

Review

Sustainable Integration of Autonomous Vehicles into Road Networks: Ecological and Passenger Comfort Considerations

Seyed Mohsen Hosseinian ¹, Hamid Mirzahosseini ^{1,*} and Robert Guzik ²

¹ Department of Civil-Transportation Planning, Faculty of Technical and Engineering, Imam Khomeini International University (IKIU), Qazvin 34148-96818, Iran; s.m.hosseinian@edu.ikiu.ac.ir

² Institute of Geography and Spatial Management, Jagiellonian University, 31-007 Kraków, Poland; robert.guzik@uj.edu.pl

* Correspondence: mirzahosseini@eng.ikiu.ac.ir

Abstract: Autonomous vehicle (AV) technology is rapidly advancing, leading to a sustainable evolution in transportation. AVs offer the promise of enhanced safety, reduced emissions, improved traffic flow, and increased mobility for passengers. However, the integration of AVs into existing traffic networks presents complex challenges related to ecological sustainability and passenger comfort. This review aims to bridge the gap in the literature by providing a comprehensive evaluation of the influence of AVs on both ecology and passenger comfort within traffic networks. The study synthesizes existing knowledge on AV technology, ecological impacts, and passenger comfort to offer a comprehensive understanding of the challenges and opportunities associated with AVs' integration. The main objectives of this research are to review the current literature on the environmental impact of AVs, analyze studies on passenger comfort in AVs, identify key challenges and opportunities, and propose future research directions. The results highlight the need for a holistic, sustainable approach that considers both ecological and passenger-centric factors in the design and deployment of AVs. Future research directions are proposed to further our understanding of the complex interplay between AVs, the environment, and passenger well-being, and inform policy decisions and technological advancements that promote sustainable and comfortable transportation solutions.

Keywords: autonomous vehicles; sustainable transportation; road networks; ecological impact; passenger comfort



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1. Introduction

1.1. Advent of Autonomous Vehicles

The advent of control theory and its application in real-time scenarios has catalyzed sustainable transformations across various automated systems. Roadway vehicles serve as a prime example of such systems. In the past few years, computers have become essential elements within vehicles, making a range of functions automatic and steering the industry towards sustainable automation. Significant research is being invested in to further advance this technology [1,2]. The overarching aim of this movement is the full automation of vehicles. The driving forces behind this initiative are the anticipated sustainable benefits in terms of safety, environmental impact, and passenger comfort that autonomous vehicles (AVs) are expected to bring [3].

In the past few years, the emergence of AVs has marked a sustainable and feasible shift in transportation [3]. It is becoming increasingly likely that autonomous driving will become central to urban transport in the years to come [4]. AVs are poised to enhance passenger safety and make journeys quicker, more pleasant, and more sustainable. In pursuit of these objectives, numerous automobile manufacturers are channeling investments into the development and integration of sophisticated driver-assistance systems in their vehicles, in alignment with sustainable transportation goals. The latest progress in intelligent transportation systems (ITSs) points to a future where our roads will be progressively populated

by AVs capable of self-navigation, as well as communication with one another and with transportation infrastructure [5,6], contributing to a sustainable mobility ecosystem.

The surge in AV research activity, which began with the inaugural AV competition in 2005, has been remarkable. The Defense Advanced Research Projects Agency (DARPA) Grand Challenge marked the start of this journey. By 2007, the DARPA Urban Challenge demonstrated significant advancements in AV technology, with multiple teams successfully creating vehicles capable of self-navigation and task completion [7]. Consequently, a multitude of research groups from universities and, more recently, private companies have successfully developed self-driving cars or AVs [8]. Over the past several years, corporations like Google, Nissan, Tesla, and various university research centers have delved into the capabilities of automated driving systems. Their efforts have validated the functionality of these systems in real-world traffic conditions, showcasing their safety and operational viability. This progress indicates that widespread use of this technology is on the horizon. Presently, certain cities in the USA have legally sanctioned the operation of AVs on public roads alongside traditional vehicles [9]. It is believed that the collaborative coordination between vehicles and infrastructure through vehicular ad hoc networks (VANETs) will enhance traffic optimization [10], leading to gains in environmental sustainability and passenger comfort.

As delineated by SAE Recommended Practice J3016, which categorizes on-road motor vehicles into six distinct levels of automation, vehicles classified within Levels 3 to 5 are equipped with automated driving features [11]. This progression begins with driving assistance systems and culminates in vehicles capable of full autonomy. As depicted in Figure 1, the spectrum of automation spans from vehicles devoid of any automated features to those that operate entirely independently.

