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Review Article

A Systematic Review of the Impact of Autonomous Vehicles on Transportation Networks

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ABSTRACT

The widespread adoption of Autonomous Vehicles made it crucial for researchers to understand how Autonomous Vehicles affect transportation networks. When studying the impact of Autonomous Vehicles on transportation networks, it is essential to consider traffic flow, infrastructure readiness, and overall performance. Furthermore, the implementation of Autonomous Vehicles raises concerns regarding safety due to various reasons including, but not limited to public acceptance and regulatory frameworks. Thus, analyzing Autonomous Vehicles interaction with existing transportation systems provides valuable insights regarding the benefits and challenges related to the of Autonomous Vehicles. This underscores the need to examine these interactions to better understand the influence of Autonomous Vehicles on travel patterns, congestion levels, and network performance. The aim of this paper is to provide a summary of the impacts of Autonomous Vehicles' integration into existing transportation system, which aids in formulating strategies and frameworks for the future that affirms optimal traffic flow and safety. The methodology used in this paper is a systematic literature review in accordance with PRISMA guidelines. Various literature sources were retrieved from Google and Google Scholar search engines, Scopus and Web of Science databases, and the AUS e-library. This paper highlights research gaps in this area that serve as a reference for future studies and provides perspectives on the impact of adopting Autonomous Vehicles.

KEYWORDS

Autonomous vehicles, Transportation networks, Traffic flow, Simulation, Safety, Human Behavior, Dedicated Lanes.

INTRODUCTION

In recent years, the advancement of Autonomous Vehicles (AVs) has emerged as a transformative force in the realm of transportation. With rapid developments in technology and increasing interest from both industry and academia, comprehending the potential impact of AVs on transportation networks has become a critical area of research. AVs harness technology to either partially or entirely supplant the human driver in guiding a vehicle from its point of origin to a predetermined destination, all while adeptly circumventing road hazards and adjusting to prevailing traffic conditions [1]. To standardize the varying degrees of human

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involvement in AV operation, the Society of Automotive Engineers (SAE) has formulated a widely adopted classification system, which encompasses six distinct levels [2]. This system, endorsed by the U.S. National Highway Traffic Safety Administration (NHTSA), serves as a pillar for categorizing and regulating AV technology [3].

According to SAE [2], vehicle automation ranges from full automation, where the vehicle has complete control over all driving tasks under all conditions without human intervention, to no automation, where the human driver is entirely responsible for directing the vehicle. Moreover, there are four intermediary levels; those include: partial automation, where the vehicle can control both steering and acceleration under certain circumstances, but the driver must remain attentive; conditional automation, where the vehicle can drive autonomously in certain situations but the driver must be prepared to intervene; and high automation, where the vehicle can operate all driving tasks under certain conditions with slight to almost no human interference.

The integration of AVs into the transportation field can generate considerable cost savings. That is, with the enhanced fuel efficiency, improved routes, and decreased labor costs, companies will significantly benefit from the reductions in operational expenses [4]. The use of AVs and Connected Autonomous Vehicles (CAVs) has shown notable reductions in fuel consumptions by up to 90% [5]. The potential for achieving 90% savings in fuel consumption from CAVs is largely dependent on high penetration rates. Positive environmental consequences, such as lower CO2 levels and energy savings, become more apparent as the penetration level rises. However, at lower levels of CAV adoption, the benefits are less significant. Studies show that fuel consumption can be reduced by anywhere from 30% to 90%, though the minimum savings vary. Furthermore, efficient coordination of AVs, such as platooning and synchronized lane changes, can help in reducing fuel usage. These systems reduce needless idling, braking, and acceleration, all of which are significant causes of fuel inefficiency. It’s also noteworthy to mention that the AV chooses the route with the lowest energy consumption after weighing the energy consumption of several routes [4].

Not only that, but the integration of AVs at 100% penetration rate has the ability of reducing Carbon Dioxide (CO_2) and Nitrogen Oxides (NO_x) emissions significantly [6]. Additionally, through the implementation of CAVs, the risk of accidents can be alleviated [7]. This in return yields lower insurance expenses and vehicle repairs [8]. Furthermore, AVs are capable of reforming traffic management systems through facilitating traffic flow [9], [10]. This is true because AVs have the ability to smoothly communicate with other Avs using Vehicle-to-vehicle communication systems (V2V) and the surrounding infrastructure using the Vehicle-to-Infrastructure communication systems (V2I) [11]. Accordingly, major congestion alleviation can be promised in addition to reduced travel time and enhanced traffic management; thus, steadier routes yielded for both autonomous and human-driven vehicles [12]. AVs are also of great advantage when it comes to areas with limited public transportation and individuals not capable of driving [13]. In such cases, AVs bridge the gap between conventional public transportation and individual vehicle ownership by offering on demand transportation services [14], [15]. The implementation of AVs has the competence of resulting in major enhancements to the transportation filed, especially for communities offered inadequate services by providing convenient mobility solutions [15]. The endorsement of AVs in existing transportation systems influences traffic flow dynamics. With AVs being able to utilize V2V and V2I, a more competent routing, lower traffic congestion, and optimized traffic flow patterns can be achieved [16], [17]. AVs may reshape the demand for transportation services and infrastructure by altering travel behavior, mode choice, and vehicle ownership patterns [18]. The widespread adoption of AVs; however, raises a multitude of challenges and opportunities [4] as shown in

Figure 1, which need to be examined carefully in order to address them with the right approach. In addition, with the deployment of AVs, major concerns are raised in regards with safety, cybersecurity, and regulatory frameworks [19]. Thereby comprehensive research is required to ensure a safe integration of AVs into transportation networks

