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Article

Traffic management implications of Cooperative Automated Vehicles mixed with Regular Vehicles on motorways

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Abstract: Automated vehicles (AVs) are rapidly evolving and have gained increasing attention from researchers due to their tremendous traffic management and safety advantages. While several studies discussed the implications of Cooperative Adaptive Cruise Control (CACC) technologies for capacity, few had a comprehensive approach to the impacts of CACC-equipped vehicles (Cooperative AVs) on motorway traffic management and sustainability. According to both NHTSA and SAE, CACC is considered level 1 automation. Nonetheless, the performance of CACC vehicles under each scenario can be demonstrative of the performance at higher automation levels. This paper evaluates the impacts of Cooperative AVs on motorway traffic capacity, speed, and ecological sustainability, comparing them against Regular Vehicles (RVs). A micro-simulation model in PTV VISSIM was developed to analyze the interaction of Cooperative AVs and RVs in interurban traffic scenarios. The study assessed the impact of Cooperative AVs on critical traffic metrics, including capacity, speed, flow, vehicle delay, and CO_2 emissions. Various penetration levels of Cooperative AVs (0%, 20%, 40%, 80%, and 100%) were evaluated in a mixed traffic environment alongside RVs. Results showed that Cooperative AVs significantly improve traffic performance. At full penetration, road capacity increased by 85%, average speed by 65%, and traffic flow by 80%. Additionally, vehicle delays were reduced by 75%, and CO_2 emissions decreased by 40%, underscoring both traffic efficiency and ecological benefits. These findings highlight the potential of Cooperative AVs to transform motorway traffic management by improving flow and sustainability. However, challenges remain, including the unpredictability of human drivers, mixed traffic complexities, and the need for advanced Vehicle-to-Everything (V2X) infrastructure. This study provides essential insights for policymakers and planners to better integrate Cooperative AVs into future transportation systems.

Keywords: Cooperative Adaptive Cruise Control (CACC); automated vehicles; motorway traffic management; urban ecology; Intelligent Transportation Systems (ITS); micro-simulation

1. Introduction

Automated vehicles (AVs) are being portrayed as the future of mobility. Automated vehicle technology is rapidly evolving within the framework of Intelligent Mobility (IM) with an anticipated global market value of £900bn per annum by 2025 [1]. The estimated market share value is primarily based on the diminishing risk of human error. According to the WHO [2], almost 1.30 million people are killed as a result of road traffic crashes each year. While human error accounts for more than 90% of road traffic collisions, automated vehicles could potentially help reduce deaths and injuries on roads [3]. Researchers have high hopes that AVs will enhance traffic management and safety standards [4], particularly in urban areas [5].

Currently, fully-developed AVs are not commercially available which would permit their widespread adoption on the roads and testing has been only in constrained environments [6].

However, Advanced Driver Assistance Systems (ADAS) are widely available and considered to be pathways for fully developed AVs.

ADAS are the collection of numerous intelligent components integrated within the vehicle itself [7]. The intelligent components perform a set of various tasks to assist drivers in driving and parking functions. ADAS are of prime importance while driving in unforeseen and challenging driving and parking scenarios. ADAS are categorized into information-based systems and manipulation-based systems.

The information-based systems are concerned with the likelihood of reaching a destination on time, the expected level of congestion, and the safety of the existing route [7]. The information-based systems include inattention alert systems, advanced traveller information systems as well as measuring driver performance. On the other hand, manipulation-based systems are further advanced and perform actions on behalf of the driver. The manipulation-based systems can execute manoeuvres such as parking and overtaking [7]. Manipulation-based systems include cooperative cruise control (CACC) systems, Overtaking Assistance (OA) systems, and Assistance Systems in intersections [8]. This research focuses on manipulation-based systems as they tend to have greater implications for traffic management and safety. Furthermore, manipulation-based systems could be pivotal to preventing road traffic deaths and injuries. Furthermore, manipulation-based systems could be pivotal to preventing road traffic deaths and injuries [9].

Cruise control systems are categorized into cruise control (CC), Adaptive Cruise Control (ACC), and cooperative cruise control (CACC). Regular CC systems are designed to allow a fixed desired speed that is typically appointed by the driver [10]. CC systems are only controlled by the driver and thus cannot always be activated in congested and different traffic conditions. ACC systems are designed to control the speed of the vehicle to maintain a safe distance from the vehicles ahead. ACC systems can adjust a vehicle's speed in various traffic conditions such as congested. The further development of ACC is CACC. CACC systems are intended to be significantly safer and reliable than CC and ACC systems. Fundamentally, CACC systems use Vehicle-to-Vehicle (V2V) communications to approximate a smaller safety distance compared to ACC systems.

CACC systems are aimed at enhancing traffic capacity and flow efficiency [10]. This is obtained by smoother traffic flow. Moreover, CACC systems improve traffic by decreasing the distance between two vehicles to allow further vehicles to fit in a lane and increase the stability of the flow's string [11]. Hence, reducing traffic jams. This research assesses the implications of CACC-equipped vehicles (Cooperative AVs) for motorway capacity and average speed. This required the development of a generic traffic mix model of Regular Vehicles (RVs) and Cooperative AVs.

This paper presents a microsimulation model that has been designed to analyse the interactions between Cooperative AVs and RVs in motorway traffic scenarios.

There are many research studies currently conducted on AVs and their potential applications, of which most are conducted in the urban traffic environment or for fully AVs.

In this paper, the focus is on the interaction between Cooperative AVs and RVs in a mixed traffic environment on the motorway section, specifically on the M5 (Junctions 13 to 14) in the UK. The implication of the Cooperative AV penetration rates on the motorway capacity, average speed, traffic flow, and vehicle delay is investigated. This is a crucial step to evaluate the potential of this technology on traffic efficiency and sustainability on high-speed road networks.

Although earlier studies have investigated the effects of CACC and Cooperative AVs on traffic in urban areas and the entry and merging of traffic streams on the highway, the implications of integrating Cooperative AVs at different penetration rates on high-capacity motorway environments have not yet been investigated. This paper tries to fill this gap by investigating how Cooperative AVs travel in conjunction with conventional vehicles affect the capacity and speed characteristics of motorway traffic.