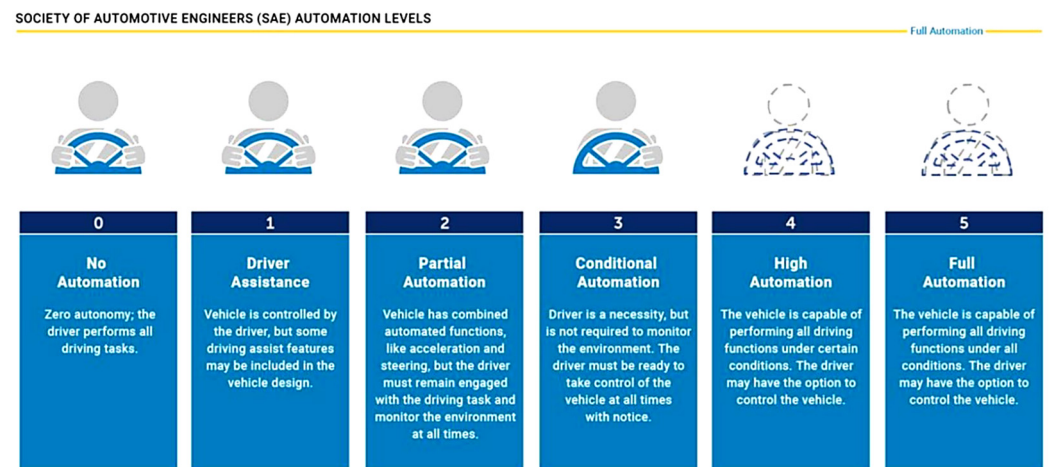


Figure 1. Levels of autonomous driving [12].

In the realm of transportation, the evolution of AVs has seen a swift escalation. These vehicles have undergone rigorous testing for nearly three decades across various sectors, including surveillance, logistics, agriculture, and transportation [13–16]. Their integration into existing traffic systems has given rise to a novel category of traffic dynamics, termed mixed traffic flows, which consist of AVs at varying levels of integration alongside traditional human-driven vehicles (HDVs) [17]. Despite this progress, the operational realities of fully automated AVs remain shrouded in uncertainty. Experts from Information Handling Services (IHS) Automotive have forecasted that the widespread adoption of AVs is likely to materialize by 2030. The IHS projections also indicate that the global count of fully operational AVs could reach approximately 21 million by 2035 [18]. It is projected that AVs could capture 20–40% of the vehicle market share by 2030; nonetheless, it is posited that a complete shift to AVs will transpire incrementally over the ensuing decades [19].

The field of AV navigation has captivated researchers in the fields of control systems and robotics for years. It is anticipated that the near future will see the emergence of semi-autonomous or autonomous driver assistance systems adept at managing intersections. The essence of autonomous navigation lies in the orchestration of vehicular movements, whether acting independently or in unison, predicated on shared and leveraged information about the vehicles and their surroundings [20].

To reduce energy consumption and improve passenger comfort, a novel approach to traffic organization within road networks is imperative. This approach encompasses multiple facets, including comprehensive route planning across networks, trajectory optimization along roadways, and intersection crossing strategies. The pinnacle of trajectory planning for AVs is achieved through the optimization of a multi-objective function that balances fuel consumption, ride comfort, and safety constraints. While safety remains the paramount concern in intersection management, considerations for passenger comfort and fuel consumption must not be overlooked. Ideally, AVs should traverse intersections swiftly, economically, and comfortably. The advent of information technology and the proliferation of vehicular ad hoc networks (VANETs) facilitating vehicle-to-pedestrian (V2P), vehicle-to-infrastructure (V2I), and vehicle-to-vehicle (V2V) communications have unlocked new prospects for enhancing intersection management systems [21,22]. This evolution has given rise to innovative, non-signalized methods for addressing intersection management challenges, collectively known as cooperative intersection management (CIM). In this paradigm, vehicles engage in communication with infrastructure and other road users to collaboratively orchestrate traffic flow [23]. Consequently, autonomous intersection management (AIM) represents one of the more intricate challenges within traffic management, raising pivotal questions regarding the optimization of delays, fuel consumption, emissions, and reliability [24]. AVs navigating on optimized trajectories are poised to offer passengers journeys that are safe, efficient, and comfortable.

The introduction of AVs heralds a suite of capabilities that surpass those of HDVs. Among the most salient attributes of these advanced vehicles are their precision in sensing their location within the world and their sophisticated path-planning algorithms. AVs are outfitted with cutting-edge automotive technologies, enabling computer systems to assist in a variety of driving tasks, thereby reducing human intervention to different extents. With the rapid progression of communication and autonomous and automotive technologies, their profound impact on the transportation industry is undeniable [25,26]. Comprehending the role of these technologies is crucial for realizing sustainable urban mobility objectives, which encompass the safe and efficient movement of people and goods in an eco-friendly fashion.

The integration of AVs into smart cities represents a transformative shift in urban mobility, offering a more efficient, safe, and sustainable transportation landscape. Smart cities, leveraging the Internet of things (IoT) and artificial intelligence (AI) technologies, can optimize traffic flow, reduce congestion, and minimize emissions by incorporating AVs into their infrastructure. This harmonization of AVs with smart city frameworks is essential for creating a seamless urban transit experience [27,28]. Furthermore, the concept of a vehicle as a service (VaaS) emerges as a natural extension of this integration. A VaaS will operate on a subscription-based model, allowing users to access a fleet of AVs for their transportation needs. This model not only reduces the need for personal vehicle ownership, but also aligns with the smart city ethos of shared resources and services. It promises to enhance urban mobility by providing on-demand transportation that is adaptable to individual needs while contributing to the overall efficiency of the city's transport system. The adoption of the VaaS concept within smart cities could lead to a significant redefinition of urban transportation, making it more accessible, less resource-intensive, and better integrated with other smart city services [29].