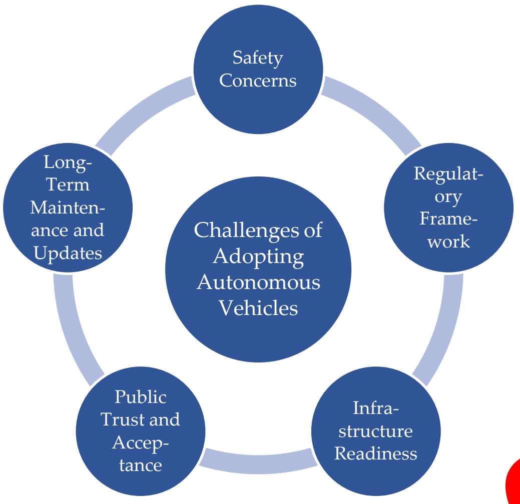

Figure 1. Challenges of Adopting Autonomous Vehicles [4]

The implementation of AVs makes the establishment of new regulations and standards necessary to guarantee a safe integration [20]. That is, regulatory bodies need to create uniform frameworks for the way AVs will operate when interacting with traditional transportation systems [21]. The NHTSA, for instance, has developed a comprehensive safety standard, where AVs are accounted for [22]. Furthermore, the acceptance of AVs by the public poses a significant challenge due to the fact that many individuals hold concerns regarding the safety of self-driving technology [23]. Thorough research and testing are required to mitigate these concerns; in addition to providing the public with comprehensive details on the advantages and limitations of AVs. This ensures the acceptance of the integration of AV technology by the majority, if not all, of the public [6]. Besides the public acceptance, the adoption of AVs also necessitates the preparation of existing infrastructure in a way that promotes safety [24]. Infrastructure readiness includes technologies that can accommodate AVs; those comprise adequate signage, road markings, and communication infrastructure. Additionally, the increasing demand of autonomous electric vehicles must be met with sufficient charging infrastructure [6].

This paper seeks to explore and analyze the diversified consequences of AV integration on transportation systems, ranging from traffic flow dynamics to strategies of AV integration. In light of the rapid advancements in the field of transportation and infrastructure, the emergence of AVs promises a revolutionary change in the way people and goods are transported [25]. Not only that, but it also introduces developed sensing and communication technologies that have the potential to enhance safety, efficiency, and accessibility in transportation networks [26].

FINDINGS

This section presents findings of previous researchers in regards with the effects AVs have on transportation systems, human behavior, and safety.

Modelling and Simulation of Autonomous Vehicles Integration

The introduction of AV technology to existing transportation systems promises a revolutionized mobility [27]. Thus, modelling and simulation of AV integration beforehand allows an optimized utilization of the technology through forecasting scenarios and assessing potential outcomes [28]. Through modelling and simulation, researchers can evaluate various factors via advanced computational techniques that replicate real-life environments, such as: traffic flow, vehicle interactions, and flow efficiency [29], [30]. The insights provided from these studies demonstrate the interactions between AVs and existing transportation infrastructure, which are crucial in developing efficient AV deployment strategies. Not only that, but they also contribute to proposing regulatory frameworks and infrastructure requirements that support the seamless integration of AVs into transportation networks.

Empirical studies on Autonomous Vehicle integration. Empirical studies on the integration of AVs play a pivotal role in the area of research as societies transition towards increasingly using automated transportation systems. Understanding the real-world impacts and challenges of AVs serves as a building block for infrastructure preparation and policy regulation across various industries. Many studies examine the possibilities and difficulties of improving AV performance in existing transportation systems. These studies suggest ways to enhance skills including, but not limited to, collision avoidance and lane-keeping. Deep learning along with the integration of cutting-edge technology into AV systems significantly improve traffic flow and collision avoidance. Empirical studies in this domain aim to spotlight into the practical implications of AV integration, addressing a wide range of topics such as safety, traffic efficiency, societal acceptability, regulatory frameworks, and infrastructural requirements. These studies employ rigorous data collection methods and analytical approaches to contribute valuable evidence-based knowledge to inform decision-making processes and shape the future of transportation in the era of autonomy. AV platoons can significantly enhance consumption of energy [31] by co-optimizing gear positions and speed [32]. Furthermore, it saves up to 16% on energy and can reduce travel time by 5% [32]. This is evident in reduction of energy consumption by the framework created for eco-driving that uses SpaT data, which in free flow scenarios, determines the energy sufficient speed profile upstream and downstream [33]. The development of AVs from theoretical concepts to practical applications showcases its potential to enhance traffic flow and safety [34]. Many researchers agree on the ability of AVs to contribute to energy consumption reduction, which makes its utilization advantageous even in the environmental sector. Energy consumption can be reduced through improved driving strategies, such as limiting needless acceleration and braking, hence eco-driving approaches can improve the energy economy of AVs. By accounting for traffic, road conditions, and vehicle state, the suggested dynamic eco-driving control framework enables AVs to function more effectively in real-time. AVs may adjust to changing driving situations and enhance fuel economy by combining this control framework with sophisticated algorithms [31]. For instance, an eco-driving framework uses Signal Phasing and Timing (SPaT) data to allow cars to change their speed beforehand to reduce energy usage. By communicating signal timings to cars, the framework enables them to adjust their speed profiles and minimize stop-and-go behaviors, which lowers fuel consumption [33]. This allows for significant energy savings while preserving safe, smooth driving behaviors. Furthermore, in CAVs, co-optimizing gear positions and speed ensures that a vehicle runs as efficiently as possible based on real-time traffic predictions, which helps cut down on energy consumption. Driving can be made more efficient by minimizing fuel usage by modifying the vehicle's speed and gear in accordance with anticipated traffic circumstances [32]. Moreover, the technology used in AVs can further be developed to assure a safer travel for the AVs and the surrounding vehicles. Although the Reinforcement Learning (RL) used in AVs operates smoothly, the Hierarchical Program-triggered Reinforcement Learning (HPRL) was proposed [35] and it divides tasks into simpler ones that are each run by a set of programs and RL agents. Additionally, a cost-effective solution would be prepping AVs with low-power hardware computers and dedicate edge servers for heavy assignments [36]. Through this approach, it can be guaranteed that the probability of hardware failure is mitigated; thus, a safer ride for AVs and their neighboring drivers. The utilization of stitching technology to increase the detection of obscured objects was observed through combining insights of surrounding Autonomous Driving Systems (ADS)

[37]. The average detection rate of the proposed system increased by 45.4% relative to the single ADS [37], promoting higher safety and efficiency. Furthermore, considering a coordination system, where AVs and CAVs are linked to a computer framework based on cloud, can reduce fuel consumption and travel time, in addition to great enhancements in average velocity [38]. The high penetration rate of level 2 automation CAVs also tends to reduce energy usage per vehicle [39]. As observed, researchers examine benefits of AVs beyond those affecting traffic flow, such as fuel or energy consumption. It is critical that the integration of AVs is studied thoroughly as it may cause revolutionary changes. Through schemes like Action Governor (AG), which is a control system that improves system performance, AVs can be integrated in traffic systems in a safer manner [40]. Table 1 provides a summary of the empirical studies' advantages and disadvantages.

