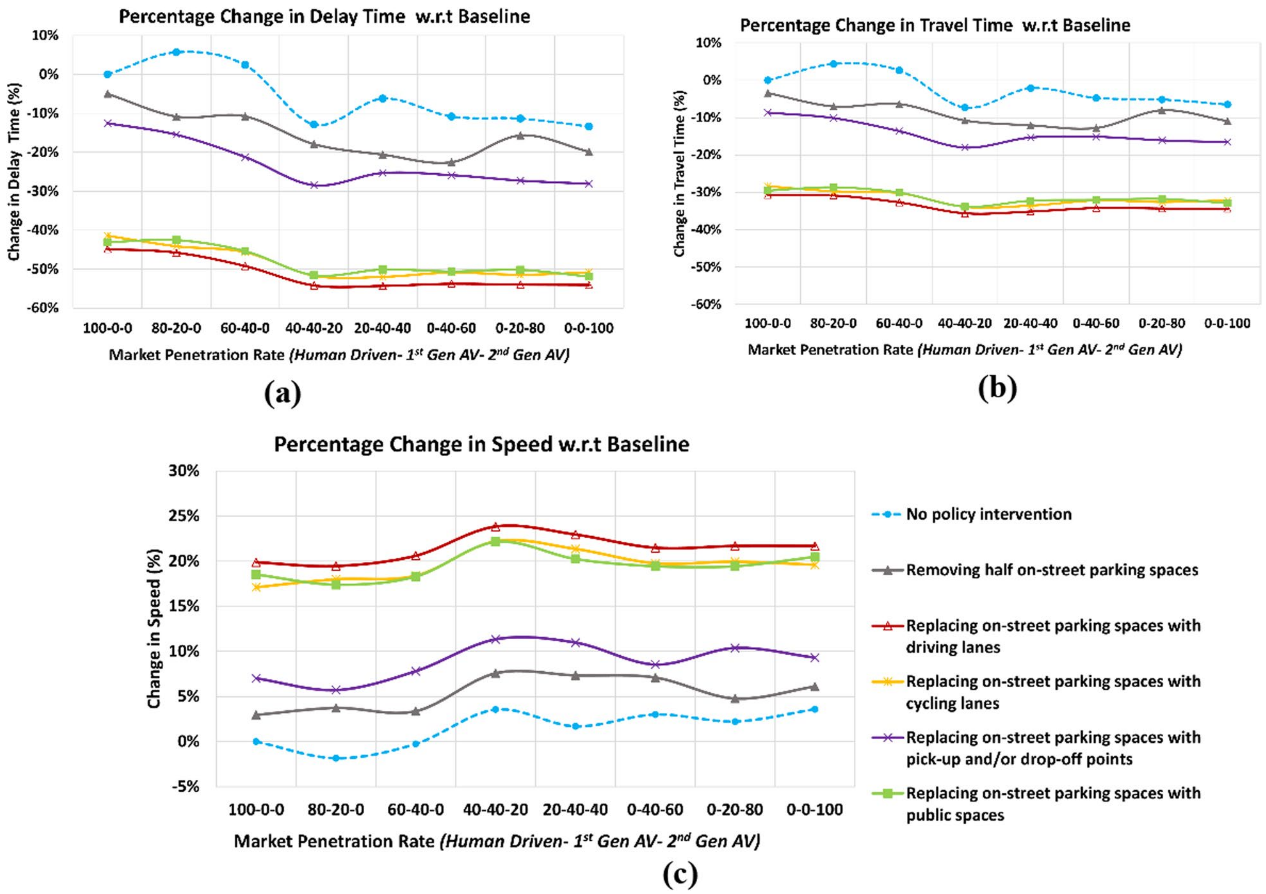


**Fig. 6** Impact on **a** delay time, **b** travel time and **c** average speed due to MPR of CAVs and interventions

Conversely, the impact of removing half of the on-street parking spaces and replacing them with pick-up/drop-off areas is relatively lower than that of other policy interventions. This could be due to frequent parking manoeuvres or vehicles picking up and dropping off passengers, causing congestion, delays, and increased travel time, which is consistent with findings from previous studies [12, 60]. Furthermore, replacing half of the on-street parking spaces may not result in the anticipated improvement in the city centre, particularly in a congested network. It is worth noting that the mixed scenarios, i.e., 40-40-20 for no policy intervention and other interventions, provide the lowest travel time and delay and also, higher average speeds were observed in the network, as shown in Fig. 6c.