The exponential growth of information technologies (IT) spanning communications, sensing, computing, signal and image processing, and robotics has been paralleled by the widespread adoption of ITSs. It is projected that the efficiency of current traffic junctions will

be significantly enhanced through the integration of AVs and communication technologies, such as V2V, V2I, and infrastructure to vehicle (I2V) communication [30,31]. As depicted in Figure 2, the AV system can be categorized into four principal segments. Employing an array of sensors and technologies, including ultrasonic sensors, cameras, light detection and ranging (LiDAR), lasers, global positioning systems (GPSs), and more, AVs are capable of acquiring a comprehensive understanding of their environment. Consequently, AVs are expected to enhance the efficiency, environmental friendliness, and passenger comfort of the transportation system.

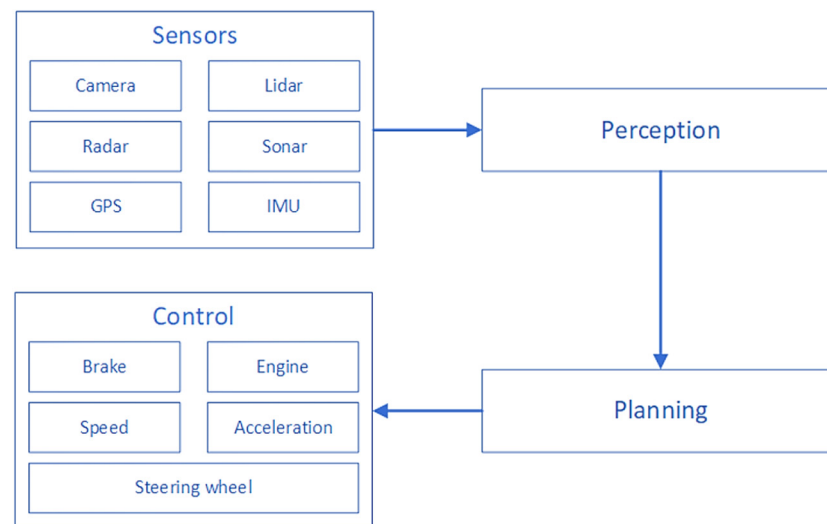


Figure 2. Block diagram of AV system [32].

The integration of AVs into urban landscapes presents a transformative shift in traffic management, urban planning, and environmental sustainability. In urban planning, they necessitate a reevaluation of infrastructure needs, potentially leading to more efficient land use and reduced need for extensive parking facilities. Environmentally, the fusion of AVs with electric vehicle technology heralds a greener future, where the synergy between automation and electrification paves the way for substantial reductions in greenhouse gas emissions and a marked improvement in air quality [33]. However, these benefits are contingent upon addressing technological challenges and developing effective regulatory frameworks. The future urban landscape with AVs is envisioned as a more efficient and environmentally sustainable environment. This future includes seamlessly integrated transportation systems where AVs complement public transit, contributing to a reduction in private vehicle ownership and urban sprawl. Urban spaces could be redesigned to prioritize pedestrian areas and green spaces, as the need for parking and wide roads would be diminished [34]. The adoption of AVs is also expected to foster smarter cities, where data-driven management of urban mobility leads to more responsive and adaptive city planning. To optimize the integration of AVs into urban environments, comprehensive policy and industry recommendations are essential. Policymakers should focus on developing standardized safety regulations, incentivizing the adoption of AVs, and ensuring equitable access to this new form of mobility [35]. Urban planners are encouraged to consider AVs in long-term city planning, and rethink infrastructure and land use. For the industry, investing in research and development to overcome technological barriers and improve public trust in AV technology is crucial. Collaboration between government, industry, and academia is vital to address these challenges effectively.

The emergence of AVs marks a pivotal transformation in mobility, reshaping the vehicular landscape and promising a sustainable revolution and significant changes in transportation dynamics. This technological revolution is characterized by the shift from human-operated to self-driving vehicles. Thankfully, advancements in information and communication technology have facilitated the integration of significant safety enhance-

ments [36,37]. Consequently, AVs have emerged as a viable, sustainable alternative with the potential to optimize the flow of road traffic, while also reducing pollutant emission and increasing comfort while driving [38], heralding a new age of sustainable mobility.

1.2. Research Objectives

The rapid advancement of AV technology has ignited a sustainable revolution, garnering significant interest for its potential to revolutionize transportation systems worldwide. AVs stand as harbingers of sustainable mobility, offering enhanced safety, reduced emissions, improved traffic flow, and increased mobility for passengers. However, the integration of AVs into existing traffic networks presents complex challenges related to ecological sustainability and passenger comfort. Understanding the multifaceted effects of AVs on ecology and passenger experience is crucial for sustainable decision-making and policy development in the transportation sector.