Table 1. Review of the advantages & disadvantages of empirical studies on AV integration

Ref.	Group/Theme	Main Focus	Advantages	Disadvantages
[31]	Empirical Studies on AVs Integration	Eco-driving techniques	Eco-driving techniques increase total efficiency by optimizing travel time and energy usage.	Current eco-driving models lack accurate models for electric vehicles and are mostly geared at internal combustion engine vehicles.
[32]	Empirical Studies on AVs Integration	Co-Optimization of Speed & Gear	Co-optimization of gear positions and speed improves driving efficiency in mixed traffic while using less energy.	Co-optimization might not work well for every kind of car or under every driving circumstance.
[33]	Empirical Studies on AVs Integration	Eco-Driving Framework	By using SPaT data, energy-efficient speed profiles can be found, assisting cars in avoiding stop-and-go situations and using less energy.	Current eco-driving models lack accurate models for electric vehicles and are mostly geared at internal combustion engine vehicles.
[35]	Empirical Studies on AVs Integration	Hierarchical Program-triggered RL (HPRL)	Enhances transparency by introducing a more interpretable and verifiable method (Hierarchical Program-triggered RL, or HPRL) that uses a master program with basic RL agents.	The method's efficacy is still predicated on the idea that each RL agent is capable of performing a simple task.
[36]	Empirical Studies on AVs Integration	Edge Computing for AVs	Heavy duties can be offloaded to neighboring edge servers to improve performance and save costs without requiring	Dependent on edge servers' performance and availability, which could cause variations in service quality.

			each AV to have powerful hardware.	
[37]	Empirical Studies on AVs Integration	Collaborative Perception System	By merging information from nearby autonomous driving systems (ADSs), it increases detection range and enhances situational awareness.	It depends on the cooperation of several ADSs, which isn't always possible in every situation or area.
[38]	Empirical Studies on AVs Integration	Cyber-Physical Framework for CAVs	CAVs on multilane freeways are coordinated using a cloud-based framework that optimizes their trajectories for safe and efficient operation.	Depends largely on cloud infrastructure, which could cause communication problems and delay in situations with high traffic density.
[40]	Empirical Studies on AVs Integration	Action Governor (AG)	In order to improve performance and safety in mixed-autonomy traffic, a supervisory scheme is introduced to supplement nominal control systems.	The AG approach's efficacy is still largely dependent on how well the simulator replicates actual traffic.

<u>Simulation tools and platforms for studying Autonomous Vehicles impact on traffic flow.</u> The possible effects of AVs on travel time and safety are better understood through simulation research. Stakeholders can predict how traffic signals, pedestrians, and other elements like energy use and environmental concerns will interact by modeling different scenarios. Numerous studies provide thorough illustrations of how AVs affect various user groups. According to the simulation results, AVs affect three different groups of people: part-time workers, senior retirees, and long-distance drivers with high incomes. The study's strength is demonstrated by the comprehensive analysis it offers on how AVs impact these various demographic groups. A significant drawback is that the results might not apply to all populations, making sure the advantages last is the difficult part [41]. Extensive insights into the behavior and implications of AVs are provided by simulation studies. For example, microsimulation is used to simulate the behavior of individual vehicles. Its strength is that it offers in-depth insights into certain vehicle behaviors. Its breadth is constrained, and it misses network-wide impacts, which is a limitation. One of the biggest challenges is making sure that real-world circumstances are accurately represented. In contrast, a much larger road network is simulated by macroscopic simulation. Its ability to capture more extensive traffic patterns and network impacts demonstrates its potency. Its inability to provide specifics on the behavior of individual vehicles is a limitation. It is still difficult to strike a balance between scope and detail for precise forecasts. Agent-based simulation examines how drivers behave in conjunction with pedestrians. Its merit is that it offers a thorough understanding of the interactions between different agents. Its computational complexity and intensity, however, is a drawback. It's difficult to incorporate a variety of behaviors into a coherent paradigm. Simulations often yield good results for AVs, with shorter trip times because of better vehicle performance and faster average speeds. As AVs are expected to closely comply with safety requirements, collision rates decline. Because of their optimal driving practices, AVs also result in reduced energy consumption and carbon emissions. Use of parking spaces is the subject of another important study [42]. As per the study's conclusion, there could be a 50% increase in

