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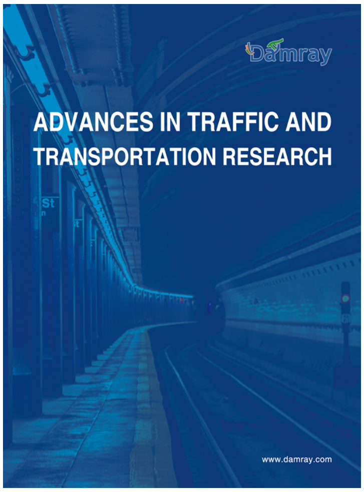

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Traffic Management Implications of Overtaking Assistance Automated Vehicles Mixed with Human-driven Vehicles

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Abstract

Automated vehicles (AVs) are widely regarded as a transformative force in the future of transportation. The market for AVs has been rapidly evolving over the past decades. This has driven researchers to explore and investigate AV impacts on road networks. Several studies have examined the implications of overtaking assistance (OA) systems for transportation. Nonetheless, few have taken a comprehensive approach to the effects of OA-equipped vehicles (Overtaking AVs) on traffic management and safety. Both NHTSA and SAE classify OA systems as level 1 automation. However, the performance of Overtaking AVs' performance under each simulated scenario can offer insights into the capabilities of higher automation levels. This study evaluates the impact of Overtaking AVs on traffic management, demonstrating significant improvements in road capacity (39%), average speed (36%), and traffic flow (53%) with increased Overtaking AV penetration. The benefits stem from Overtaking AVs' enhanced decision-making and lane-change efficiency. However, real-world challenges like sensor limitations, infrastructure readiness and driver compliance, require further investigation. This research offers valuable insights for policymakers and transportation planners to facilitate the progressive adoption of OA technologies, ultimately laying the groundwork for safer, more efficient road networks.

Keywords

Overtaking assistance (OA); automated vehicles (AVs); mixed traffic flow; car-following models; intelligent transportation systems (ITS); micro-simulation; traffic management; PTV VISSIM

1. Introduction

Automated Vehicles (AVs) are perceived as the future of transport. AV technology is being developed within the framework of Intelligent Mobility (IM) with an estimated global market share of £900bn annually by 2025 [1]. The anticipated market value is based on the reduction risk of human error. In the UK, it is estimated that there will be 27,400 jobs related to the manufacturing and assembling of connected and autonomous vehicles (CAVs) by 2035 [2]. Every year almost 1.3 million people are killed on roads because of road traffic injuries (RTAs) while around 50 million suffer non-fatal injuries [3]. Unlike human-driven vehicles (HDVs), AVs could potentially reduce RTAs and save lives as human error accounts for more than 90% of RTAs [4]. Furthermore, researchers predict that AVs could improve traffic conditions and safety standards [5]. At present, fully developed AVs are not commercially available to permit their widespread adoption, and testing has only taken place in restricted areas [6]. Advanced Driver Assistance Systems (ADAS) are currently available and widely spread. ADAS lay the groundwork for the implementation of AVs.

ADAS are defined as a collection of numerous intelligent components that are built into the vehicle itself [7]. The intelligent components assist drivers with driving and parking functions by performing a variety of different tasks. ADAS is critical while driving in unexpected as well as challenging driving and parking scenarios. Primarily, ADAS are classified into two groups: information-based and manipulation-based systems. Information-based systems deal with the anticipated level of congestion, the safety of the current route, and the likelihood of arriving at a destination on time [7]. Advanced traveller information (ATIS), inattention alert systems, and driver performance measurement are among the information-based systems. Manipulation-based systems, on the other hand, are more advanced and perform actions on behalf of the driver. Manipulation-based systems, on the other hand, are more advanced and perform actions on behalf of the driver. Manipulation-based systems can perform manoeuvres like parking and overtaking [7]. Safety alert and emergency stopping systems, cooperative cruise control (CACC) systems, overtaking assistance (OA) systems, and intersection assistance systems are examples of manipulation-based systems [8]. This study focuses on manipulation-based systems because they have a greater impact on traffic management and safety. Additionally, manipulation-based systems could be critical in reducing traffic fatalities and injuries. By integrating ADAS systems like OA, AVs are poised to revolutionize traffic management, enhancing both safety and efficiency. Despite their potential benefits, AVs face unique challenges when interacting with HDVs in mixed-traffic environments, which must be addressed.