Despite the growing body of research on AV technology, there remains a gap in the literature regarding the comprehensive evaluation of the effects of AVs on both ecology and passenger comfort within traffic networks. Existing studies often focus on isolated aspects of AV performance or overlook the interconnected nature of ecological and passenger-related factors. This research aims to bridge this gap by providing a holistic review of the ecological and passenger comfort implications of the sustainable integration of AVs into traffic systems. This research seeks to innovate by synthesizing existing knowledge on AV technology, ecological impacts, and passenger comfort to offer a comprehensive understanding of the challenges and opportunities associated with AV integration. By exploring the intersection of ecology and passenger experience, this study aims to uncover novel insights that can inform sustainable policy decisions, urban planning strategies, and technological advancements in the field of autonomous transportation. Therefore, the main objectives of this research are:

- To review current literature on the environmental impact of AVs, focusing on sustainable energy efficiency, emission reduction, and fuel consumption;
- To analyze studies on passenger comfort in AVs, including vehicle motion characteristics, passenger physiological characteristics, and intelligent driving technology;
- To identify the key challenges and opportunities associated with the sustainable integration of AVs into existing traffic systems from both an ecological and passenger-centric perspective;
- To propose future research directions and policy recommendations that prioritize sustainability, with the aim of maximizing the benefits of AV technology while mitigating the potential drawbacks related to ecology and passenger comfort.

Through the pursuit of these goals, this study seeks to offer significant contributions to the evolving conversation surrounding the incorporation of AVs into transportation infrastructures, with a focus on promoting sustainability, ecology, and passenger comfort in the era of autonomous mobility. Figure 3 provides a visual representation of the research procedure adopted in this study, illustrating the systematic investigation of the application of AVs within traffic networks. The figure is structured to reflect the dual focus of our study, namely the ecological impact and passenger comfort considerations of AVs. For our explanation of the ecological impacts, we delve into the sub-topics of fuel consumption and emissions, analyzing how AVs can contribute to environmental sustainability. The subsequent section indicates the challenges and opportunities associated with the integration of AVs into the traffic network, leading to the conclusions and future directions which encapsulate the study's insights and propose pathways for continued exploration.

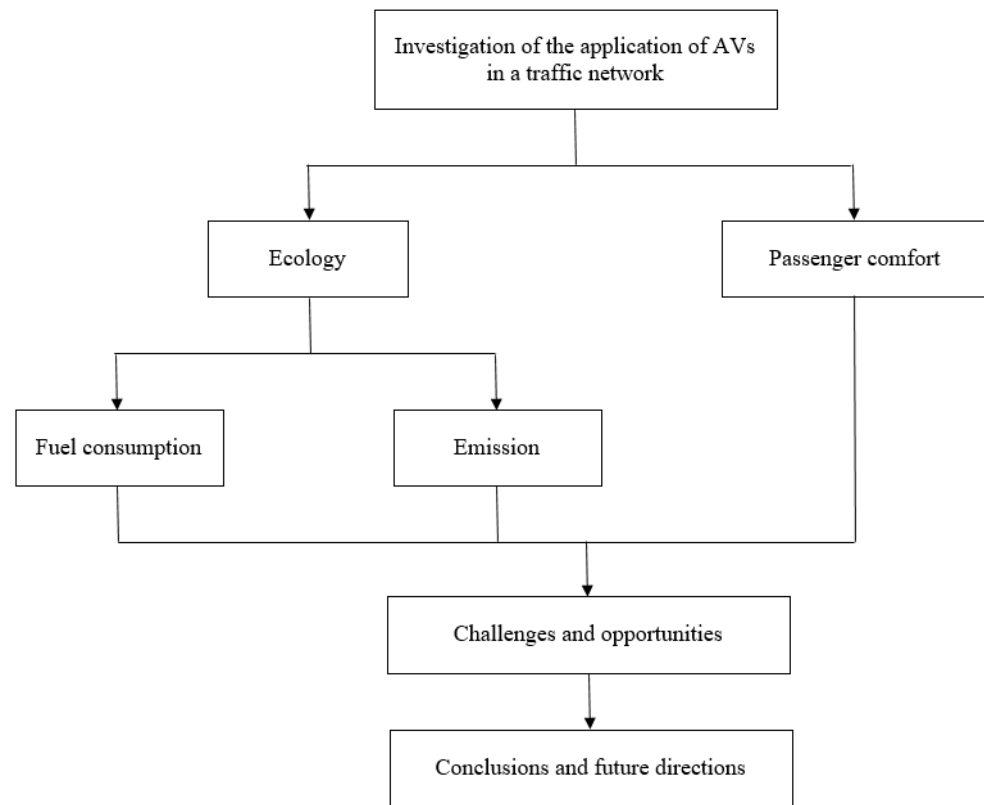


Figure 3. Framework overview of the research.