**Table 3** Percent change in total distance travelled w.r.t corresponding baseline for parking space regulations

| CAVs penetration rate | No policy intervention (%) | Removing half on-street parking spaces (%) | Replacing with driving lanes (%) | Replacing with cycling lanes (%) | Replacing with pick-up and/or drop-off points (%) | Replacing with public spaces (%) |
|---|---|---|---|---|---|---|
| 100-0-0 | 0 | −9 | 11 | 11 | −15 | 10 |
| 80-20-0 | −2 | −6 | 11 | 11 | −1 | 11 |
| 60-40-0 | −11 | −7 | 9 | 10 | −6 | 9 |
| 40-40-20 | 9 | −7 | 12 | 9 | −3 | 11 |
| 20-40-40 | −2 | −5 | 11 | 12 | −17 | 10 |
| 0-40-60 | −9 | −5 | 12 | 8 | −3 | 12 |
| 0-20-80 | 2 | −9 | 12 | 12 | −7 | 12 |
| 0-0-100 | −6 | 2 | 13 | 12 | −2 | 12 |

Table 3 shows the impacts of the interventions, where the total distance travelled by vehicles is presented as a percentage change compared to the corresponding value in the baseline. The results indicate that almost all interventions lead to an increased distance travelled compared to the no policy intervention. Only removing half of the on-street parking spaces intervention and replacing with pick-up/drop-off points intervention has reduced the distance travelled. For instance, the total distance travelled has decreased by around 9% and 7% for the interventions of removing half of the on-street parking spaces and replacing them with pick-up/drop-off points, respectively, in the full MPR of CAVs (0–20-80 scenario). One potential explanation is that these interventions can create stops and queues in the traffic stream due to frequent parking manoeuvres or vehicles picking up and dropping off passengers, leading to increased congestion and delays. Furthermore, replacing on-street parking with driving lanes, cycle lanes, and public spaces has better traffic performance in the network than removing half of the on-street parking spaces or replacing them with pick-up/drop-off points, resulting in less delay, less travel time and increased traffic flow. In other words, more vehicles enter the network, which, in turn, increases the total distance travelled.

### 4.2 Environment

The environmental impacts were derived directly from the AIMSUN Next microscopic simulation, which utilises the emission model proposed by Panis et al. [44]. This emission model calculates the instantaneous pollution emissions resulting from vehicle acceleration, deceleration, and speed for all the vehicles present in the simulation [3].

Figure 7 presents an overview of the emission results for “No policy intervention” and all interventions based on fleet MPR. The emissions for all three indicators ($CO_2$, NOx, and PM) decrease significantly with the increase in CAV MPRs. This is to be expected, since all CAVs were assumed to be electric in the study. Moreover, CAVs are anticipated to travel at a constant speed, resulting