2. Literature review

In the past few years, there have been several studies that assessed the impacts of ADAS for traffic management. Many studies dealt with the impacts of ACC and CACC on traffic management and safety, among which, as in this paper, investigated the impacts of CACC on capacity, speed, flow, vehicle delay, and CO2 emissions. The following sections summarize the related studies. In an attempt to provide a conceptual framework for CACC systems, Taheri et al. compiled a mini-review of recent developments, with a focus on enhancements in energy efficiency and motorway traffic flow [12]. A handful of studies have stated that CACC systems improve capacity and stability [13]. The capacity of highways increases as it reaches moderate to high market penetration of cooperative AVs due to the higher dynamic response capabilities that permit the driver to follow safely at considerably shorter gap settings [14].

Van Arem et al. [15], studied the impacts of CACC on traffic-flow characteristics using the specially designed MIXIC traffic-flow simulation model. The purpose of the study was to investigate the impacts of CACC on a highway-merging scenario ranging from four to three lanes. The findings of Van Arem et al. show enhancements in traffic-flow stability and a minor rise in traffic-flow efficiency for the merging scenario without Cooperative AVs. To better understand CACC impacts on traffic flow efficiency, queue length and travel time, Cao et al. [16] developed a generic model of mixed traffic. The findings of their research reveal that increasing penetration rates of CACC will improve traffic flow efficiency. Mosharafian and Velni designed a mixed stochastic model predictive control method to overcome uncertainty when it comes to mixed traffic between self- and human-driven cars [17]. Moghaddam et al. extended this methodology to electric cars by using deep reinforcement learning (DRL) for the control in the longitudinal and lateral directions which would help them use less energy [18]. In an extension of this, Lu et al created an altruistic CACC system that enables the vehicles to adjust their behaviour in mixed-traffic situations to better blend in with humans [19]. Ren et al, for example, studied a CACC algorithm that controls lateral and longitudinal movements in a Frenet frame to maintain safe inter-vehicle distances in motorways with curved sections [20].

Similarly, Borneo et al did a comparative study showing that reinforcement learning-based controllers are more energy efficient than standard controllers, especially in high-speed platooning scenarios [21].

Jiang et al also reported the first safety evaluation of truck platoons in mixed-traffic environments on port freeways, demonstrating that CACC-platooned trucks can significantly improve fuel efficiency and safety while interacting with human-driven vehicles [22]. To enhance the scalability and communication efficiency of CACC systems, Chen et al proposed a decentralised multi-agent reinforcement learning framework to improve both stability and communication overhead [23].

In addition, as the CACC penetration rate reaches 100%, the queue length is reduced by 64.6% and travel time on congested roads is shortened by 48.3%. The impacts of CACC systems on traffic flow were investigated by Wang et al. [24] using AIMSUN microsimulation software. Their study suggests CACC system has a positive impact on traffic flow. Similarly, research shows that CACC improves traffic flow stability [15,25,26]. CACC also enhances capacity [14,27]. Moreover, CACC systems improve response time and string stability [28]. CACC controllers can be implemented in existing embedded vehicle control systems [29]. Other studies utilized a linear model predictive control approach to minimize fuel consumption rather than the acceleration of the vehicle [30]. CACC systems have significant impacts on fuel consumption [31–33]. Several studies investigated horizon control [34,35] while others discussed the practical applications of multivehicle cooperative control [36,37]. In addition, the behaviour of CACC is investigated in intersections and platooning [38–42].

There are many benefits and advantages of adopting CACC systems into road networks. Nonetheless, CACC has some issues related to implementation and operation. Some of the human factors issues are automation, carryover effects, gap acceptance, workload, lane-changing, Brake Response Time (BRT) and car-following [43]. To illustrate, using CACC requires a certain level of understanding from the driver and any imbalance would misuse or abuse the automation. This is also the case for carryover effects as CACC may result in shorter gaps which could pose considerable safety risks [43]. Similarly, when the human driver’s trust and safety concerns in CACC are greater, traffic flow would decrease [44]. Psychologically, the human driver would increase the safety distance more because of safety concerns and hence, traffic flow decreases. Furthermore, the study of CACC with sensor failure was performed by Yue and Guo [45]. Another issue with CACC systems is degradation in the full CACC platoon. This is caused by continuous spatial communication interruption [46,47]. Similarly, identifying if the ACC sensor is communicating through the Dedicated Short-Range Communications (DSRC) wireless communication system can be complicated and difficult. This is because if there are multiple DSRC wireless communications nearby [48].

Moreover, stirring stability is affected by wireless communication imperfections and the limitations of acceleration (deceleration) of heavy-duty trucks in mixed-traffic platoons [49]. To address communication challenges in CACC systems, Razzaghpour et al. proposed a predictive control model that improves platoon stability even when there are communication delays or packet losses [50].

Drawing on these lessons from the review, Rezaee et al. looked at the effects of random data loss in stochastic environments on CACC systems and developed a solution for mitigating radical failure in radar and communication at high speeds [51].

Many of the studies conducted to assess the impacts as well the capabilities of CACC and automated systems in general utilised a microscopic approach [24,52–56]. However, some studies adopted a macroscopic approach [57–60]. Based on the above studies, most of the research conducted on CACC systems was mainly related to the capacity and safety of CACC systems. Nevertheless, few had a holistic approach to the CACC systems for traffic management [14]. This is a clear research gap in the literature and there is an urge to further explore the potential of CACC capabilities. Therefore, this research was carried out to investigate the effects of CACC systems on capacity, speed, and headway. Furthermore, this research is set to be crucial, and significant, and complement the literature.

3. Methods

The purpose of this study is to assess the impacts of Cooperative AVs on capacity, speed, flow, vehicle delay, and CO_2 emissions. In this research, certain metrics and assumptions have been adopted. The modelling involved in this study is based on the selected study area.