The OA system is an important component of ADAS. A typical OA system consists of a speed radar to measure the speed of the host vehicle, following vehicle, and preceding vehicle [9]. Generally, overtaking is a complex and dangerous action that requires intelligent vehicles to make accurate estimations [10]. These systems are aimed to enhance the overall traffic safety and flow. OA system performs two crucial tasks: the decision-making of overtaking trail and the literal action of overtaking [7]. Likewise, OA systems are intended to safely assess the driver when overtaking other vehicles.

OA systems are designed to minimize the risk of collision and improve the overall safety of vehicles during the action of overtaking. OA systems can support drivers by accelerating the vehicle towards the ahead vehicle before reaching the overtaking lane. Moreover, OA systems are designed to avoid potential accidents due to vehicle overtaking and forward collision [11]. Therefore, this research utilizes a microsimulation based on VISSIM to assess the implications of OA-equipped vehicles (Overtaking AVs). The study examined the impacts of Overtaking AVs on capacity, average speed, and traffic flow. This required the development of a traffic mix model composed of HDVs and Overtaking AVs.

2. Literature review

Several studies have been conducted in recent years to assess the effects of ADAS on traffic management and safety. Over the last decades, several studies considered OA systems about the technology itself, its impacts on traffic flow and safety, system efficiency, and driver comfort. Other studies examined the desirable overtaking gap acceptance. The following sections summarize the relevant investigational studies. Researchers have utilized the use of microsimulation software to better evaluate the impacts of ADAS on traffic management. Traffic microsimulation modelling is developed to simulate the movement and behaviour of vehicles in the road network at the individual level [12]. Traffic microsimulation software includes DRACULA, VISSIM, and AIMSUN. The behaviour of AVs and ADAS are typically simulated using two strategies: inbuilt models and application programming interface (API) [13]. While Inbuilt models simulate AVs and ADAS by adapting the parameter of the model, APIs are programmed.

Some studies considered the implications of CACC systems for traffic management. The capacity of highways was observed to increase as the market penetration rate of CACC-equipped vehicles (Cooperative AVs) increased to moderate and high rates. This is due to the higher dynamic response capabilities [14]. Wang et al. [15] assessed the impacts of CACC systems on traffic flow using AIMSUM. Their outcomes demonstrate a positive impact on traffic flow. Moreover, other studies suggested similar results for traffic flow stability [16-18]. Furthermore, CACC systems have great impacts on fuel consumption [19-21].

Several studies have considered the cooperative overtaking assistance system based on vehicle-to-vehicle (V2V) communications [8, 21-23]. OA systems improve road safety and driver comfort [24, 25]. OA systems improve road safety as they provide the opportunity for safe overtaking and ultimately enhance road safety. Additionally, some studies considered the effects of OA systems for two-lane rural roads using microsimulation modelling [26]. The study used the RuTSim traffic simulator, which was designed to reduce the number of overtaking-related accidents on two-lane rural roads and enhance driver comfort. The findings of this study indicate that OA assists the driver in deciding whether an overtaking opportunity based on the time gap of the approaching vehicle is safe. Moreover, the study illustrates the safety benefits of the increased time to collision with oncoming vehicles. OA systems can be only beneficial and valuable when they can assist before the emergence of the appropriate gap in the oncoming traffic stream [27]. Similarly, one experiment used a driving simulator to test the functionality and acceptance of a standardized overtaking assistant design [28]. The study considered the simulation of a two-lane road and 24 participants drove 15 min with and without a prototype overtaking assistant. It was concluded that it is possible to design a standardized OA as the performance of overtaking manoeuvres. Likewise, in research to determine opportunities for OA combined with a user needs survey and interaction model. Based on survey results, respondents indicated a significant need for OA to support when interacting with other road users [29]. OA systems were also tested in country road scenarios. Sulejmani et al. [30] researched overtaking manoeuvres on country roads, and a stochastic model predictive control (MPC) algorithm was implemented to handle this task. In addition, the behaviour of the surrounding vehicles was stochastically predicted using Bayesian networks, and overtaking algorithm was tested for various country road scenarios. The results show that the control algorithm provides the safest trip in acceptable travel time.

Other studies focused on the problem of optimally controlling an autonomous vehicle and safely overtaking a slow-moving vehicle [31]. Some studies considered the spatial and temporal formulation of Overtaking AVs [32]. Shamir [33] discussed the three-phase overtaking manoeuvre as well as designing a smooth optimal lane-change trajectory under normal conditions. The results of the suggested model show that AVs equipped with appropriate sensors can estimate the best time and place to perform overtaking.