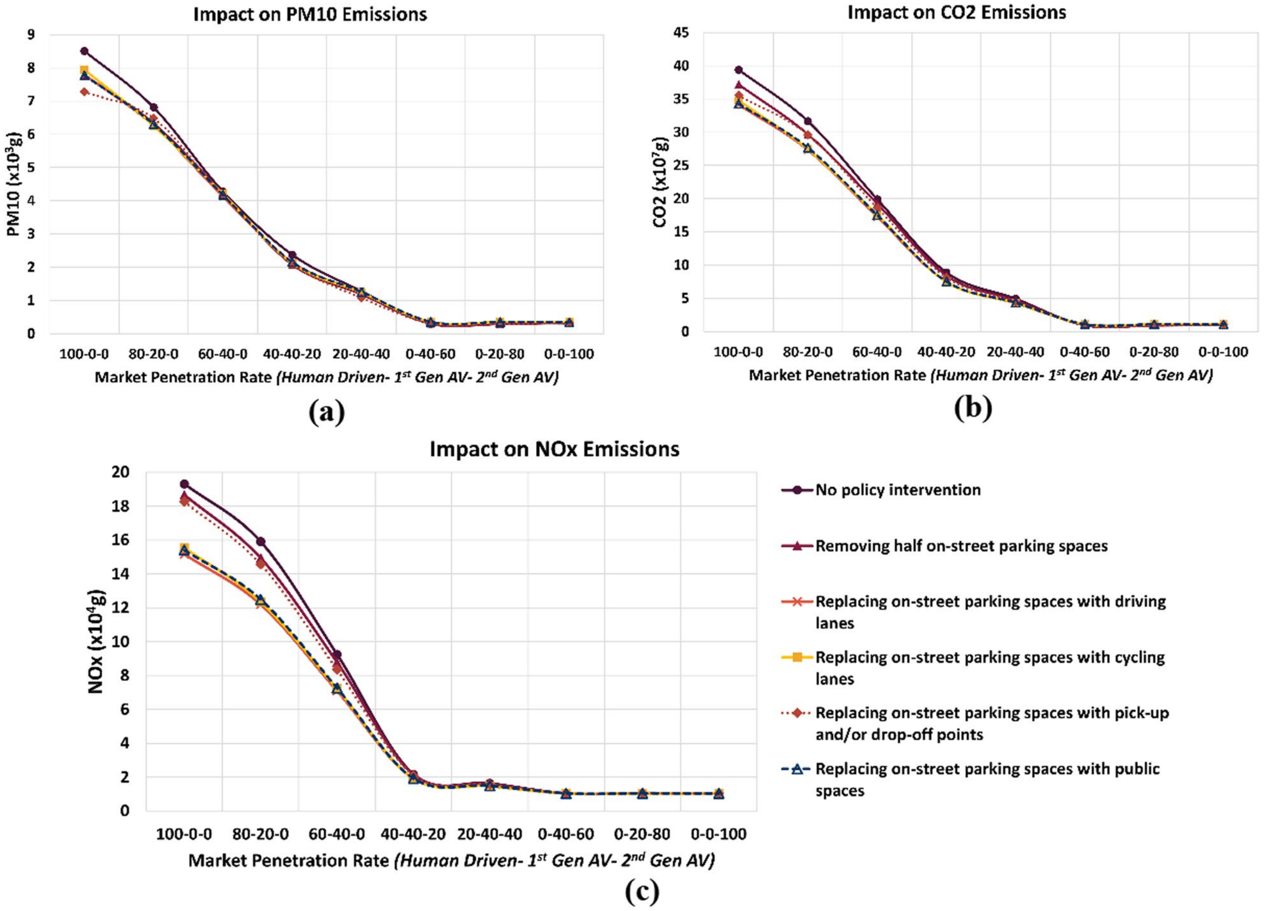


**Fig. 7** Impacts on $CO_2$, NOx, and PM10 emissions due to MPR of CAVs and regulations

in fewer stop-and-go situations in the traffic flow, which would lessen traffic emissions [54]. However, it is worth noting that a negligible amount of emissions can be identified in full MPR scenarios (0-40-60 to 0-0-100). These are due to the background public transport (bus) vehicles in the network, which were not modelled as electric vehicles.

Transitioning to electric vehicles (EVs) is a key strategy in mitigating carbon emissions from the transport sector. Research conducted by Abbasi et al. [1] underscores the potential of EVs in significantly reducing transport-related emissions. The same authors, in a separate study (2021), highlight the pivotal role of consumer motivation in the uptake of EVs, and emphasize the contribution of plug-in hybrid electric vehicles (PHEVs) to carbon emission reduction in Malaysia.

Financial incentives are a proven catalyst for promoting EV adoption. A study by Hardman et al. [27] affirms the effectiveness of financial purchase incentives in boosting sales of battery electric vehicles. In a subsequent study, they delve into the role of PHEVs in electrifying passenger transportation, underscoring their potential as both transitional and enabling technologies that can spur more consumers to switch to EVs [28]. This is echoed by research from Jain et al. [32], which identifies environmental concerns, perceived risk, and government support as key determinants for the intention to adopt EVs in India.

While CAVs with electric powertrains account for the majority of emissions reductions, replacing of on-street parking with various measures can still lead to some changes in emissions, particularly when HDVs are present. In order to determine the exclusive impact of each intervention, the percentage change in $CO_2$, NOx, and PM emissions was calculated by comparing values with no policy intervention scenario (Table 4). The interventions of replacing on-street parking with driving lanes, cycle lanes, and public spaces demonstrated a more significant reduction in emissions compared to removing half of the on-street parking spaces and replacing them with pick-up/drop-off spaces. The findings in the mobility section indicate that pick-up/drop-off parking spaces can negatively impact traffic flow by increasing stop-and-go operations and causing intermittent