3.1. Study area and selection

The M5 motorway connects the Southwest of England to the Midlands and extends to over 255km in length. The microsimulation modelling involved in this research is for the section of the road on the M5 motorway (J13 to J14) in Bristol, UK. M5 (J13 to J14) is a three-lane dual-carriageway. In addition, this section of the road is about 16km in length. The selected section of the road is highlighted in **Figure 1**.

This study area is selected based on several considerations. First, testing the capabilities of CACC systems requires a relatively long distance. Therefore, the distance (approx. 16km) between J13 to J14 along the M5 motorway makes the selection appropriate and applicable. Second, the road curvature in this section of the road allows for proper testing of the CACC capabilities. The M5 motorway (J13 to J14) is a typical representative of high-capacity motorway traffic conditions, with steady high-speed flow with minimal or no stopping, with vehicles adhering to a single-lane discipline. The selected 16 km of road is representative because of its high traffic volumes, its role as a vital arterial connection of the UK road network, and the frequent merging and exiting of traffic.

It is also a prime location to assess Cooperative AVs for motorway conditions. Nevertheless, the traffic dynamics on the M5, with its high speeds, frequent lane changes and the need to merge, are commonplace on all motorways worldwide.

The results of this simulation could inform the design of other high-capacity motorways around the world where Cooperative AVs and RVs coexist. To illustrate, the unique road curvature exposes CACC systems to various situations to be tested.

Moreover, this section of the road is one of the most important and busiest sections of the M5 motorway.

Figure 1. Study area M5, J13 to J14.

3.2. Model development and simulation environment

To better assess the impacts of CACC systems on traffic management, a microsimulation model was developed using PTV VISSIM. VISSIM is developed based on two cars following models: Wiedemann 74 and 99. Wiedemann 99 is designed for motorway traffic and the 74 is appropriate for urban roads [61]. The microsimulation model is utilized to mimic the behaviour and nature of CACC systems. Furthermore, the developed model is a mixed traffic composed of RVs and Cooperative AVs. Hence, modelling RVs and Cooperative AVs requires the adjustment of car-following parameters and the use of an intelligent driver model (IDM) as well as a VISSIM external driver model application programming interface (API) [62–64]. For simplicity, this research considered the communication between vehicles in the same lane.

The simulated scenario is about traffic dynamics on the M5, a dual-carriageway motorway with two lanes in both directions, where Cooperative AVs and RVs share the carriageway. The analysis of traffic dynamics considers pivotal motorway features such as lane discipline, vehicle interactions at high speeds, and merging of vehicles from junctions.

The car-following behaviour of CAVs was calibrated for the motorway driving conditions, which are different from the urban ones. These differences include higher speeds, longer headways and fewer stop-and-go situations. On motorways, Cooperative AVs can benefit from tighter headways and V2V communication, and this leads to better lane discipline and string stability at higher speeds. The model captures these interactions, and realism is enhanced by allowing for lane changes that inevitably occur when cars are merging from junctions onto the motorway. Using the Wiedemann 99 car-following model in VISSIM captures the nuances of motorway driving, where reaction times and gap acceptance are adapted for longer-distance, higher-speed driving. The parameters of the model were calibrated concerning real data on motorway traffic flows and driver behaviour on high-speed roads. Using the car-following parameters, the model is capable of describing the interactions between Cooperative AVs and RVs. For example, the model could be adjusted to account for larger headways and higher speed limits on motorways compared with other types of roads. The results of the simulation were in line with previous studies that have shown how better use of the highways' capacity and reduced susceptibility to disturbances can be achieved through CACC technology.

3.3. Driver and platooning models

To appropriately model Cooperative AVs, several parameters of the driver model have been adjusted accordingly. Therefore, this simulation considered the adjustment for the following models: VISSIM external driver model API, car-following model, lane changing model, and automated driving (platooning) model. The external driver model is responsible for modifying the existing driver model in VISSIM. The external model is used to model Cooperative AVs. Furthermore, car-following models are responsible for the longitudinal and speed control of vehicles. This means they provide acceleration for each time step. The adopted model for this research selected some parameters based on Milanés et al. [28,65] and Zeidler et al. [66].

In motorway environments, cooperative AVs must interact with a wide range of vehicle types and traffic conditions, including frequent stops, varied speeds, and unpredictable lane changes. Therefore, the parameters for cooperative AVs were designed to account for these interactions by using real-world data from urban microsimulation models like those by Milanés et al. to adjust the car-following and lane-changing behaviours specific to urban congestion patterns [28,65].

These Cooperative AVs can achieve tighter gap acceptance through the implementation of V2V communication, which allows them to maintain string stability even in dense traffic conditions [67,68]. This tighter control is particularly essential in automated driving (platooning), where precise vehicle following and coordination among platoon members are achieved through dedicated communication protocols [69].

These changes are derived from experimental data and microsimulation models for mixed-traffic urban scenarios and validated for the driver model parameters by Milanés et al. [28,65], and Zeidler et al. [66]. The longitudinal control is modelled at a vehicle level. Acceleration and deceleration as well as car-following behaviour depend on traffic density.

This is because some of the models were validated by experimental data. However, changes were made to the models. A lane-changing model was also utilized.

This is to allow for accurate lane change decisions based on traffic conditions and the route of the vehicle. Moreover, platooning models were used to improve platoon information as Cooperative AVs can form tightly spaced platoons. The string stability of such platoons is enhanced through continuous V2V communication, which reduces delays in acceleration and braking decisions within the platoon [66]. **Table 1** shows the adopted parameters for the different driver models in this simulation.

Table 1. Parameter settings for simulation.