There are several advantages to the implementation of OA systems in road networks. However, OA systems also have some disadvantages. Designing a standardized overtaking assistant should suit the different drivers' perception [28]. Moreover, some OA models did not incorporate the changes in driver behaviour due to driver assistance systems. The implementation of ADAS has both implicit and explicit cons [34]. Implicitly, ADAS mismatch with user expectations. On the other hand, explicitly, ADAS requires attention as well as effort complexity.

Many studies assessed the impacts of ADAS on traffic systems. Several studies have evaluated the impact of OA systems on traffic management and safety. Most research on ADAS has used a microscopic approach [15, 35-39], while some studies have considered a macroscopic perspective [40-43]. Based on the aforementioned studies, the majority of research lacks a comprehensive perspective on the implications of OA systems. Most of the studies consider the longitudinal control of vehicles. Previous research has extensively studied various ADAS components, including CACC systems, which have been shown to improve traffic flow stability and fuel consumption. However, the literature lacks a comprehensive analysis of OA systems' impact on traffic management, which this study aims to address. Notably, this is a clear research gap in the literature and hence this research is set to further explore the potential of OA systems. Hence, this research was performed to assess the effects of OA systems on capacity, average speed, and traffic flow. In addition, this research is performed to complement the literature and bridge the knowledge gap. Additionally, this research is beneficial to the literature as it presents a holistic approach to the implications of OA systems for traffic management and safety.

3. Materials and methods

The purpose of this study is to investigate the effects of overtaking AVs on capacity, average speed, and traffic flow. Some metrics and presumptions have been used in this study. The chosen study area serves as the basis for the modelling performed in this study. The microsimulation model developed in PTV VISSIM incorporates distinct car-following models for HDVs and Overtaking AVs, with parameters adjusted to reflect their driving behaviours. Overtaking AVs, for instance, have a reduced headway time and standstill distance, enabling closer following and efficient lane changes.

3.1 Study area and selection

The M5 motorway links the Southwest of England to the Midlands. M5 extends to over 255 km in length. The microsimulation modelling concerned in this research is based on the section of the road on the M5 motorway (Junction 13 to Junction 14) in Bristol, United Kingdom. This section of the road is a three-lane dual-carriageway. Furthermore, this section of the road is approximately 16km in length. The study area for this research is better demonstrated in Figure 1.

Primarily, the study area is carefully chosen based on several considerations. Mainly, assessing the capabilities of CACC systems demands a relatively long distance. Hence, the selected area distance (approx. 16 km) between J13 to J14 on the M5 motorway makes this selection reasonably applicable and appropriate. Furthermore, this section of the road is one of the busiest and one of the most important sections of the M5 motorway. Moreover, the curvature of the road in this section permits adequate testing of the ADAS capabilities. To clarify, the unique road curvature exposes ADAS systems to various situations to be tested. Therefore, testing would consider different road conditions and geometries.

Figure 1. Study area M5, J13 to J14.

3.2 Model development and simulation environment

To assess the implications of Overtaking AVs for traffic management a microsimulation model was built on PTV VISSIM. VISSIM was designed based on the two car-following models: Wiedemann 74 and 99. Wiedemann 74 is used for urban roads while the 99 is designed for motorways traffic [44]. Hence, this research utilizes the 99 car-following model. Moreover, the created model is a traffic mix comprised of HDVs and Overtaking AVs. Therefore, modelling HDVs and Overtaking AVs requires the adjustment of car-following parameters and the use of the overtaking model as well as criteria.

3.3 Driver and overtaking models

Table 1. Parameter selection

	Parameter	HDVs	Overtaking AVs
Car-following (Wiedemann 99)	CC0 (Standstill Distance)	1.5 meters	0.5 meters
	CC1 (Headway Time)	1.8 seconds	0.9 seconds
	CC2 (Following Variation)	4.0 meters	1.0 meter
	CC3 (Threshold for Entering Following State)	-8.0 meters	-12.0 meters
	CC4 (Negative Following Threshold)	-0.35 m/s²	-0.1 m/s²
	CC5 (Positive Following Threshold)	0.35 m/s²	0.15 m/s²
	CC6 (Speed Dependency of Oscillation)	12.0 m/s²	6.0 m/s²
Lane change	Min Headway	1.2 meters	0.8 meters
	Safety Reduction Factor	0.7	0.4
Driving characteristics	Look Ahead Distance	100 to 150 meters	150 to 300 meters
	Look Back Distance	50 to 100 meters	100 to 150 meters
	Observed Vehicles	1	3
	Desired Speed (km/h)	110 km/h	110 km/h