**Table 4** Percentage change in $CO_2$, NOx and PM Emissions with respect to no policy intervention

| Emission | MPR | Removing half on-street parking spaces (%) | Replacing on-street parking spaces with driving lanes (%) | Replacing on-street parking spaces with cycling lanes (%) | Replacing on-street parking spaces with pick-up and/or drop-off points (%) | Replacing on-street parking spaces with public spaces (%) |
|---|---|---|---|---|---|---|
| Carbon dioxide ($CO_2$) | 100-0-0 | −6 | −13 | −12 | −10 | −13 |
| | 80-20-0 | −6 | −14 | −13 | −6 | −13 |
| | 60-40-0 | −3 | −13 | −12 | −6 | −12 |
| | 40-40-20 | −5 | −16 | −16 | −8 | −15 |
| | 20-40-40 | −6 | −14 | −13 | −10 | −12 |
| | 0-40-60 | 3 | 19 | 16 | 5 | 19 |
| | 0-20-80 | -9 | 9 | 9 | -7 | 9 |
| | 0-0-100 | 6 | 14 | 13 | 2 | 11 |
| Nitrogen oxides (NOx) | 100-0-0 | −3 | −21 | −20 | −5 | −20 |
| | 80-20-0 | −6 | −23 | −22 | −8 | −21 |
| | 60-40-0 | −5 | -23 | −22 | −10 | −21 |
| | 40-40-20 | −1 | −12 | −12 | −3 | −12 |
| | 20-40-40 | −3 | −11 | −10 | −4 | −9 |
| | 0-40-60 | 0 | 0 | 0 | −1 | 1 |
| | 0-20-80 | −2 | −3 | −2 | −1 | −2 |
| | 0-0-100 | 1 | 0 | 0 | −1 | −1 |
| Particulate matter (PM) | 100-0-0 | −8 | −8 | −7 | −14 | −9 |
| | 80-20-0 | −7 | −8 | −8 | −5 | −7 |
| | 60-40-0 | −1 | −3 | −2 | −3 | −2 |
| | 40-40-20 | −12 | −10 | −11 | −11 | −9 |
| | 20-40-40 | −7 | −3 | −3 | −16 | −2 |
| | 0-40-60 | 2 | 20 | 16 | 7 | 21 |
| | 0-20-80 | −10 | 9 | 9 | −7 | 9 |
| | 0-0-100 | 6 | 14 | 13 | 3 | 11 |

queues in the network. These are the main reasons for increased emissions, as indicated by previous studies [12, 31, 60].

### 4.3 Safety

The results of the surrogate safety assessment can be seen in Fig. 8, which displays the percentage change of conflicts against varying fleet composition for the studied network. The conflicts have been normalised with respect to Vehicle Kilometres Travelled (VKT) to mitigate any inconsistencies in traffic volume within the simulated area. In general, conflict reduces as CAVs MPR increase, it anticipated to reduce significantly by more than 90%, particularly when 2nd generation CAVs are in full operation (0-0-100). Nonetheless, the outcomes of the interventions in this study show minimal deviations from the no policy intervention, where on-street parking is still present.

This study aims to present the impact of road safety in terms of crashes or crash rates. To achieve this, the estimated number of conflicts have been converted into crashes using a probabilistic method proposed by Tarko [56]. Figure 9 illustrates the total number of crashes normalised per 1000 veh-km, which has been calculated based on the baseline scenario, where the current situation is maintained. The results are presented for varying market penetration rates (MPR) of CAVs. As shown, the safety benefits emerge even in the 100-0-0 (only HDVs) scenario for all interventions. The estimated percentage reduction in crashes ranges from 3% for pick-up/drop-off points to 18% for public spaces without CAVs introduced. The safety benefits continue to increase with the MPR of CAVs, with an estimated reduction in crashes between 92 and 94% for all tested scenarios at full market penetration. It is important to note that the safety benefits of these interventions can be realised only if they are implemented effectively.

It is worth noting that the microsimulation software is limited to simulating motor vehicles on the road and does not include interactions involving vulnerable road users (VRUs) such as pedestrians and cyclists. According to Weijermars et al. [59], increasing the penetration levels of CAVs is expected to reduce fatalities among VRUs by over 90% when there is 100% penetration. However, replacing on-street parking with alternative facilities is expected to have a greater impact on VRUs due to their proximity on the road, numerous interactions, and the potential to allocate road space to VRUs.