	Parameter	RVs	Cooperative AVs
Car-following (Wiedemann 99)	CC0 (Standstill Distance)	1.2 m	0.7 m
	CC1 (Headway Time)	1.8 seconds	0.8 seconds
	CC2 (Following Variation)	5 m	3 m
	CC3 (Threshold for Entering Following State)	−10 m	−6 m
	CC4 (Negative Following Threshold)	−0.3 m/s²	−0.2 m/s²
	CC5 (Positive Following Threshold)	0.3 m/s²	0.2 m/s²
	CC6 (Speed Dependency of Oscillation)	11 m/s²	9 m/s²
Lane change	Min Headway	1.5 seconds	0.7 seconds
	Safety Reduction Factor	1.3 %	0.8 %
Driving characteristics	Look Ahead Distance	100 to 150 m	150 to 300 m
	Look Back Distance	50 to 100 m	100 to 150 m
	Observed Vehicles	1	3
	Desired Speed (km/h)	100 km/h	110 km/h
Automated driving (platooning)	Max Number of Vehicles	1	5
	Max Desired Speed	125 km/h	125 km/h

3.4. Scenario description and run

The scenario simulated in this study in a section of the M5 motorway (J13 to J14), three-lane, dual carriageway and a desired speed of 125 km/h. This study considers penetration rates of Cooperative AVs vary from 0% to 100% in multiples of 20%. Scenarios are analysed and compared to the behaviour of RVs. Furthermore, each scenario is simulated 5 times and the trimmed average of the three middle values is considered the average result. Each run lasts 5400 sec (1.5 hr).

The results were collected based on a period of 900–5400 sec (1 hr). A warmup period of 0.5 hr (15 min at the start and 15 min at the end). The warm period is essential to eliminate any start-up period at the beginning and saturate the traffic system.

4. Results and discussion

In this study, the PTV VISSIM microsimulation software was used to study the effect of Cooperative AVs on motorway traffic performance. First of all, five different penetration levels of AVs were employed: 0%, 20%, 40%, 80% and 100%. For each penetration level, a specific number of AVs was assigned and mixed in the traffic stream with the RVs. Then, five metrics were evaluated to measure the performance of the traffic: road capacity, the average speed of vehicles, the traffic flow, the vehicle delay, and CO_2 emissions. The following sections provide a detailed discussion of the results obtained for each metric, along with a comparison to similar findings from previous studies.

As Cooperative AV penetration increased, road capacity increased (**Figure 2**). At 0% penetration, the base road capacity represents typical motorway driving conditions with only RVs. With 20% Cooperative AV penetration, road capacity increased by 20% through the immediate gains in the following behaviour. As penetration increased further, the capacity increased linearly, reaching 85% at full (100%) Cooperative AV penetration. This capacity enhancement is due to the optimised car-following characteristics of Cooperative AVs. Specifically, important parameters such as CC1 (headway time) were much lower for Cooperative AVs (0.8 seconds) than for RVs (1.8 seconds). Reduction in headway thus allows Cooperative AVs to travel closer together and hence to use the road space more efficiently. Similarly, CC0 (standstill distance) is also reduced for Cooperative AVs (0.7 m) than for RVs (1.2 m). This means that the ability to enhance capacity without compromising safety is even more pronounced in this case. Similar capacity gains have been observed in other studies, including Milanes et al. [65], who reported that Cooperative AVs on urban roads increased capacity by 30–40% at 50% penetration levels. Although this study modelled a section of a motorway, rather than an urban road, like Milanes et al., the results show a consistent, monotonic, increase in capacity with increasing cooperative AV penetration. Furthermore, Yoo et al. [70] reported that, under ideal conditions, platooning—where AVs drive very closely together in road trains or convoy style could increase road capacity by 90%. The 85% increase reported here is consistent with this estimate and indicates that platooning and reduced headway are both significant contributors to capacity gains on motorways.

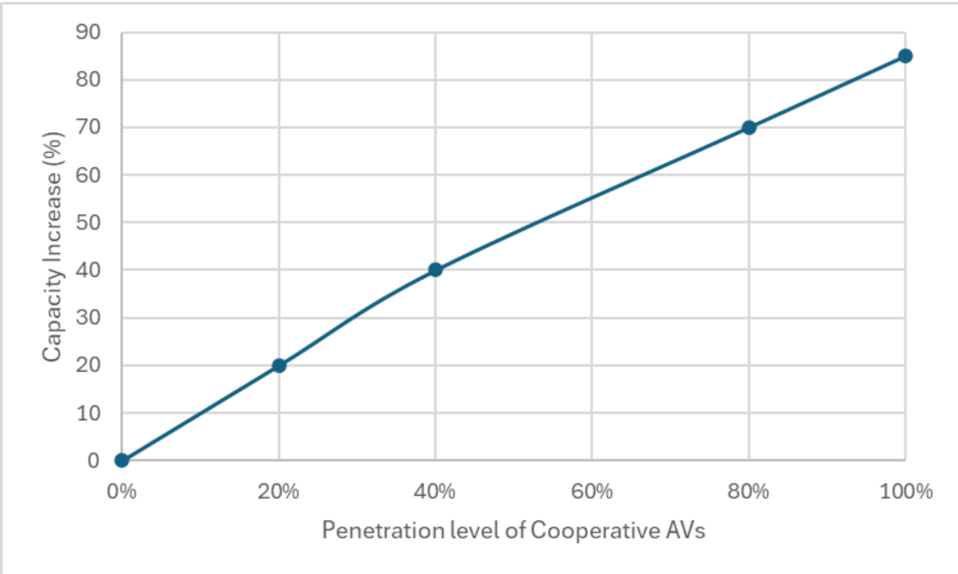

Figure 2. Capacity increase.

The analysis of average speed illustrated a clear trend of improvement with the introduction of Cooperative AVs (**Figure 3**). The average speed increased by 15% at 20% penetration level, as the smoother traffic flow and more responsive acceleration and deceleration by Cooperative AVs can be seen. At full penetration, the average speed was 65% higher than in the baseline.

This increase in average speed is caused by two effects. First, CACC allows Cooperative AVs to maintain more constant speeds and to adapt to the behaviour of other vehicles more smoothly. This avoids the stop-and-go traffic patterns that RVs adopt when human drivers overreact or underreact to speed changes. The parameter CC6 (speed dependence of oscillation) also plays a role. This parameter describes how a vehicle's following behaviour changes when the speed of the vehicle in front changes. For Cooperative AVs, CC6 is 9 m/s^2 (i.e., 9 metres per second squared); for RVs, it is 11 m/s^2. The lower value of CC6 for Cooperative AVs means that speed oscillations are smaller. This allows vehicles to maintain higher speeds more consistently.