Simulating Overtaking AVs required the adjustment for the following models: VISSIM external driver model application programming interface (API), car-following model, lane changing model, and overtaking model. The external driver model is responsible for modifying the existing driver model in VISSIM. The external model is used to model Overtaking AVs. The adopted model for this research selected some parameters based on Milanés et al. [45, 46] and Zeidler et al. [47]. This is because some of the models were validated by experimental data. Nonetheless, changes were made to the models. The Lane lane-changing model was also incorporated. Moreover, overtaking criteria were selected to allow overtaking based on [26-28]. These represent experimental data. An OA threshold of 8 sec is selected. Tables 1 and 2 shows the adopted parameters for the different driver models and overtaking models, respectively.

Table 2. Overtaking criteria

	OA threshold (s)	OA penetration rate (%)	Driver compliance (%)
Base scenario (HDVs)	-	0	-
Overtaking AVs	0.7	20, 40, 60, 80, 100	100

3.4 Scenario description and run

The simulated microsimulation in this is based on the section of the M5 motorway (J13 to J14), three-lane, dual carriageway, and a desired speed of 110 km/hr. This study considers penetration rates of Overtaking AVs vary from 0% to 100% in multiples of 20%. Scenarios are analysed and compared to the behaviour of HDVs. 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 (1.5hr). The results were collected based on a time span of 900-5400 sec (1hr). A warmup period of 0.5hr (15min at the beginning and 15min at the end). Furthermore, the warmup period is essential to eliminate any start-up period at the beginning and saturate the traffic system.

4. Results and discussion

The simulation in this study explored the effects of Overtaking AVs on key traffic metrics, namely average speed and traffic flow. A range of Overtaking AV penetration rates [0%, 20%, 40%, 60%, 80%, and 100%] was considered to evaluate how different levels of AV adoption influence overall traffic conditions. The results show that as Overtaking AV penetration increases, significant growth is observed in road capacity, average speeds, and traffic flow. These effects are analysed for both vehicle types using the Wiedemann 99 car-following model. The tables and figures provided support a thorough understanding of how OA systems impact traffic performance.

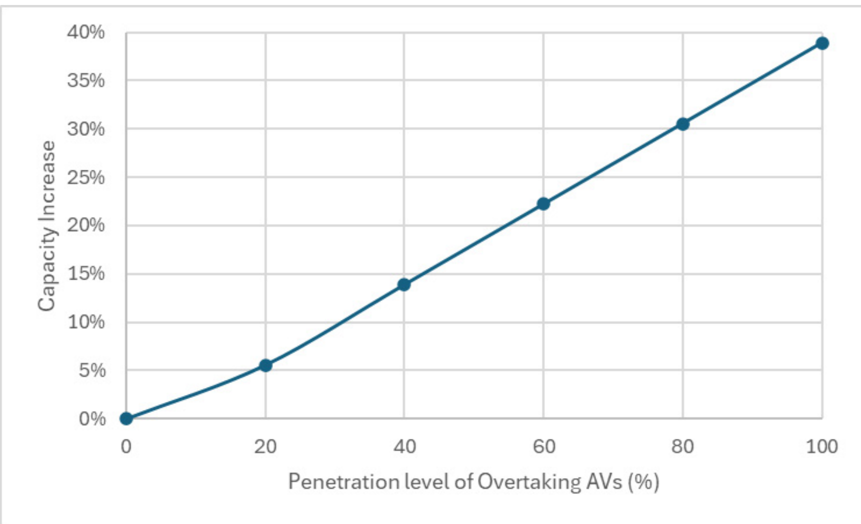

Figure 2. Capacity increase.

The simulation results indicate that as the penetration of Overtaking AVs increases, there is a significant improvement in road capacity, average speed, and traffic flow. Figure 2 illustrates the capacity increase with varying Overtaking AV penetration rates, demonstrating the potential benefits of integrating OA systems into traffic management strategies. In the base scenario (0% penetration), when all the vehicles are only HDVs, the capacity is fixed. After reaching 20% penetration of Overtaking AVs, the capacity level rises to 6%. The improvement continues and reaches 40% at 100%

penetration level, which is a considerable improvement of the roadway capacity. This shows how Overtaking AVs in mixed traffic can use the roadway space more efficiently than HDVs since the automated decision-making capabilities of the AVs are far superior to the human drivers.