journey time for autonomous vehicles; however, it is possible to reuse 15% to 32% of the parking area. This reinforces the study's strength by highlighting an important secondary benefit of AVs in urban planning. A drawback is that the conclusion of longer journey times is at odds with the majority of other investigations. This is an issue of optimizing urban space, while maintaining commute time efficiency. A different research study provides evidence that AVs can greatly increase intersection efficiency [43]. The study demonstrates the potential to enhance time-to-collision results and traffic efficiency at crossings by over 18%. This highlights the study's strength and shows a definite effect in high-traffic regions. A drawback is that these upgrades can necessitate considerable infrastructural modifications. The implementation of these improvements in pre-existing urban areas is a problem. A human-like speed planning technique is suggested to reduce travel time on predetermined routes [44]. This highlights the strength of the study and improves travel time efficiency by imitating human driving behaviors. Its downside is that it depends on predetermined routes, which reduces flexibility. Integrating this approach with dynamic real-world traffic conditions is a challenging task. The effective deployment of AVs depends on safety regulations and procedures. A framework to handle problems with mixed traffic situations and human-machine interaction is proposed [45]. The study examines the shortcomings and difficulties in creating shared safety standards for autonomous vehicles. This highlights the study's strength and provides a thorough approach to safety standards. A flaw in the framework would be that it requires a lot of validation and modification. Reaching a worldwide agreement on safety regulations is still quite difficult. Furthermore, it is anticipated that as AVs usage increases, fewer parking spots will be required, freeing up space in cities for other purposes. The assumptions entered into the simulator, such as technical details and interactions, form the basis of the simulation results. In order to ensure accuracy, simulation results must be validated using real world data. For AVs to be widely used, it is imperative that laws, rules, and technical standards are continuously improved. Stakeholder cooperation can result in the creation of thorough regulatory frameworks that address these problems and encourage the safe and effective use of AVs. Realizing the full potential of AVs also requires developing a global database and encouraging public adoption. Another crucial aspect is how AVs and pedestrians interact. The necessity of AVs having knowledge of pedestrian crossing behavior is considered in some studies [46], particularly in situations when a vehicle's camera may be obscured. This study shows the benefits of edge computing and real-time data processing in enhancing AVs safety. But in places with poor connectivity, the dependence on cutting-edge computing infrastructure presents a problem. In order to improve data transmission and processing speed, future research may investigate merging edge computing with technologies such as 5G networks. Zhang et al. [47] also examined the coordination between AVs and pedestrians. The project focuses on enhancing pedestrian and CAVs cooperation to increase traffic efficiency and safety at industrial sites. The findings may not be applicable everywhere, especially in urban and suburban settings, but their strength rests in addressing safety in complicated environments. Adapting these techniques to various contexts is a difficulty. Simulation analysis aids in forecasting and comprehending the effects of implementing autonomous vehicles in diverse contexts. These insights aid in achieving optimal traffic flow and safety, which in turn lead to suggestions for essential actions by stakeholders and policymakers. The stage can be set for a time in the future, when AVs are integral to the development of safer, more effective, and environmentally friendly transportation systems, by tackling the related difficulties and concentrating on ongoing advancements.

Impact of Autonomous Vehicles on network performance

It is crucial to assess how AVs influence traffic flow and congestion levels before integrating them within transportation networks, especially during the transition period, where AVs have to interact with human driven vehicles. Furthermore, the operation of AVs within existing systems alters a multitude of factors some of which are vehicle behavior, traffic patterns, and infrastructure requirements; these factors can notably affect network performance. These challenges can be addressed by researchers studying the impact of AVs on network performance, where they can devise strategies to optimize the integration of AVs into existing transportation systems. These strategies will ultimately pave the way towards safer, more sustainable, and more efficient transportation solutions.

Impact on traffic flow stability and smoothness. The effectiveness of integrating AVs has been assessed in accordance with the penetration rate of AVs. Variable factors were considered, including but not limited to travel and delay times, road capacity, and traffic speed. AVs can have great impacts on traffic flow if integrated in the right manner, as it enhances overall traffic behavior and increases safety near bus bays [48]. For urban networks, an average reduction of 31% in delay time and 17% in travel time was reported for increased AV penetration rates [49]. A penetration rate surpassing 40% has been noted crucial for a prominent network enhancement [50], [51]. However, for wider road segments, specifically those compromising three or four lanes, an AV penetration rate exceeding 30% exhibited notable traffic flow improvements. This indicates that wider roads derived greater benefits from the integration of AVs, as evident by the clearer impact on the mitigation of average delay time experienced on those road segments [49]. Besides wide roads, congested roads also experience substantial benefits from the presence of AVs [52], where travel time exhibits a reduction of 7.1% [53]. Travel time also reduces by 59%, when CAV are controlled at intersections by a system of CAVSMulti-Agent Deep Reinforcement Learning (MADRL) alongside an advanced Reinforced Autonomous Management system (adv.RAIM) [54]. The Optimal Routing and Signal Timing (ORST), which is a CAV control strategy, reduces travel time by 49% [55]. Travel time tends to reduce in the presence of AVs in high penetration rates [56] and even at low penetration rates it exhibits a reduction by 20% and 4% [57]. It also undergoes notable reduction when a hierarchal control model called COOR-PLT is utilized [58]. Different AV scenarios with variable levels of penetration and automation rates exhibit substantial disparities in delay time mitigation, ranging from 3.50% for basic automation and low AV penetration to 28.53% for a full automation [59]. Through research, it has been proven that AVs have the ability to significantly reduce Time Headway (THW) and increase traffic capacity; thus, alleviating traffic congestion [60]. Congestion can also be reduced through a framework that utilizes collision-avoidance approach called the multi-agent reinforcement learning [61]. Congestion can be mitigated through the use of Roadside Units (RSU) [62], or even entirely eliminated at high AV penetration rates [63]. At the autobahn segment, a 100% AV penetration rate improved the average density significantly by 8.09% during peak hours [64]. In addition, there was an improvement in the average travel speed by 8.48% improvement on autobahn and 7.86% improvement on weaving segments in the same scenario; as a consequence, the average travel time improved by 9% when compared to the scenario without AVs [65]. Furthermore, the network performance of Daejeon City showed that when AVs operate conservatively, passenger's safety and comfort are promoted; however, these conservative driving behaviors result in trade-offs, as evidenced by a decrease in road capacity of approximately 35%, when AVs comprised 100% of its road vehicle mix [66]. However, road capacity increases by 35% to 59% as per [67], when the AV penetration rate ranges between 25% to 35%. The AV simulation results are summarized in Table 2.