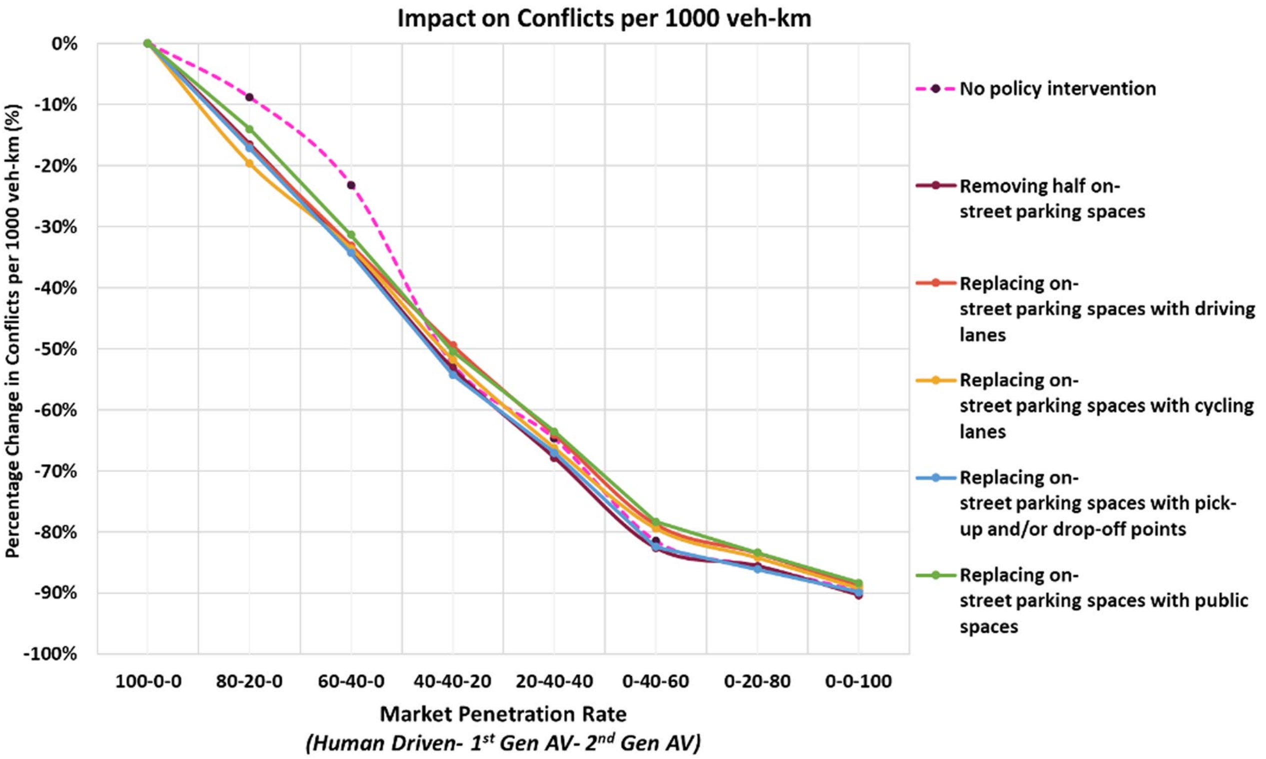


**Fig. 8** Percentage change in conflicts per 1000 veh-km travelled

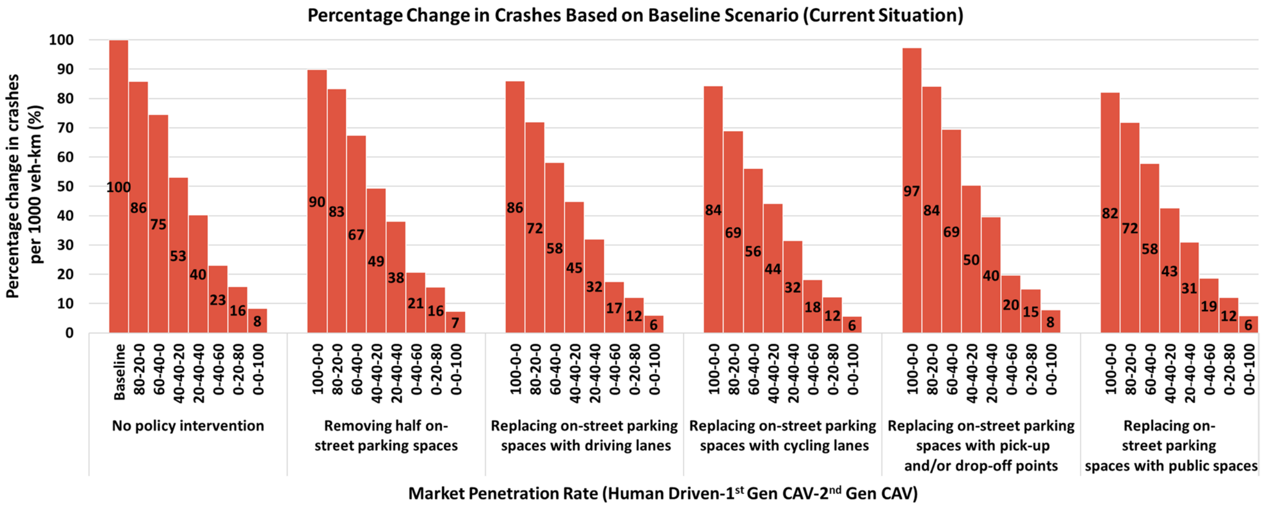


**Fig. 9** Percentage of crashes per 1000 veh-km travelled based on varying MPR

### 4.4 Research implications and novelty

The research underscores the transformative potential of CAVs in reshaping urban mobility. However, the policy implications of this transformation require a thorough understanding. For instance, while on-street parking replacements with public spaces, driving lanes, and cycle lanes emerge as a promising measure, the introduction of pick-up/drop-off spaces demands careful consideration due to its potential to increase traffic interruptions. Policymakers need to approach these findings not just as a checklist of interventions but as a comprehensive framework. Drawing on this study and corroborating with other significant works in the domain, it's evident that regulations need to be adaptive, prioritising a balance between mobility, environment, and safety. The insights from this research can guide regional decision-makers in formulating efficient parking space regulations that not only optimise urban mobility but also ensure that the environment and safety are given paramount importance. Furthermore, the impending integration of the findings into the LEVITATE project's web-based policy support tool [35] will provide an enhanced user experience assisting transport planners and public authorities with an evidence-based toolset to navigate the challenges and opportunities of the CAV era.

As the research explores new frontiers, there is a genuine novelty in understanding the impacts of on-street parking regulations across CAV deployment. The key novelty lies in the comprehensive modelling and comparison of parking interventions incorporating CAVs across multiple impact areas, generating new data-driven insights of practical relevance to cities preparing for an automated mobility future. More specifically, it is one of the first studies to model and simulate the impacts of modifying on-street parking regulations specifically in the context of mixed traffic conditions containing conventional vehicles as well as connected and automated vehicles (CAVs). The investigation incorporates multiple aspects—mobility, environment, and safety—providing a holistic evaluation of parking interventions across different domains, unlike most existing research that examines only isolated factors. Moreover, the paper provides new data-driven insights into the differential effects of various parking modifications and reveals how interventions can have varying effects on traffic, emissions, and road safety.