CC0 (Standstill Distance) is 0.5 metres for Overtaking AVs, vs 1.5 metres for HDVs, so that, at a standstill, more vehicles can be packed within the same road length. In high-traffic scenarios, this is particularly advantageous. CC1 (Headway Time) reduces to 0.9 seconds for Overtaking AVs, vs 1.8 seconds for HDVs, meaning that vehicles can closely follow one another safely so that the number of vehicles per lane per hour increases.

The more Overtaking AV penetration, the higher the average speed of traffic is. When the penetration is 20%, it will be an average speed gain of 7% and reach 36% at 100% penetration as illustrated in Figure 3. This is because Overtaking AVs can safely and rapidly overtake without interfering too much with the flow of traffic. Overtaking AVs perform lane-change manoeuvres more efficiently, and can get as much headway as 0.8 meters at minimum (in comparison with 1.2 meters for HDVs). This loss of headway, coupled with a Safety Reduction Factor of 0.4 for Overtaking AVs allows overtaking more quickly without compromising safety. AVs for overtaking can evaluate and perform the overtakes more effectively than humans who are typically more cautious and need more room to do so. Additionally, the Look Ahead Distance and look-back distance for Overtaking AVs are much higher than HDVs' so that Overtaking AVs could observe traffic over longer distances and slowdown in advance. This avoids excessive braking and deceleration, leading to higher average speeds.

Abbreviations: ITS, Intelligent Transportation System; AVs, Automated Vehicles; HDVs, Human-Driven Vehicles; OA, Overtaking Assistance; ACC, Adaptive Cruise Control; CACC, Cooperative Adaptive Cruise Control; Overtaking AVs, OA Equipped Vehicles; Cooperative AVs, CACC Equipped Vehicles; ADAS, Advanced Driver Assistant Systems; ATIS, Advanced traveller information; NHTSA, National Highway Traffic Safety Administration; SAE, Society of Automotive Engineers; IM, Intelligent Mobility; RTAs, Road Traffic Injuries; CAVs, Connected and Autonomous Vehicles; V2V, Vehicle to Vehicle; API, Application Programming Interface; MPC, Model Predictive Control; API, Application Programming Interface; AI, Artificial Intelligence.

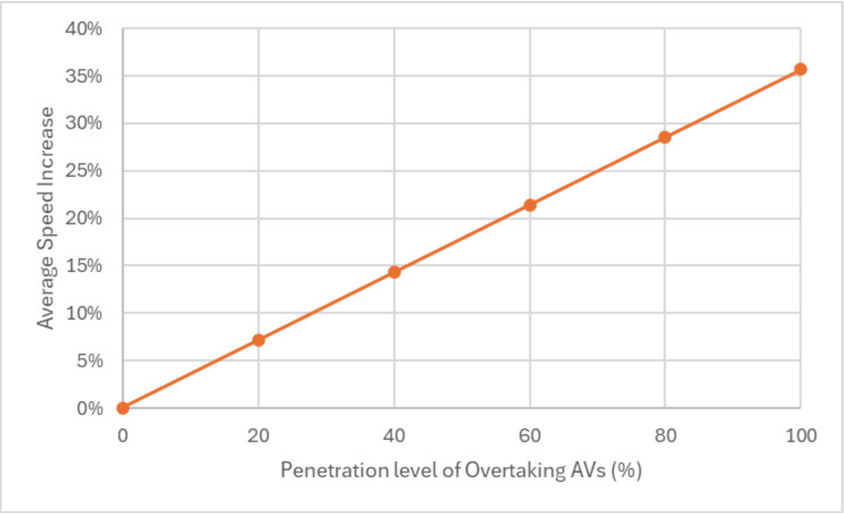

Figure 3. Average speed increase.

Traffic flow, measured in terms of vehicles reversing a point per unit of time, improves exponentially with Overtaking AV. At 20% penetration, traffic volume is up 7%, at 100% penetration, traffic volume is up 53% as illustrated in Figure 4. This boost in traffic volume is mainly due to the steadier driving style of Overtaking AVs, with a CC2 (Following Variation) of 1.0 meters (as opposed to 4.0 meters for HDVs). This lack of variation allows Overtaking AVs to proceed at more predictable speeds, decreasing stop-and-go traffic flow that interferes with traffic flow.