Table 2. Review of the advantages & disadvantages of AV simulation results on traffic flow

Ref.	**Group/Theme**	**Main Focus**	**Advantages**	**Disadvantages**
[49]	AVs Simulation Results on Traffic Flow	Delay time	A noticeable 31% decrease in network delay, particularly on	There is variation in delay reduction among all links. A delay increase is observed with certain links.

			multi-lane and left-turn links.	
[49]	AVs Simulation Results on Traffic Flow	Travel Time	With higher AV penetration, average travel time is significantly reduced (17%).	Does not account for the consequences of higher traffic demand.
[53]	AVs Simulation Results on Traffic Flow	Travel Time	Reduces travel times by up to 7.1% in high-density, fully autonomous traffic. Evaluates several traffic distributions on different routes.	Overlapping confidence intervals in the results reduce statistical significance in certain situations.
[54]	AVs Simulation Results on Traffic Flow	Travel Time	Significant improvement is demonstrated with AIM at low and medium flow rates (up to 59% less travel time and 95% less time loss). Showcases the enhanced flexibility of adv.RAIM in dynamic traffic situations.	AIM functions similarly to conventional traffic lights at high traffic volumes which reduces its unique advantage.
[55]	AVs Simulation Results on Traffic Flow	Travel Time	Utilizing CAV data can result in a significant reduction in travel time of up to 49% compared to Stochastic User Equilibrium and 10% compared to User Equilibrium.	The scalability of results to large cities networks may be limited due to their sensitivity to network size and structure.
[57]	AVs Simulation Results on Traffic Flow		Reduces travel time on main lanes (by 20%) and on merging lanes, especially at higher MPRs.	Benefits of merging lanes are lower with low Market Penetration Rate (MPR) (around 4%),
[59]	AVs Simulation Results on Traffic Flow	Delay Time	Delays are significantly reduced by 28.52% with fully automated fleets.	Congestion spillover effects and other dynamic traffic behaviors are not fully taken into consideration.
[60]	AVs Simulation Results on Traffic Flow	Time Headway/ Congestion	It highlights the effect of time headway on traffic flow. Because cars can move closer together when CAVs have shorter headway times, traffic flow is	Does not examine every AV/CAV parameter, such as sensor performance or vehicle acceleration.

			improved and overall traffic efficiency is increased.	
[61]	AVs Simulation Results on Traffic Flow	Congestion	Effectively reduces traffic congestion in bottleneck areas.	Reliant on the simulation environment; it might not accurately reflect the intricacies of the real world.
[62]	AVs Simulation Results on Traffic Flow	Congestion	Uses Roadside Units (RSUs) to reduce traffic congestion, particularly in critical areas like traffic circles.	Assumes vehicle connectivity, which isn't always the case in real life, particularly when it comes to older cars.
[64]	AVs Simulation Results on Traffic Flow	Density	Notable enhancements in traffic flow during peak hours. A density improvement of 8.09% at the p.m. peak.	The results are limited in their potential to be applied to other traffic periods because they are based on particular peak hours (7:15–8:15, 16:15–17:45).
[64]	AVs Simulation Results on Traffic Flow	Travel Speed	Significant improvements in average travel speed are noted (8.48% improvement on autobahn, 7.86% improvement on weaving segments).	The assessment does not consider the long-term impact of the increased speeds on overall safety or congestion reduction.
[67]	AVs Simulation Results on Traffic Flow	Travel Time	It shows that AV penetration can improve vehicle travel times by increasing urban networks' capacity by 35% to 59%.	The study lacks an investigation of signal controls and their effects, and it does not completely take user choices in movement or mode into consideration.

<u>Impact on human and vehicle's behavior.</u> Despite the fact that AVs contribute greatly to improving traffic factors, they give rise to certain concerns; such as potential loss of situational awareness, over dependence on automation, and system failure. This indicates the significant distinction in the behavior of drivers, when driving and trailing a human-driven vehicle versus an AV. This alteration in driver behavior is shown in a decrease in both the mean and variance of THW observed, when human drivers follow an AV [68]. When driving near AVs with short THW, human drivers tend to reduce their own THW and spend more time below their critical THW. Not only that, but driving alongside highly automated vehicles can also diminish the human driver's situational awareness and may increase the risk of drowsiness, especially in cases of light traffic [65]. Nevertheless, it is important to note that in most cases AVs tend to stay at an adequate distance from other vehicles and road users [69]. A study carried out by Kanazawa University [70], which focused on the behavioral algorithm of AVs, demonstrates that with an increase of 10% to 45% in the proportion of AVs within the traffic mix, there is an escalation in the delay observed between Origin-Destination (OD) intervals. Nevertheless, as the penetration rate increases from 45% to 50%, the delay gradually diminishes. Furthermore, with the proportion of AVs ranging from 50% to 100%, the delay remains

consistent. These analytical findings highlight the influence of integrating autonomous vehicles on vehicle's behavior and provides insight on the importance of identifying suitable distribution scenarios, and implementation areas within societal frameworks [70]. The impact of AVs on varying age groups was assessed through simulation; three work types were considered: drivers who travel long distances and gain high income, elderly drivers that are retired, and drivers who are part timers [71]. Results revealed that AV penetration impacts each group differently depending on the demand of AVs on the road system and Value of Travel Time (VOT) [72]. It is also important to note the preferred AV transportation modes since it affects human behavior and comfort. In another study [73], travelers tend to incline more towards individual-ride AVs and less towards shared AVs. Moreover, in the case of AVs being utilized as a transportation mode, 64% of the drivers are going to utilize AVs whereas only 15% will use public transportation modes [71]. It is noteworthy to mention that travel patterns and congestion levels are affected by the human's in-vehicle activities [74].