2. Research Methodology

This research study followed the guidelines specified in previous research [39] to ensure a comprehensive investigation. This study attempted to employ a systematic literature review (SLR) methodology, which involves a systematic and rigorous approach to reviewing existing literature. The study was conducted in multiple iterations, with each iteration focusing on different aspects such as review preparation, organization, and reporting. This iterative process allowed for a thorough evaluation of the SLR, ensuring that all relevant aspects were carefully examined and addressed.

2.1. Selecting Previous Studies

This review paper utilized a straightforward search query to identify pertinent research published in relevant journals or search engines. The search was conducted in May 2024 which implies that it included recent articles, published up until that point, that could provide valuable insights. To ensure the selected articles were relevant, the query string was limited to searching the titles, abstracts, and keywords of papers. The search terms used in the query included variations of terms:

“AV” or “autonomous vehicle” or “driverless vehicle” or “self-driven” + “ecology” or “environment” + “passenger comfort” or “passenger experience” + “road network” or “traffic network”).

By narrowing down the search to these specific areas, the study aimed to focus on articles that addressed the intersection of AVs with ecological considerations, passenger well-being, and the overall impact on road and traffic networks.

Table 1 displays the comprehensive scope of the investigation, which encompassed five digital databases. The initial search conducted in the digital libraries yielded a total of 351 items. Subsequently, the study employed the inclusion/exclusion criteria outlined in Section 2.2 to analyze the titles, abstracts, and keywords of the papers in the search results. Through this analysis, the researchers identified an additional 187 papers.

Table 1. Scientific databases used in this study.

Scientific Database Accessible Online	URL Address
Web of Science	https://www.webofscience.com/ (accessed on 1 July 2024).
Scopus	https://www.elsevier.com/solutions/scopus/ (accessed on 1 July 2024).
Springer	https://link.springer.com/ (accessed on 1 July 2024).
IEEE Xplore	http://ieeexplore.ieee.org/ (accessed on 1 July 2024).
Science Direct	https://www.sciencedirect.com/ (accessed on 1 July 2024).

To further refine the selection, the complete texts of the remaining articles were compared against the inclusion/exclusion criteria, resulting in a final set of 151 papers. These results served as the foundation for the subsequent snowballing technique, as detailed in previous research [40]. The study employed both forward and backward snowballing methods, following a specific sequence. First, a reverse snowballing approach was implemented, involving an examination of the reference lists of all publications. This was followed by a forward snowballing process. Consequently, the remaining publications that were not initially included were thoroughly examined to determine their relevance. These publications were identified based on their correlation with the previously discovered set of papers.

2.2. Inclusion/Exclusion Criteria

To be included in this systematic review, the findings were required to meet specific criteria related to computerized approaches to ecological considerations and passenger comfort in the context of AVs, particularly in road networks. The selected articles needed to provide analytical conclusions that aligned with the applications and objectives of the study. Additionally, the articles needed to be published in the peer-reviewed journals listed in Section 2.1 and written in English. Articles that primarily discussed road safety and efficiency were excluded from the review. The primary inclusion criteria for article selection are as follows:

- The articles must examine autonomous automobiles;
- The articles must be from peer-reviewed journals;
- The manuscript must present analytical information pertaining to the application and study goals;

Furthermore, the following criteria were considered for exclusion:

- Non-English articles were excluded from consideration;
- Technical reports or official government papers were excluded;
- Papers that focus solely on human-driven vehicles were excluded;
- Papers that solely assess and compare the effectiveness of existing approaches were excluded.

3. Ecology

3.1. Role of AV in Reducing Air Pollution

The transport sector has been at the forefront of initiatives to combat climate change and diminish air pollution [41]. The contribution of fossil fuel combustion to global warming has escalated dramatically since the late 19th century [42]. Presently, the world sees about seven billion tons of carbon dioxide discharged into the atmosphere annually [43]. A comprehensive 30-year survey by the United States Environmental Protection Agency identified the transport sector as the primary source of greenhouse gas (GHG) emissions compared to other sectors [44]. A closer examination reveals that an average passenger vehicle, weighing less than 8500 pounds, is responsible for emitting 4.6 metric tons of carbon dioxide each year, accounting for 57% of the entire transport sector's emissions [45]. With the rising reliance on personal vehicles, the environmental repercussions of trans-

portation infrastructures are increasingly evident. Therefore, urban planners must devise and implement groundbreaking strategies to address these environmental challenges.

Contemporary transportation networks are grappling with challenges due to escalating travel demands and the finite capacity of road infrastructure [46–48]. In contrast to highway systems, urban roadways are plagued by prolonged travel times, inconsistent journey durations, excessive fuel consumption, and heightened emission levels, particularly at intersections where vehicles engage in frequent stopping and starting [49]. It has been reported that travelers in the United States have faced approximately 1.92 billion hours of delays on urban roads [50]. The mandatory halts at traffic signals in city environments, necessitating repeated braking and acceleration, exert a substantial strain on the throughput of these networks and contribute to vehicular emissions. Streamlining traffic management can significantly curtail the number of stops, thereby alleviating congestion [51] and reducing pollution in metropolitan areas [52,53] in alignment with the European standards aimed at curbing levels of SO₂, NO₂, NO_x, and PM₁₀ [54].