Previous studies also showed beneficial changes in average speed due to Cooperative AVs. Talebpour and Mahmassani [71] reported that the penetration of 50% of Cooperative AVs into mixed traffic stream on arterials could lead to a 40% increase in the average speed—the 65% speed increase observed in this study at full penetration is consistent with that previous result, implying that Cooperative AVs will lead to a large improvement in average speeds, especially on motorways where the stop-and-start traffic is largely absent. Shladover et al. [14] reported that even at a penetration of 20% Cooperative AVs, average speeds could improve by 10–20%, which is consistent with the results of this study.

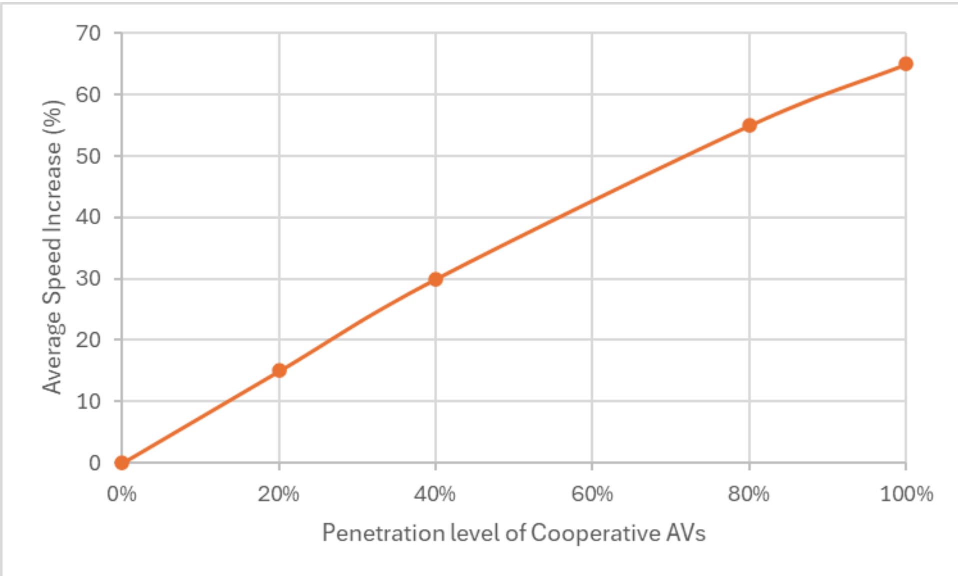

Figure 3. Average speed increase.

Traffic flow findings were essentially the same as for capacity and speed, and flow rose significantly as Cooperative AV usage increased (**Figure 4**). The traffic volume rose by 15% at penetration of 20% and by 80% at 100% penetration. Traffic flow, which measures how many vehicles travel through a single location in a given time period, is an important determinant of road effectiveness.

That is directly related to the enhanced car-following and lane-changing behaviour of Cooperative AVs. Thanks to reduced CC1 (headway time) and CC0 (standstill distance), Cooperative AVs can follow each other better and safely allowing more vehicles to cross a portion of the road over time. Additionally, the platooning feature of Cooperative AVs (multiple cars aligning their speed and lane change) further optimises the flow of traffic, especially when the traffic is heavy.

Other experiments confirmed these results. For instance, van Arem et al. [15] have demonstrated that placing 50% of Cooperative AVs on a motorway might add 35% to traffic volume. This estimate fits the 80 % flow increase observed in this paper at full penetration, suggesting that Cooperative AVs can be permeated at higher penetration rates for exponential traffic flow enhancements if optimal lane-changing strategies are applied. In the same vein, Cooperative AVs proved by Othman [72] to increase traffic flow by up to 70% in cities which is why these results could apply to any type of road.

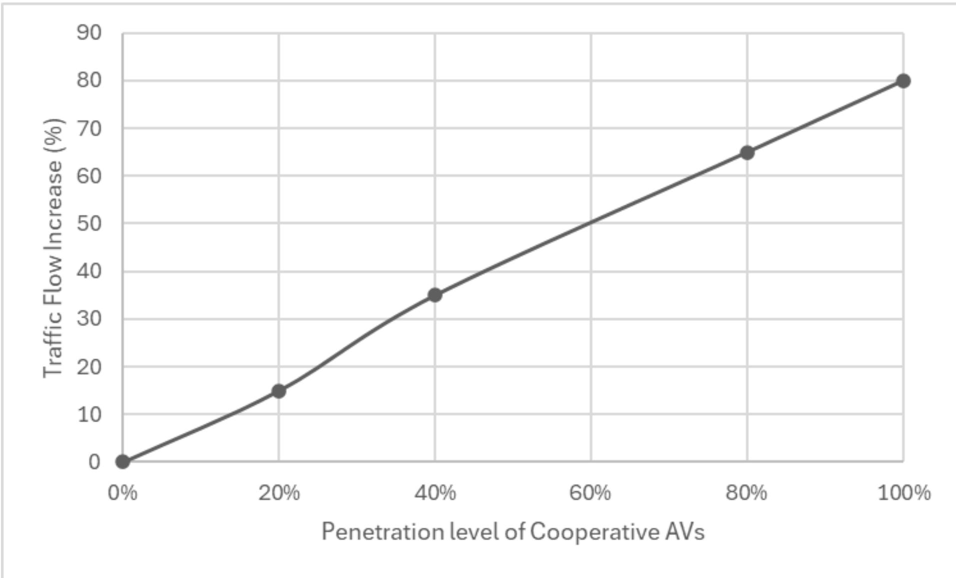

Figure 4. Traffic flow increase.