The practical application of the Aimsun modelling platform to test and compare discrete parking regulation scenarios with modified parameters to model CAVs and human driver behaviour is an innovative approach not widely adopted previously. The simulations offer robust evidence on realistic outcomes of implementing these parking changes in a CAV transition period.

Finally, the integration of the findings into a policy support tool (within LEVITATE project) to assist transport planning and decision-making regarding CAVs and parking is a unique contribution, enhancing the actionable value of the research.

## 5 Conclusion and future works

This study explores and discusses the impact of on-street parking regulations on three aspects—mobility, environment, and safety—in the context of mixed traffic fleets with the introduction of CAVs. The Aimsun simulation software was used to model the behaviour of HDVs, CAV passenger cars, and freight vehicles, based on existing literature findings.

Based on the modelling results, it has been found that the replacement of on-street parking with public spaces, driving lanes, and cycle lanes can bring a significant improvement in traffic performance while reducing vehicle emissions. The findings indicate that compared to other measures, such as removing half of the parking spaces or replacing on-street parking with pick-up/drop-off spaces, these replacements can reduce travel time by 27–30% and delays by 43–47%. However, it should be noted that replacing on-street parking with pick-up/drop-off spaces may not be as effective. This is due to the increase in stop-and-go events that occur during passenger pick-up and drop-off, leading to more flow interruptions and increased delays, which would in turn increase traffic emissions. To mitigate this impact, dynamic pick-up/drop-off points could be introduced in the network as an improvement measure. The microsimulations showed an increase in travelled distance when on-street parking spaces were replaced with driving and cycle lanes, and public spaces, compared to the baseline scenario and other tested interventions. The reason for this was the improvement in network flow, which allowed more vehicles in the network during the simulation period, consequently increasing the distance travelled. Moreover, the results show that replacing half of the on-street parking spaces may not necessarily reduce delays in the city centre, especially under congested traffic conditions.