Impact on safety. Achieving the required safety levels for AVs involves eliminating human errors, which are the primary cause of accidents. Deep learning algorithms train AVs to avoid such errors by adhering to safety regulations like maximum allowed speed and safe distance. However, technology does not come free of risk. Expected risks include software malfunctions, sensor quality issues, and the critical risk of AVs being unable to predict the behavior of human-driven vehicles. These risks are integral to the broader challenge of capability integration. Fortunately, new risk management strategies are emerging to enhance and mitigate potential risks. These strategies include redundancy for critical systems (e.g., steering and braking systems) to ensure safety in case of a component failure. Advanced algorithms can analyze risks in real-time and provide suitable and safe solutions. Additionally, Vehicle-to-everything communication system (V2X) technology provides real-time information, enabling AVs to interact with risks as they occur. One effective strategy is to simulate expected risky scenarios, allowing AVs to be trained in advance before real-life deployment [75]. The outspread implementation of AVs holds the promise of reducing traffic crashes and enhancing road safety. Safety is further enhanced by pedestrian detection which is accounted for with the use of accurate positioning systems with sensors [76]. AVs contribute remarkably in enhancing safety, particularly at high penetration rates [77], as they operate with shorter headways in order to optimize road capacity and mitigate delays. At signalized intersections, AVs lead to a noteworthy reduction in conflicts ranging from 20% to 65% with AV penetration rates between 50% and 100%. Similarly, at roundabouts, conflicts are decreased by 29% to 64% with a 100% AV penetration rate [78]. These percentages are demonstrated in Figure 2. This is also evident in the findings of another study, which focuses on a specific freeway crash hotspot in Wuhan, China. Results reveal that at penetration rates below 50%, no significant improvement in safety measures is exhibited such as conflicts, acceleration, and velocity difference. However, as penetration rates exceed 70%, traffic flow at the freeway hotspot demonstrates fewer conflicts, reduced acceleration, and decreased velocity difference, particularly when CAVs are confined to their lanes [79].

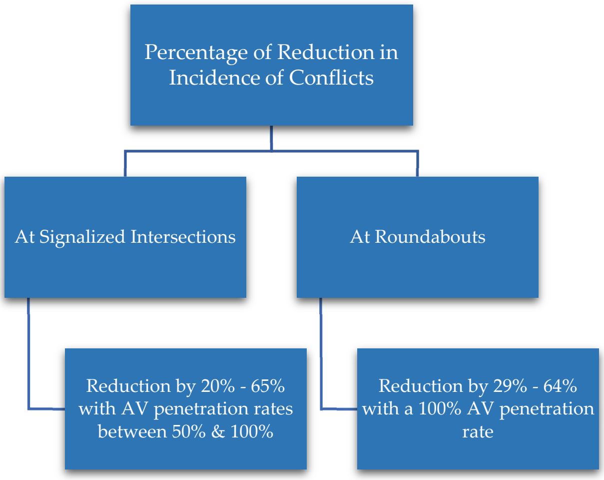

Figure 2. Percentage of Reduction in Incidence of Conflicts [80]

Despite its wide uses and great benefits, the safe implementation of AVs is critical in promoting efficient utilization. Nevertheless, road accidents are inevitable and have to be thoroughly considered and assessed. One study concluded that when Time To Collision indicator (TTC) is less than 4s, AVs are more likely to collide with other vehicles [80]. However, when compared to human driven vehicles, the rate of crashes and fatalities was decreased when AVs were utilized [81]. According to Parseh and Asplund [82], accident analysis is crucial to propose decision-making strategies that are useful in studying the implications of these collisions. Three decision making strategies have been proposed, including: advanced Safety Surrogate Measures (SSM) [82], [83], where severity levels are examined; unconsidered heterogeneity that results from collision restructuring must be included; collision configurations are to be recorded for feedback and study [82]. Risk analysis was also studied, where an advanced Network-Level Safety Metrics (NSM) set is proposed to evaluate the safety of traffic flow. It was observed that the use of NSM regulates the probability of collisions [84]. Safety can also be promoted through Model Predictive Control (MPC) planner that creates route tracking, collision-free movements [85], and simulates car-following behavior [86]. A Soft Actor-Critic (SAC)-based driving policy was proposed [87], which predicts intervals and yields safer vehicle driving evident by the collision reduction of 15%. Not only does MPC planner improve safety, but it also enhances driver's comfort through reducing acceleration [85]. Comfort is also promoted through Deep Deterministic Policy Gradient with External Knowledge (EK-DDPG), which is a suspension control strategy [58]. A significant regulatory challenge is the lack of unified testing protocols for AVs, alongside data security and privacy issues. The absence of standardized protocols means AVs cannot operate seamlessly across different countries due to varying standards. Infrastructure policies also need to be updated [88]; all road-building manuals must be reviewed and updated to include the required infrastructure for smooth autonomous operations. Decision-makers and stakeholders must work collaboratively to produce effective regulatory frameworks to address these challenges [89]. This includes defining liability, insurance, infrastructure requirements, information security, and privacy protocols to ensure the safe deployment of AVs across different regions. By addressing these issues, the way can be paved for the successful integration of AVs into the current transportation systems. The literature includes various studies that address the gaps and challenges in establishing safety standards for AVs. One study [59], investigates the primary gaps and challenges in creating shared safety standards for AVs. It proposes a comprehensive framework to facilitate future research on safety issues related to mixed traffic environments, interactions between AVs and pedestrians or cyclists, and the transition of control from machine to human drivers. This framework provides a structured approach to address these safety challenges, highlighting its strength in offering a thorough overview of current issues. However, the proposed framework may require extensive validation and adaptation to different regulatory environments. Future research could focus on developing specific protocols and guidelines for mixed traffic scenarios and improving human-machine interaction during control transitions. Another study [90], discusses the importance of providing AVs with information about pedestrian crossing behavior, particularly when a vehicle's camera may be obstructed. The study emphasizes the role of edge computing in enhancing safety-related reactions. The strength of the research lies in its emphasis on real-time data processing and the potential of edge computing to improve AV safety. However, reliance on edge computing infrastructure may pose challenges in areas with limited connectivity. Future work could explore the integration of edge computing with other technologies, such as 5G networks, to improve data transmission and processing speed, thereby enhancing the overall safety and reliability of AV systems. Addressing safety concerns for AVs requires not only eliminating human errors but also implementing robust risk management strategies and developing unified standards and protocols worldwide. Public acceptance is also crucial, as it influences the successful deployment of AVs. By focusing on these areas, the safety and reliability of AV technology can be enhanced, paving the way for its widespread adoption. The main advantages and disadvantages of the AV simulation results related to traffic safety are presented in Table 3.