The escalating volume of vehicles has also exacerbated fuel consumption and impeded the efficacy of urban transportation systems, with forecasts indicating that private vehicle ownership could soar to 14.7 billion by 2030 [55]. Indeed, numerous elements influence vehicles' fuel efficiency and the overall effectiveness of transportation, including road capacity and the design of infrastructure. Signalized intersections in cityscapes are particularly influential in this regard. As vehicles approach these intersections, they often halt at red signals, remaining idle while awaiting the transition to green. This idling period results in stationary vehicles that continue to consume fuel and emit GHGs [56]. A study by the Texas Transportation Institute highlights that the fuel squandered during such idle periods has surpassed 2.8 billion gallons [57].

The recent escalation in transport activities has markedly influenced energy usage and the emission of pollutants. Back in 2015, the US transport sector was responsible for consuming around 27.71 quadrillion BTUs, representing 28.4% of the country's total energy use across all sectors. Moreover, in 2013, the emissions of GHGs from transportation were the second highest in the nation, making up about 27% of the US' overall emissions [58]. These statistics have heightened the public's consciousness regarding the imperative to decrease the energy and emissions footprint of the transportation industry.

Traffic jams significantly escalate CO₂ levels, the predominant GHG released from transportation. Idle vehicles at traffic lights notably increase carbon monoxide (CO) emissions, with the International Energy Agency noting that idling vehicles can emit 5–7 times more CO than those moving at 5–10 mph [59,60]. In 2020, transportation was responsible for a quarter of the 37 GtCO₂eq in global GHG emissions [61,62]. The objective, from a control and optimization perspective, is to devise strategies that enhance traffic capacity without altering current road structures. This involves closer vehicle spacing on roads and improved management at traffic system pinch points, such as intersections, merging lanes, and zones where speeds drop [63,64]. As transportation is a major GHG emitter, implementing an automated highway system (AHS) could help ease congestion and, consequently, lower energy consumption and emissions.

3.2. Causes of GHG Emissions Due to AVs

This part of the research delves into a detailed discussion of various elements that could potentially lead to a decrease in GHG emissions as a consequence of the automation of vehicles. It explores the intricate relationship between vehicle automation and environmental impact, highlighting how advancements in this field could contribute to more sustainable transportation practices. The discourse extends to the broader implications of such technological progress, considering both the immediate and long-term benefits of reducing GHG emissions through smarter, self-regulating vehicular systems. Figure 4 indicates the general factors that affect the reduction and increase of emissions [65].