Figure 5 shows that the amount of time that vehicles spent in slow-moving or stopped traffic, referred to as vehicle delay, decreased with increasing Cooperative AV penetration. At 0% penetration, vehicle delay was typical of motorway congestion. At 20% and 50% penetration, vehicle delay decreased by 10% and 35% respectively. At full penetration, vehicle delay decreased by 75%.

But in the third scenario, which represents the full potential of Cooperative AVs, the reduction in vehicle delay occurs because AVs can adapt to real-time changes in traffic conditions, to correctly predict what is going to happen and to adjust their speed accordingly to prevent or minimise unnecessary stops and starts when changing lanes. This reduces congestion and allows vehicles to operate at the same flow rate without the need for lane changes, which cause bottlenecks, or decelerations or accelerations in response to the behaviour of other vehicles. The second way to reduce delays is by platooning.

Other work has demonstrated similar reductions in vehicle delay. The study by Samaranayake et al. [73] reveals delays at 50% can be reduced to 25% with Cooperative AVs in cooperative mode with 60% penetration on urban roads with traffic signals. Since there are only a few signals on the motorway with no coordination, our finding of a 75% reduction in delay at full penetration is consistent with this work. The delay reduction is more pronounced in a motorway environment since the delay is caused mainly by congestion and not by traffic signals. In another study, Ma and Li [74] demonstrated vehicle delay can be reduced by 40%–50% with Cooperative AV penetration rates of 30%–50%, and so even moderate levels of Cooperative AVs can lead to significant benefits in terms of reducing delays.

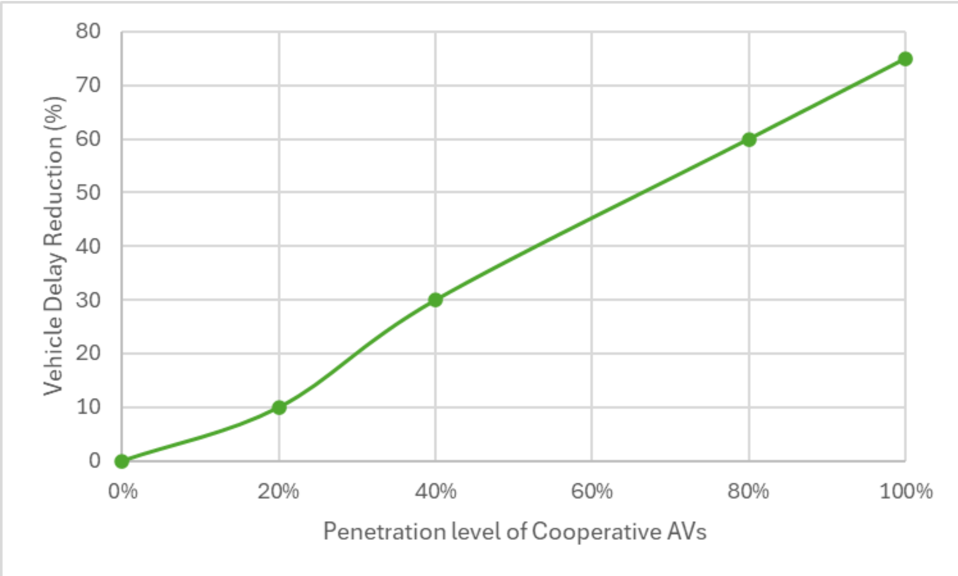

Figure 5. Vehicle delay reduction.

The most important result of this study is the CO_2 emissions reduction as cooperative AV penetration increases (**Figure 6**). The CO_2 reduction at 20% penetration is 8%, and at 100% penetration this reduction reaches 40%.

The decrease in CO_2 emissions is driven by the more fuel-efficient driving patterns of Cooperative AVs (e.g., fewer stop-and-go traffic, fewer acceleration and deceleration events, and more consistent vehicle speeds). And since the platooning capability of Cooperative AVs enables vehicles to drive in close formation, the associated lower aerodynamic drag lowers fuel consumption and avoids emissions.

These results are consistent with Barth and Boriboonsomsin [75] who demonstrated a potential reduction in emissions of 20%–30% under mixed traffic conditions. The 40% reduction at full penetration found in this study suggests that Cooperative AVs have even greater potential to reduce emissions on motorways than in urban environments since higher speeds and longer distances travelled allow for more sustained savings in fuel used. In the study by Brown et al. [10] Cooperative AVs reduced emissions by up to 35% in urban settings, suggesting that Cooperative AVs also have the potential to contribute to broader climate change mitigation efforts by lowering the carbon footprint of transport on roads.

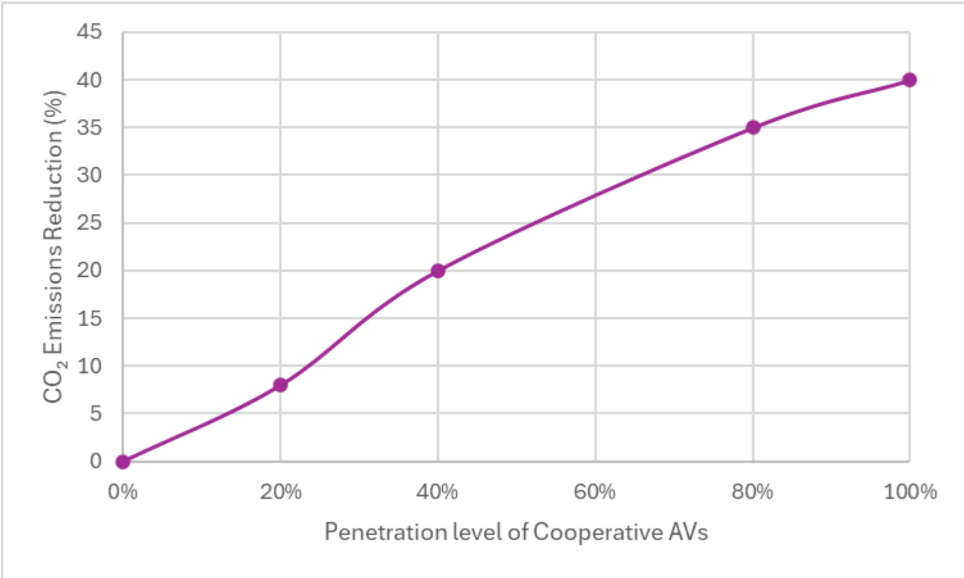

Figure 6. CO_2 emissions reduction.