This CC6 (Speed Dependency of Oscillation) for Overtaking AVs is 6.0 m/s^2 vs 12.0 m/s^2 for HDVs and thus Overtaking AVs exhibit less speed oscillation and can travel at constant velocities. This has deep implications for the flow of traffic, especially in mixed-vehicle environments where different speeds may result in congestion. Look Ahead and Look Back distances (300m in advance, 150m in reverse for Overtaking AVs) provide added efficiency because they help cars to decide more informedly based on the traffic conditions further away.

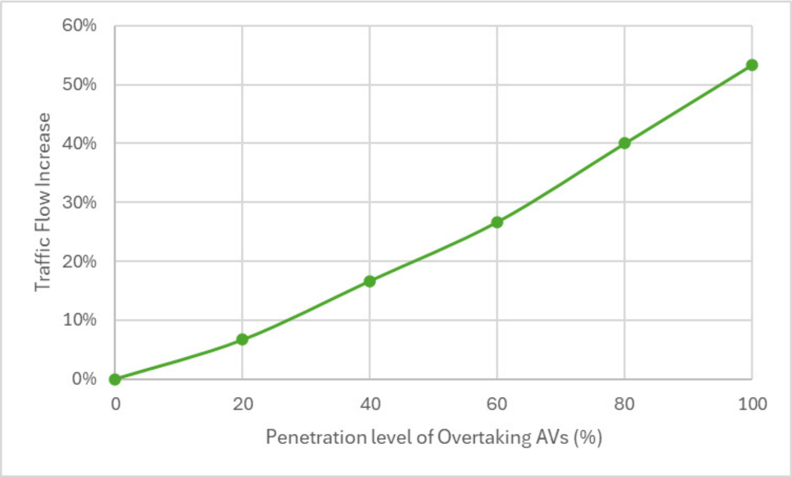

Figure 4. Traffic flow increases.

5. Limitations

While the simulation results are promising, real-world implementation of Overtaking AVs may face challenges such as sensor performance in foggy or rainy conditions and the need for extensive real-world testing to validate the simulation outcomes. The simulation assumes 100% compliance with the OA systems by human drivers. However, in reality, humans may not always trust or follow the system. This may lead to hesitation and unsafe behaviour. In addition, may not always be compliant with the Overtaking AVs. They may choose to disengage the system and override the lane-changing recommendation. This would reduce the effectiveness of the OA systems in mixed-traffic environments where driving HDVs and Overtaking AVs coexist. Deteriorated or foggy weather could prevent Overtaking AVs from functioning effectively. Additionally, Overtaking AVs depend on the quality of sensors and the quality of the road conditions. For example, the poor function of sensing equipment and the sensor-fusion algorithms during harsh weather (rain, fog, snow) could lead to poor decision-making, which could reduce the effectiveness of the OA system. Poorly marked roads, when lane markings are worn off or when roads are too curvy, may reduce the effectiveness of the system as well. This could result in a situation where Overtaking AVs behave erratically.

There is a high likelihood that the transition between the HDVs and the Overtaking AVs could present issues. Indeed, as was shown in the simulation, higher Overtaking AV penetration rates result in better performance. However, this improvement is likely to reach its limit when mixed-traffic environments are considered. For example, the findings indicate that conflicts are likely to take place when the penetration rate is between 20% and 60%. HDVs may not always respond to Overtaking AVs' behaviour predictably, resulting in slower reaction times, lane-change manoeuvres, or even accidents due to miscommunication between human drivers and automated systems. These conflicts were not investigated in detail in the simulation.

However, the assumption in the simulation that the OA systems operated smoothly ignores the hardware and software limitations of real-world automated vehicles. For instance, limited software, sensor failure, or slow system response times could reduce the efficiency of Overtaking AVs in live traffic environments. These limitations must be accounted for when implementing OA systems on a large scale.

6. Conclusions

This research aimed to evaluate the impact of Overtaking AVs on traffic management, focusing on metrics like capacity, average speed, and traffic flow. The findings of this study demonstrate that Overtaking AVs can offer substantial benefits to traffic management when mixed with HDVs. As the penetration of Overtaking AVs increases, road capacity, average speed, and traffic flow all increase significantly.