Table 3. Review of the advantages & disadvantages of AV simulation results on safety

Ref.	**Group/Theme**	**Main Focus**	**Advantages**	**Disadvantages**
[76]	AVs Integration Impact on Safety	Safety	AVs exhibit improvements like decreased crashes, less traffic, and improved passenger safety.	Safety concerns could arise if interactions with non-autonomous road users are not completely taken into consideration.
[76]	AVs Integration Impact on Safety	Safety	Using sensors in conjunction with precise positioning technologies reduces uncertainty and enhances pedestrian detection.	AVs may mistake pedestrians for other objects in low-visibility situations, which might result in accidents if pedestrian detection is inconsistent.
[77]	AVs Integration Impact on Safety	Safety	Conflicts in traffic are greatly decreased with AVs. Conflict reduction (20%–65% at signalized crossings, 29%–64% at roundabouts) is a metric used to quantify safety improvements.	Restricted to particular case studies (roundabouts and signalized intersections). Might not fully represent the complexity of the real world.
[79]	AVs Integration Impact on Safety	Safety	Traffic flow significantly improves with fewer collisions, less acceleration, and smaller velocity differences when the	No noticeable improvements in safety parameters such as collisions, acceleration, and velocity differential

			CAV PR surpasses 70%.	are seen when the CAV PR is less than 50%.
[79]	AVs Integration Impact on Safety	Safety	Compared to unmanaged lanes, CAVs in managed lanes exhibit fewer collisions and improved overall traffic safety.	Lane management's effect is contingent upon the rate at which CAVs are deployed; at lower penetration rates (less than 50%), it might not result in appreciable safety gains.
[87]	AVs Integration Impact on Safety	Safety	Using an interval prediction model in conjunction with the IP-SAC approach resulted in a 15% improvement in collision rate.	It is restricted to simulated settings and does not integrate with real-world sensor methods.

Autonomous Vehicles moving on dedicated lanes

Despite the promising future AVs hold, their impact is restricted to their respective penetration rates implemented [91]. This is particularly true at the initial stages of market penetration. To counteract this, dedicated AV lanes have been considered in order to optimize their efficiency and maximize their benefits [78]. Various potential effects of reserving lanes to AVs have been assessed through different scenarios discussed in this section.

<u>Impact of exclusive Autonomous Vehicles' lanes on traffic flow.</u> Detailed analysis revealed that permitting AVs optional access to dedicated lanes exhibited improvements in capacity that yields reduced congestion and diminished variance in fundamental traffic characteristics [92], [93]. Moreover, AV-exclusive lanes allow an increase in AV speeds of over 15 km/h [93]. The efficacy of reserved AV lanes is dependent on the MPR and characteristics of the roadway [94]. Moreover, AV reserved lanes exhibited an advantageous potential at penetration rates surpassing 50% for two-lane highways and 30% for four-lane highways [95]. However, another study evaluated the effects relative to penetration rates and it was noted that AV dedicated lanes should be introduced at 20% to 30% penetration rates in order to optimize road capacity [96]. Moreover, a more sensitive capacity increase effect was observed for lower MPR [94]. The study of models demonstrated that dedicated lanes may not yield significant advantages at low CAV penetration rates [97]; nevertheless, their introduction at higher CAV MPRs, led to a notable reduction of 53% to 58% in traffic conflicts, and an increase in lane capacity [98]. The use of CAV lanes by human driven vehicles, when the presence of CAVs on these lanes is low, enhances travel time and speed [95]. Additionally, traffic crashes that were estimated from traffic conflicts decreased with the presence of CAVs, by up to 48% [98], [99]. Through simulation, it was observed that optimal safety benefits for CAVs in dedicated lanes result from an MPR combination of 40% human-driven, 40% 1st generation AVs, and 20% 2nd generation AVs. These findings could serve as a foundation for developing regulatory frameworks for local authorities and practitioners; in addition to the crucial insights provided into the safety implications of dedicated lanes for CAVs [98]. Initially, especially at low MPRs, turning a regular lane into a dedicated lane for CAVs may negatively impact total traffic flow. This detrimental effect usually lasts until about 50% of people adopt CAV. However, the most noticeable improvement in network speed occurs when the dedicated lane is implemented as part of an obligatory usage policy, particularly when the MPR is between 50% and 60%. The advantages of this approach tend to decrease as CAVs drive more aggressively, but they are further enhanced in situations with heavy traffic demand.

Furthermore, the driving mode and the degree of CAV penetration have a significant impact on how well dedicated lane deployment works. When CAVs are driven in safe or conservative modes and the MPR stays below 80%, the mandatory-use policy continuously performs better than the optional-use strategy. The optional-use approach becomes increasingly beneficial beyond this point. This transition point moves to a 90% MPR when driving in a neutral manner. Notably, the mandatory-use strategy continues to produce better results at all CAV adoption levels, even in situations where CAVs display aggressive driving behavior [100].

Impact of AV exclusive lanes on safety and human behavior. A narrow (9 ft) lane designated for AVs influences driver behavior was assessed for safety, focusing on drivers in the adjacent lane to the right. With the use of a tailored driving simulator that replicates conditions of the Interstate 15 smart corridor in San Diego, participants were divided into two groups: one group drove next to a simulated 9 ft narrow AV lane, while the control group drove next to a standard 12 ft AV lane. The findings exhibited no significant differences in speed among drivers, but notable distinctions in lane positioning. It was observed that drivers adjacent to the 12 ft lane exhibited better lane centering compared to those next to the 9 ft lane. Furthermore, analysis suggested that female drivers tend to maintain greater distance from the 9 ft lane and showed poorer lane centering performance, yet outperformed male drivers when traffic was present in the right lane [101]. Table 4 presents the summary of the reviewed studies in this section.