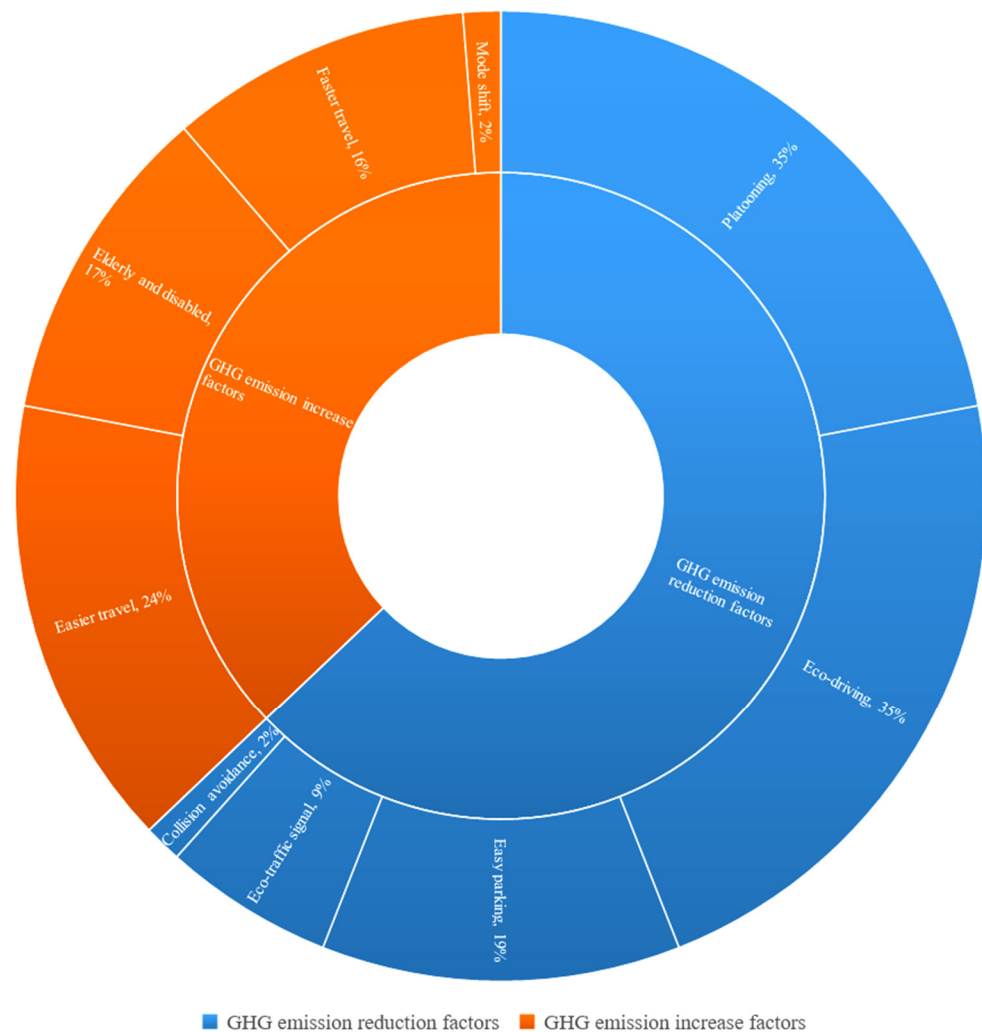


Figure 4. Typical impact of various factors on the decrease and increase of GHG emissions.

3.2.1. Easy Parking

In the context of fuel conservation, the search for parking poses a twofold problem. Vehicles roaming for parking not only use more fuel but also exacerbate congestion, leading to increased fuel usage by others. It has been noted that the quest for parking contributes to roughly a third of urban traffic [66]. The act of parking itself is a significant factor in urban carbon emissions [67]. The pursuit of parking is linked to 2–11% of emissions in central business districts [68]. Full use of AVs could cut emissions by 5–11% by reducing the need to drive around looking for parking [69]. The concept of ‘easy parking’ involves using communication technologies to inform drivers of available parking spots, potentially reducing the need for parking space by 80% with shared AV use [70]. This reduction is possible during both busy and less busy times when parking is in high demand. While semi-AVs can also lower emissions by finding parking more efficiently, the impact may be less than with full automation. Overall, the ‘easy parking’ feature in vehicle automation is poised to lower greenhouse gas emissions, depending on several factors, by minimizing idle time and the time spent searching for parking.

3.2.2. Efficient Driving Practices

Efficient driving, commonly termed eco-driving, encapsulates the practice of optimizing driving efficiency by fine-tuning speed and acceleration patterns. This approach, also known as “hypermiling”, involves a series of driving techniques aimed at enhancing fuel efficiency by reducing the frequency of braking and acceleration, as these actions lead

to energy loss [71]. A synchronized eco-driving system leverages a digital traffic control center to oversee and analyze vehicle speed and acceleration data, enabling collective driving decisions that improve traffic conditions and benefit all vehicles in the convoy. This method has the potential to reduce emissions by 5–10% in areas with dense traffic congestion [72]. The implementation of eco-driving systems in AVs promotes seamless transit across networks, thanks to advanced communication with other vehicles and road infrastructure, thereby contributing to a decrease in greenhouse gas emissions.

3.2.3. Intelligent Traffic Signal Interaction

The eco-traffic signal concept enables AVs to autonomously interface with traffic control systems, especially at intersections. This system provides data that assist vehicles in altering their driving behavior, which effectively reduces stoppage frequency at intersections. The opportunity for lowering fuel usage and greenhouse gas emissions at these junctures is substantial, given that vehicles operating at reduced speeds in these areas are prone to higher fuel consumption [73]. Consequently, urban intersections equipped with signals present a significant opportunity for the mitigation of greenhouse gas emissions on a network scale. AVs, outfitted with an array of advanced sensors, facilitate communication with the traffic environment, empowering drivers and vehicles to refine their driving strategies, limit halts, and maintain consistent speeds. These adjustments are instrumental in decreasing fuel consumption and, by extension, vehicular emissions.

3.2.4. Preventing Accidents

Over 90% of vehicular mishaps are due to human mistakes [74]. Driving fatigue and behavior can also seriously threaten traffic safety [75,76]. Advanced driver-assistance systems (ADASs) in AVs are engineered to pre-emptively relay critical data to the vehicle through sophisticated onboard sensors, thereby averting potential collisions. These sensors diligently monitor the proximity of other vehicles and objects, alerting the system to take proactive safety measures. Beyond the clear benefit of preventing individual accidents, these systems also contribute to broader ecological and fuel efficiency gains by reducing the likelihood of the traffic build-up typically caused by accidents. Both semi-autonomous and fully autonomous vehicles equipped with ADASs are expected to lower greenhouse gas emissions by averting the traffic snarls and congestion that often result from vehicular accidents.

3.2.5. Vehicle Platooning

The concept of vehicle grouping, or platooning, involves a convoy of vehicles driving in close formation to significantly reduce aerodynamic drag, thereby conserving energy and cutting down on emissions. This method is made possible through the use of automation and connectivity technologies [77]. Given that a considerable amount of fuel is expended to overcome aerodynamic resistance, this strategy is particularly beneficial. The fuel-saving potential of platooning is more pronounced for vehicles positioned within the center of the formation, with the average fuel economy improving as the number of vehicles in the group increases. Thus, the practice of vehicle platooning with AVs is anticipated to contribute to a reduction in greenhouse gas emissions in the transportation sector, mainly through the mitigation of drag forces and the stabilization of vehicular speeds.