At 100% penetration, Overtaking AVs increases road capacity by 39%, average speed by 36%, and traffic flow by 53%. These gains are the result of the ability of Overtaking AVs to reduce headway, reduce following variability, and execute smoother overtaking manoeuvres than HDVs. The higher speeds, smoother traffic flow, and increased capacity suggest that Overtaking AVs could offer significant congestion reduction benefits, especially in high-density traffic scenarios.

However, these benefits are evident only at higher penetration levels: starting at 20% to 40% Overtaking AV penetration, the safety benefits of OA systems start to become apparent, but the full advantages are realised only at a high penetration of the system. Indeed, several real-world constraints are still not well understood and need to be studied more carefully, such as driver compliance, sensor limitations and mixed-traffic dynamics. The simulation outcomes demonstrate that while Overtaking AVs have a modest positive impact on traffic dynamics, further advancements in automation technology could lead to more substantial improvements. Although this study only considered Level 1 automation, the performance of Overtaking AVs under the simulated scenarios provides insights into the potential benefits of higher levels of automation. Future studies should focus on examining the implications of more advanced AV technologies and other ADAS components, as well as addressing the inherent challenges of predicting AV performance in real-world conditions.

Additionally, as discussed in [48], fully developed AVs hold the potential to drastically reshape urban transportation systems by reducing traffic congestion, fuel consumption, and improving safety. However, these benefits can only be fully realized through comprehensive research, policy development, and technological advancements. For instance, AVs are expected to significantly reduce traffic accidents, particularly on freeways, with studies indicating a potential reduction in accidents by up to 70% when AVs make up at least 40% of the traffic flow [49, 50]. Moreover, the complete deployment of AVs could lead to the total elimination of human-error-related accidents. This research serves as a precursor for the broader implementation of AVs, emphasizing the importance of continued exploration into how AVs can transform our transportation systems shortly [49, 50]. In conclusion, Overtaking AVs have the potential to significantly improve traffic management when integrated with HDVs. However, the full realization of these benefits requires addressing real-world challenges and further advancements in automation technology.

7. Recommendations and forward look

Based on the findings of this study, several recommendations can be made to enhance the integration and effectiveness of Overtaking AVs in traffic management. Table 3 presents key recommendations based on the findings of this study, highlighting necessary policy, infrastructure, and research actions to facilitate the adoption of Overtaking AVs in mixed-traffic environments.

Table 3. Key recommendations for Overtaking AV integration

Recommendation	Expected Outcome/Regulation	Rationale/Comment
Encourage gradual adoption of Overtaking AVs through regulatory incentives	Increased penetration of Overtaking AVs, leading to improved road capacity, speed, and traffic flow	The study found that higher penetration rates of Overtaking AVs (above 40%) significantly improve road efficiency (capacity ↑ 39%, speed ↑ 36%, flow ↑ 53%). Regulatory support (tax incentives, subsidies) would accelerate adoption.
Enhance infrastructure readiness (lane markings, V2V/V2I communication, smart traffic signals)	Better performance and reliability of Overtaking AVs, reducing safety risks in mixed-traffic environments	Poorly marked roads, lack of communication systems, and limited infrastructure readiness were identified as challenges for seamless Overtaking AV integration. Enhancing infrastructure will improve safety and efficiency.
Develop policies for mixed-traffic management (e.g., dynamic lane allocation, AV-only lanes)	Improved traffic flow and reduced conflicts between Overtaking AVs and HDVs	The findings highlight that interaction between AVs and HDVs can cause lane-change inefficiencies, especially at low AV penetration rates (20-60%). Dynamic management strategies will mitigate this issue.
Mandate safety compliance and testing standards for Overtaking AVs in real-world conditions	Minimised risks due to sensor failures, system disengagement, and unpredictable HDV behaviour	The study's limitations indicate that compliance with OA systems and adverse weather conditions could reduce their effectiveness. Standardised safety measures and rigorous testing protocols will ensure reliability.
Further research on AV-human driver interaction and behavioural adaptation	Better understanding of driver compliance and behavioural responses in mixed traffic	The study assumes 100% compliance but notes that HDV drivers may react unpredictably. Future studies should examine real-world human behaviour with Overtaking AVs.
Investigate the environmental and economic benefits of Overtaking AV integration	Quantified reduction in fuel consumption, emissions, and congestion costs	The study suggests that smoother AV traffic flow could reduce fuel consumption and emissions, but this was not explicitly analysed. Future research should explore sustainability impacts.
Explore the potential of higher-level automation for overtaking manoeuvres	Increased efficiency and safer overtaking strategies	The study focused on Level 1 automation, but findings suggest that advanced AV capabilities (e.g., AI-driven decision-making) could further enhance safety and traffic performance.