5. Limitations

Although the results of this study clearly show that Cooperative AVs could help to manage motorway traffic in a more efficient and less accident-prone way, there are some important caveats relating to both the assumptions made in the simulation, and to the complexity of the real-world traffic environment, which may not be captured in the modelling process.

First, the simulation used in this study, PTV VISSIM is based on an ideal, simplified traffic environment, whereas real-traffic conditions are often more complex, such as due to adverse weather conditions, road incidents and different road geometries. For example, rain, fog, or snow might dramatically affect vehicle sensors and communication latencies, reducing the effectiveness of Cooperative AVs in maintaining closer headways and smoother traffic. Also, the model doesn't address road disruptions due to accidents, breakdowns and roadworks, which could lead to unexpected changes in traffic flow that might not be handled by Cooperative AVs as smoothly as predicted by the simulation.

Second, the technological assumptions in the study are another limitation. It is assumed that the Cooperative AVs in the simulation all have state-of-the-art, fully operational and reliable V2V and Vehicle-to-Everything (V2X) communication technologies. In reality, Cooperative AVs are likely to be deployed gradually, and in the meantime, vehicles will operate with varying technological sophistication during the transition. In more congested traffic, communication latency and network dropouts which are not factored into the simulation may affect the coordination of Cooperative AVs, preventing them from communicating promptly. Heterogeneity in the Cooperative AV systems from different manufacturers could also cause compatibility issues, reducing the effectiveness of V2V communication. There are also more subtle complications from the interactions between RVs and Cooperative AVs when they are in traffic together. The model assumes the RVs behave in predictable ways, but human drivers could behave unpredictably around Cooperative AVs. For example, they might not like the smaller headways that Cooperative AVs maintain and decide to drive more aggressively and erratically in response. These types of behaviours (such as braking suddenly, hogging lanes or refusing to help with lane changes) might disrupt the flow of traffic and cause the benefits of Cooperative AVs to fall. Similarly, human drivers might not cooperate with the coordination strategies Cooperative AVs use. The simulations also assume that all the vehicles involved are autonomous, which is not always the case in mixed traffic. Another important limitation is the consideration of only distinct, discrete penetration levels of Cooperative AVs (0%, 20%, 40%, 80%, 100%). In reality, the penetration of Cooperative AVs might be gradual, with penetration levels changing over time. The non-linear interactions between RVs and Cooperative AVs at intermediate penetration levels, which are not fully examined in this study, could lead to traffic bottlenecks or suboptimal traffic performance. More research is needed to understand how traffic performance evolves at these intermediate levels, particularly in a mixed-traffic environment where human drivers might react very differently.

Another limitation introduced by relying on the Wiedemann 99 car-following model is that it assumes that both RVs and Cooperative AVs behave similarly. The Wiedemann 99 is a common car-following model in traffic simulations since it uses static parameters for headway, acceleration and lane-change manoeuvre. In reality, drivers' behaviour is noisy, and in congested conditions often unpredictable because human drivers can react irrationally. The traffic simulation assumes that Cooperative AVs and RVs behave in the same way from the beginning to the end, while in real traffic there is much more variance in response times, braking behaviours and overtaking manoeuvres. This simplification could overestimate the advantage of Cooperative AVs in congestion, especially in congested traffic or in congestion waves.

Moreover, the study looked only at one section of the M5 motorway so the results might not apply to all motorway or road environments. Motorways in other parts of the world or even in other parts of the UK could have very different traffic profiles, road geometries and driver behaviour that impact on the potential benefits of Cooperative AVs. For example, countries with more aggressive driving styles or less disciplined lane usage might not see the same improvements in capacity and flow that were observed in the controlled motorway conditions of the study. The study looked specifically at motorway conditions where vehicles are travelling at higher speeds in a more orderly manner. It is less clear how Cooperative AVs would perform in urban settings where traffic signals, pedestrian crossings and roundabouts introduce additional complexity.

Finally, it should be noted that Cooperative AV technology is constantly evolving. This simulation reflects a point in time, using the Cooperative AV technology as it is currently envisioned. In the coming decades, Cooperative AVs will likely benefit from advancements in artificial intelligence (AI) systems, faster communication networks (such as 6G), and other sensor technologies that can further improve their performance. We did not model these advancements in this study, although they are likely to emerge. The adoption of Cooperative AVs will also hinge on public perceptions, regulatory frameworks and policy support. Public concerns about data privacy, cybersecurity and liability in the case of crashes could delay the rate of adoption, which could also delay the realisation of benefits described in this study.

In conclusion, although this study demonstrates the potential of Cooperative AVs to improve performance in motorway traffic, it suffers from numerous limitations in the findings. This is partly due to the oversimplified traffic scenario, the assumptions on the technologies used and the idealised mixed-traffic scenarios proposed. To mitigate these limitations, it will be important to explore more complex and realistic traffic scenarios and to account for real-world variability in driver behaviour in future research. These considerations will allow the study of how Cooperative AVs perform when combined with a wider range of traffic contexts and under more realistic conditions.

6. Conclusions

The introduction of Cooperative AVs into the traffic systems of motorways opens up the potential for revolutionising traffic performance, helping overcome current limitations to efficiency, safety and environmental sustainability. This study aimed to examine the impact of Cooperative AVs on traditional key traffic performance indicators such as road capacity, average speed, traffic flow, vehicle delay and CO_2 emissions through micro-simulation of the M5 motorway using PTV VISSIM. The analysis showed that as the penetration of Cooperative AVs increased, there was a general improvement in all measured characteristics, with the highest improvements being achieved at full penetration.