Table 4. Review of the advantages & disadvantages of AV exclusive lanes on traffic flow

Ref.	Group/Theme	Main Focus	Advantages	Disadvantages
[92]	AVs' exclusive lanes	Managed Lane Concepts	Free access for AVs and toll access for HVs are provided by AVT Lanes which enhance road efficiency and encourage the use of AVs.	In some areas, the cost of installing dedicated AV and AVT lanes, along with the necessary infrastructure for communication and tolling, may be unaffordable.
[93]	AVs' exclusive lanes	Traffic Efficiency with AV-Only Lane	When an AV-only lane is implemented, AVs can travel at speeds of more than 15 km/h faster than mixed traffic.	Due to decreased lane capacity, the remaining lanes for manual vehicles experience congestion as AV-only lanes are implemented.
[95]	AVs' exclusive lanes	Traffic Capacity Improvement	At higher CAV penetration rates (50 percent for two-lane highways and 30 percent for four-lane highways), dedicated CAV lanes can	Dedicated CAV lanes can waste road resources and exacerbate traffic situations when CAV penetration is low.

			greatly increase traffic throughput.	
[98]	AVs' exclusive lanes	Traffic Conflicts & Crashes	Dedicated CAV lanes reduce traffic conflicts by 53–58% and crashes by up to 48% at high CAV MPRs.	Dedicated lanes may not improve safety at low penetration rates and may even decrease system performance.
[100]	AVs' exclusive lanes	Mandatory & Optional Dedicated Lane Use Policies	At 50–60% MPR, mandatory-use policies work better and improves traffic flow when driving in a safe or conservative manner.	In the safe/conservative mode, the optional-use policy becomes more advantageous when the MPR above 80%.

CONCLUSIONS

The integration of AVs into existing transportation systems promises revolutionary changes in many aspects including traffic flow. Its implementation, however, must be rigorously examined to avoid concerns like safety and regulatory frameworks. Through many studies, it was proven that the introduction of AVs with certain penetration rates substantially enhances traffic efficiency, travel routes, fuel consumption, and causes reductions in operational expenses. In this paper, numerous studies are examined regarding the impact of AVs on transportation networks in terms of flow, human and vehicle behavior, and safety. Not only that, but it also covers empirical studies on AV integration. These studies are summarized and discussed throughout this paper in an attempt to determine the advantages and limitations. The main findings of this paper can be summarized as follows:

- With societies inclining towards automated transportation systems, empirical studies on AVs integration are becoming increasingly pivotal as they provide real-life implications of AV integration, where various topics are tackled, including but not limited to safety, societal acceptance, regulatory frameworks, and traffic efficiency.
- Understanding and predicting the impacts of AV integration is made easier with the utilization of simulation analysis. The observations made through simulation help achieve optimal traffic flow and safety and set the basis for necessary regulations.
- The introduction of AVs into existing transportation systems at certain penetration rates can improve road capacity, reduce travel time, and mitigate congestion.
- The presence of AVs on current transportation networks at certain penetration rates may affect human drivers negatively, as it may weaken the human driver's situational awareness. However, AVs keep satisfactory distances from other vehicles; thus, the negative impacts can be owed to the acceptance and familiarization of the pubic with the AV technology.
- Dedicating lanes exclusively for AVs can result in great benefits, especially at high penetration rates. Travel time, congestion, and safety are usually enhanced with the use of exclusive AV lanes.

RECOMMENDATIONS AND FUTURE RESEARCH DIRECTION

Research gaps were analyzed through examining limitations of previous studies and based on that this section provides recommendations that aim to assess the use of AV technology in the existing transportation systems.

Recommendations

AV implementation requires careful studying of various factors. The studies examined in this paper provide numerous advantages and drawbacks of AV integration at different penetration rates and certain scenarios. The following points summarize research gaps observed along with the recommendation based on it:

- The majority of the previous research focused on studying the impact of AVs on either intersections or freeway systems, which is not the case in real life. Thus, it is recommended that a thorough study that considers traffic networks that represent real-life network structures is carried to provide more realistic measures of the AVs impact.
- The focus on the use of technology in transportation infrastructure like ORST is minimal. Accordingly, more efforts should go towards studying the environment or more specifically the transportation infrastructure, where AVs are to be implemented, this way optimal use of technology will be guaranteed.
- Numerous papers study the effect of AVs on human behavior; nevertheless, few discuss strategies to mitigate the negative effects such as increased drowsiness and delay. Therefore, it is recommended that more effort should be directed to develop approaches to alleviate the negative impacts of using.
- Exclusive AV lanes can significantly improve traffic flow and smoothness; however, the examined studies suggest that for such lanes to be used optimally, AVs have to be introduced at relatively high penetration rates. The issue here is that restricting lanes to AVs might lead to potential congestion in other lanes and raise concerns about equitable road usage. Few papers discussed this issue [95]. Thus, it is essential to consider the smooth integration of AV technology with existing infrastructure.

Research Direction

Taking into account the research gaps and recommendations discussed in previous sections, the following future research directions are suggested:

- A comprehensive study should consider both intersections and freeway systems. This ensures simulation results closer to real-life systems; thus, promoting safety and the various traffic factors.
- The implementation of advanced technology in developing more robust communication systems between the AV and its surrounding (other vehicles, infrastructure, or other transportation network elements).
- The utilization of technology in optimizing the use of AV exclusive lanes, such that concerns regarding neighbouring-lane's congestion and travel delay are diminished.
- Human-focused research that studies ways to mitigate the effects and best integrate AVs into existing transportation networks.

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NOMENCLATURE

Abbreviations

AVs	Autonomous Vehicles
SAE	Society of Automotive Engineers
NHTSA	National Highway Traffic Safety Administration
CO_2	Carbon Dioxide
NO_x	Nitrogen Oxides
V2V	Vehicle-to-Vehicle communication systems
V2I	Vehicle-to-Infrastructure communication systems
RL	Reinforcement Learning
HPRL	Hierarchical Program-triggered Reinforcement Learning
ADS	Autonomous Driving Systems
CAVs	Connected Autonomous Vehicles
AG	Action Governor
MADRL	CAVSMulti-Agent Deep Reinforcement Learning
adv.RAIM	advanced Reinforced Autonomous Management system
ORST	Optimal Routing and Signal Timing
THW	Time Headway
RSU	Roadside Units
OD	Origin-Destination
VOT	Value of Travel Time
V2X	Vehicle-to-everything communication systemsV2X
TTC	time to collision indicator
SSM	Safety Surrogate Measures
NSM	Network-Level Safety Metrics
MPC	Model Predictive Control

SAC	Soft Actor-Critic
EK-DDPG	Deep Deterministic Policy Gradient with External Knowledge
MPR	Market Penetration Rate

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