Incremental adoption of Overtaking AVs should be encouraged, as even a gradual increase in AV penetration rates can lead to slight but meaningful improvements in traffic conditions. While this study focused on Level 1 automation, further exploration of higher automation levels is essential, as they may offer more substantial benefits in terms of traffic efficiency and safety. Additionally, the enhancement of ITS and supporting infrastructure, such as V2V communication, is recommended to maximize the coordination and effectiveness of Overtaking AVs during manoeuvres. Governments and policymakers should encourage the gradual adoption of Overtaking AVs through tax rebates, subsidies and regulatory support to manufacturers who are integrating OA systems into their vehicles; this support should extend to consumers as well, especially those running fleets and mass transit systems. Investment in smart road infrastructure will be the third major challenge in enabling Overtaking AVs. Clear lane markings, real-time traffic information systems, and V2I communication systems will improve the performance of Overtaking AVs by enabling them to take better advantage of the available road space and avoid potential hazards. Since HDVs and Overtaking AVs will be driving side by side for a long time into the future, traffic management strategies will be needed to accommodate the mixed-traffic environment. Dynamic lane allocation, intelligent traffic signals and CACC systems can potentially help us manage such mixed traffic. There is much more work needed to develop and test CACC systems. As future generations of OA systems are developed and deployed for more applications, advanced systems will be needed to provide smooth, coordinated and safe lane changes and overtaking manoeuvres in complex traffic environments. Sensor technology and active communication systems must continue to advance to ensure that OA systems perform at their best in all weather and environmental conditions. This means improving sensor accuracy in low-visibility conditions, and enhancing V2V communication so that Overtaking AVs can act in unison under different traffic conditions. Finally, future generations of OA systems will require more advanced adaptive learning algorithms that can react in real-time to changing traffic conditions and road environments. OA systems should be capable of learning to recognise and react to human-driven vehicles and other automated systems and should be able to coordinate their lane changes and overtaking manoeuvres in mixed-traffic environments. We identified several critical areas for future research. For example, while this study simulated idealised environments with 100% compliance among Overtaking AVs, in the real world we will be dealing with human drivers who may prove to be quite unpredictable, especially at first. We need to study how human behaviour affects the performance of Overtaking AVs, especially during overtaking manoeuvres, lane changes and other critical driving environments. Future research should move beyond simulation and begin to deploy pilot programmes in our urban and highway environments. We envision programmes that could involve a mix of Overtaking AVs and HDVs, and we should collect real-time data on traffic flow, speed, capacity and safety. Actual deployment will give us a much better sense of the true benefits of OA systems, as well as the areas that need further improvements. This study focused on improved traffic flow in general, but future studies should look at how Overtaking AVs perform under different road environments, including urban roads, rural highways and multilane freeways. Future studies should also examine how traffic conditions, such as rush hour congestion versus off-peak traffic, affect the performance of overtaking AVs. For example, the management of Overtaking AVs across different traffic densities. In terms of environmental and economic impacts, this study side-stepped such discussions. For example, the smoother traffic flow facilitated by O there will be less fuel consumption and less greenhouse gas emissions. This trend would have positive sustainability benefits. Also, the potential economic benefits of reduced traffic congestion (e.g., higher productivity and lower transportation costs) should be quantified in more detail. As previously mentioned, this study had limitations due to the nature of the CACC system used in this work. However, OA systems need to be tested in a variety of adverse environmental conditions, such as rain, snow and fog. The issue of sensor failure under adverse conditions must be researched in more detail, and contingency plans should be developed. Another area of future research is studying the integration of platooning systems with coordinated driving. Platooning systems allow Overtaking AVs to operate nearby: they will be driving next to one another, rather than side by side. This will reduce aerodynamic drag and potentially increase fuel efficiency. OA systems should be able to interface with platooning systems to take advantage of both types of driving strategies to facilitate not only overtaking manoeuvres and lane changes but also speed control for entire fleets of vehicles. Future research should address these limitations by incorporating more realistic traffic scenarios and extending the analysis to higher levels of automation to fully realise the potential of Overtaking AVs in improving traffic systems.

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Conflicts of interests

The author declares that he has no conflict of interest regarding the publication of this paper.

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