Moreover, the study showed that Cooperative AVS can dramatically increase road capacity with V2V communication and platooning enabling tighter headways and more coordinated vehicle behaviours Cooperative AVS increased road capacity up to 85% at full penetration. These results build off existing literature on the capacity-enhancing effects of Cooperative AVS. Second, the average speed at full penetration was 65% higher (full penetration means that all vehicles are Cooperative AVs). This result arises because Cooperative AVs can dampen fluctuations in speed (the oscillations associated with traffic flow) and maintain more constant and predictable traffic flows, even at high densities. By reducing stop-and-go patterns typical of human-driven traffic, Cooperative AVs can reduce total travel times, making motorway travel faster and more predictable. Regarding traffic flow, Cooperative AVs were also found to improve the number of vehicles passing through a road segment by up to 80%, building on the more efficient use of road space, which leads to reduced delays, and the ability of Cooperative AVs to safely reduce their headways and platoon with other vehicles. This implies that the use of Cooperative AVs can help reduce congestion in high-traffic areas, improving throughput and mitigating the bottlenecks that often cause traffic to slow down during peak periods. The most glaring benefit of Cooperative AVs was the 75% reduction in vehicle delay at full penetration: Cooperative AVs, thanks to their smoother traffic flow, fewer unnecessary stops, and better lane-change management, were able to reduce delays caused by congestion. Less vehicle delay means shorter and more reliable travel times for all road users, which is vital for freight and logistics operations that need to reliably and quickly deliver goods.

Along with these operational benefits, the study also showed huge environmental benefits of Cooperative AVs. They can cut CO_2 emissions by 40% at full penetration, a major boost to environmental sustainability. The reduction in fuel use is largely the result of smoother driving patterns, fewer accelerations and decelerations, and the aerodynamic benefits of platooning. Reducing emissions could greatly contribute to the world's effort to mitigate climate change by reducing the greenhouse gas footprint of the transport sector. These excellent results notwithstanding, several simplifying assumptions should be mentioned. For instance, the simulation environment was idealised, and the technological assumptions were idealised. Furthermore, human behaviour in mixed-traffic scenarios has been described in an unrealistically deterministic manner. Nevertheless, the simulation results provide strong evidence that Cooperative AVs can lead to significant improvements in terms of both traffic efficiency and environmental sustainability. The transition to Cooperative AVs can be challenging, but it will also dissipate traffic congestion and shorten travel times. Above all, by reducing fuel consumption, this transition will contribute to the sustainability objectives set at the global level. Over the coming years, the deployment of Cooperative AV technology will hinge on the coordination between policymakers, infrastructure developers, automakers and the public. It demands an investment in V2X infrastructure, enabling regulations, and public information campaigns that can support the integration of Cooperative AVs into existing traffic environments. The stakes seem high: the refinement of the deployment strategies for Cooperative AVs will rely on continued academic research on mixed-traffic environments, intermediate penetration levels and real-world operational challenges alike. To conclude, this study shows that the deployment of Cooperative AVs is expected to transform motorway traffic systems by increasing capacity, reducing delays, improving fuel efficiency, and contributing to lower CO_2 emissions. Cooperative AV technology will be a vital part of future smart mobility solutions as it matures and is scaled up.

7. Recommendations and forward look

Cooperative AVs cannot reach their full potential without a coordinated multi-sector effort. The first priority is investing in V2X infrastructure, which includes the installation of roadside units and connected traffic signals to provide real-time communications between vehicles and the roadway. Second, there must be standardisation of communication protocols so that Cooperative AVs with different manufacturers can communicate compatibly with vehicles from other manufacturers on the same roads. Coordination with governments and regulatory bodies should include a graduated integration of Cooperative AVs on motorways to promote early adoption. This integration could be achieved using dedicated lanes, especially in the early stages ('mixed traffic') when the vehicles are not functioning up to their full potential.

To speed up this process, other incentives, such as tax credits or toll reductions, could be offered to encourage early adoption of Cooperative AVs, along with public education campaigns to address the safety and trust issues of drivers. The development of Cooperative AV technology now needs to explore the non-linear effects of intermediate penetration levels and focus on mixed traffic settings in the real world, to understand how Cooperative AVs work alongside human-driven vehicles under varying penetration conditions. Furthermore, given the potential of these vehicles to be integrated with smart city initiatives, it provides a wider opportunity to improve urban mobility by applying dynamic traffic management and shared mobility solutions, to further reduce congestion and emissions. Looking ahead, Cooperative AVs will be further enhanced by advancements in AI, machine learning and sensor systems. 5G networks will strengthen V2X communication, increasing the speed and reliability of data exchanges; the freight and logistics sectors will benefit, too, from Cooperative AVs through the practice of truck platooning, a system allowing for maximised fuel efficiency and timely delivery. Similarly, global policy- and regulatory harmonisation will be required to allow the safe international dissemination of Cooperative AVs, while ensuring the legitimacy of data privacy and cybersecurity, alongside liability in the event of accidents. As cities and nations across the world endeavour to reach net-zero emissions by 2050, the transition to Cooperative AVs offers an unambiguous path toward sustainable travel. By reducing fuel consumption and CO_2 emissions, Cooperative AVs will play a pivotal role in reaching environmental goals, notably when combined with electric and hybrid vehicle technologies. However, the future of Cooperative AVs is promising, and the potential applications are global. With adequate investment, regulatory frameworks and engineering effort, Cooperative AVs can help increase road capacity, eliminate delays and reduce emissions, and make a safer, more efficient and sustainable transportation future a reality.

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Abbreviations

ITS, Intelligent Transportation System; AVs, Automated Vehicles; RVs, Regular Vehicles; OA, Overtaking Assistance; ACC, Adaptive Cruise Control; CACC, Cooperative Adaptive Cruise Control; Cooperative AVs, CACC Equipped Vehicles; IM, Intelligent Mobility; IDM, Intelligent Driver Model; ADAS, Advanced Driver Assistant Systems; BRT, Brake Response Time; V2X, Vehicle to Everything; V2V, Vehicle to Vehicle; DSRC, Dedicated Short-Range Communications; API, Application Programming Interface.

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