According to the road safety analysis conducted in this study, it is expected that conflict rates will decrease by more than 90% in all tested scenarios with full market penetration of CAVs. Additionally, crashes are estimated to be decreased by 92–94%. The microsimulation results suggest that removing half of spaces or replacing on-street parking with pick-up/drop-off spaces does not show significantly different impacts on the crash rate of car-car collisions, compared to replacement of on-street parking with public spaces, driving lanes, and cycle lanes. Moreover, replacing on-street parking with cycling lanes or public space is likely to have an impact on the number of VRU accidents. On the other hand, replacing pick-up and drop-off points could affect pedestrian safety by creating random interactions between pedestrians and cyclists or cars.

Several critical limitations must be acknowledged in this study. Firstly, the assumption that all Connected and Autonomous Vehicles (CAVs) are electric, while Heavy Duty Vehicles (HDVs) are non-electric, may not fully represent the real-world vehicle mix. The simulations conducted during lunchtime rush hour, though critical, might not capture the full spectrum of traffic scenarios. The omission of residential parking and the static representation of disabled on-street parking locations limits the model's capacity to depict real-life conditions. The pick-up/drop-off scenario, although based on Shared Autonomous Vehicles (SAVs), may not account for variations in real-world usage. Lastly, the absence of cyclist representation due to software limitations and calibration issues restricts the assessment of scenarios involving cycling lanes. These limitations underscore the need for caution when generalizing the findings to broader contexts.

The paper offers practical examples of interventions that regional decision-makers and local authorities can implement for on-street parking after the introduction of CAVs. The findings offer valuable insights for city governments and policy makers in identifying how parking space regulations in the CAV environment can mitigate any potential adverse impacts on urban mobility, environment, and safety in the short term. An ongoing task is to integrate these results into the web-based policy support tool (PST), which will significantly enhance the user-friendliness of the LEVITATE impact assessment framework for public authorities and transport planners. With this integration, the PST will enable policy makers to make informed decisions regarding the implementation of CAVs and parking regulations to ensure sustainable urban mobility. To further enhance the practicality and relevance of the findings, future work will involve testing and analysing the impacts of these interventions in different study areas to identify any variations and transferability of the results. The validation of the results will be examined and compared to real-world data once it becomes available. Such efforts will provide additional insights and guidance for policy makers and local authorities in their efforts to improve urban mobility and enhance safety in the context of a CCAM era.

## Abbreviations

| | |
|---|---|
| CAV | Connected and Autonomous Vehicles |
| CCAM | Cooperative, Connected and Automated Mobility |
| HDV | Human-Driven Vehicles |
| LEVITATE | Societal Level Impacts of Connected and Automated Vehicles |
| VMT | Vehicle Miles Travelled |
| SAV | Shared Autonomous Vehicles |
| OD | Origin–Destination |
| EV | Electric Vehicles |
| HDV | Human-Driven Vehicle |
| MPR | Market Penetration Rate |
| SSAM | Surrogate Safety Assessment Model |
| FHWA | Federal Highway Administration |
| PET | Post-Encroachment Time |
| TTC | Time-To-Collision |
| VRU | Vulnerable Road Users |
| PST | Policy Support Tool |

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that this work is original and has not been published elsewhere nor is it currently under consideration for publication elsewhere. My co-authors and I remain at your disposal for any further information, and we look forward to hearing of your decision.

**Author contributions**
Following contributions to the work have been confirmed by the authors: Study conception and design: HS, RH; Literature review: HS, RH, SM, EP; Micro-simulation and SSAM analysis: HS, RH; Analysis and interpretation of results: HS, RH, MS, MQ; Draft manuscript preparation: HS, RH, MS, EP; Review of the paper: HS, RH, MS, EP, MQ, AC, PT, AM. All authors reviewed the results and approved the final version of the manuscript.

### Availability of data and materials

Not applicable.

## Declarations

### Competing interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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