3.2.6. Optimizing Vehicle Dimensions

Innovations in automation allow for reductions in vehicle dimensions, while maintaining safety standards [78]. Downsizing vehicles can lead to marked improvements in fuel economy. Light duty vehicles (LDVs) on US roads are typically built to accommodate four passengers [79], yet the average occupancy rate was only 1.67 in 2009 [80]. Tailoring vehicle size to match actual usage can greatly lower the energy consumption per trip. This strategy is most effective when combined with shared mobility options like car sharing or pooling. A network of shared AVs could provide appropriately sized vehicles based on

real-time demand, thus avoiding the inefficiencies of underutilized, oversized vehicles [81]. The energy required and fuel used during travel are directly related to vehicle size. With the integration of AV technology, manufacturers have the opportunity to produce smaller, more energy-efficient vehicles that contribute to significant reductions in energy use and greenhouse gas emissions.

3.2.7. Streamlining Traffic and Routing

Intermittent traffic, characterized by frequent stops and idling, leads to higher fuel consumption and greenhouse gas emissions compared to smooth-flowing traffic. AVs possess the capability to synchronize with other vehicles and infrastructure (V2I and V2V) at intersections, enhancing traffic flow and decreasing the likelihood of accidents, thereby saving energy and reducing greenhouse gas emissions [78]. While the response to congestion varies across different powertrains, electrically powered AVs are particularly effective at reducing greenhouse gases [82]. Additionally, V2I technology in AVs can redirect traffic within the network to manage sudden increases in traffic volume, such as those caused by events [83]. An advanced infrastructure in a city can process data from vehicles to predict traffic patterns and assign optimal routes, prioritizing emergency and public service vehicles [84–86]. The intelligent communication capabilities of AVs can provide early alerts about traffic conditions, enabling vehicles to choose the best routes and maintain a steady flow, thus minimizing greenhouse gas emissions.

3.2.8. Enhancing Carpooling

Vehicle occupancy rates significantly influence the greenhouse gas emissions associated with vehicle travel. Lower occupancy leads to more vehicles on the road than necessary, multiplying emissions. For example, only 11 percent of Americans carpool to work, while an overwhelming 113.6 million people commute alone daily [87]. AVs present an opportunity to revolutionize the business model of transportation by promoting ridesharing, potentially causing a shift from private vehicle ownership to shared mobility services. This shift is likely to result in a substantial decrease in transportation-related greenhouse gases. AVs also offer carpooling and ridesharing options that can further reduce greenhouse gas emissions by decreasing the need for personal vehicle ownership and encouraging the use of more sustainable transport alternatives.

3.2.9. Ensuring Compliance with Traffic Laws

The precision of AVs in obeying traffic laws surpasses that of human drivers, thanks to their sophisticated onboard programming [88]. This adherence to speed regulations, which are often calibrated for maximum fuel efficiency, is expected to lead to a significant reduction in greenhouse gas emissions. Furthermore, AVs' strict compliance with traffic signals contributes to smoother traffic flow, mitigating the common disruptions and bottlenecks associated with human driving behaviors. The consistent and predictable driving patterns of AVs not only improve road safety but also optimize traffic dynamics, which can result in lower fuel consumption and decreased greenhouse gas emissions. By minimizing erratic driving, sudden stops, and accelerations, AVs promise a more environmentally friendly and efficient transportation system.

4. Passenger Comfort

The concept of comfort is inherently subjective, shaped by a myriad of internal and external influences, and manifests in response to various stimuli [89]. The scientific realm has yet to converge on a universally accepted definition of comfort, with ongoing debates about whether comfort and discomfort are diametrically opposed or can exist simultaneously [90–92]. The discourse primarily grapples with distinguishing comfort from discomfort, with some experts proposing that comfort exists in two distinct states: its presence or absence [93]. Hence, comfort is often equated with a sense of well-being and a

positive response to the source of comfort, and from some perspectives, it is defined by the absence of discomfort and unease.

Within the domain of transportation, comfort plays a pivotal role in influencing passengers' preferences for AVs. The level of comfort in an AV is intrinsically linked to its control algorithm. Predictions of passenger comfort based on influential factors and tailoring of the control algorithm accordingly can enhance the comfort levels in AVs [94]. Additionally, the disparity between anticipated and actual driving experiences, along with the sensation of losing control, are significant determinants of comfort [95,96]. Moreover, there is a discernible connection between comfort, trust, and the acceptance of AVs, with both trust and acceptance being crucial for the adoption of new technologies [97,98]. Therefore, comfort can act as a hurdle to the widespread acceptance of AVs, underscoring the importance of evaluating driving style preferences in autonomous driving scenarios.

In the era of AVs, all occupants will become passengers, free from the responsibilities of vehicle control, and will be likely to engage in non-driving activities such as reading, using mobile devices, or conversing with fellow passengers. The enhanced comfort offered by AVs and the necessity of efficient time management suggest that passengers will increasingly partake in such in-vehicle activities. However, this could potentially lead to a rise in car sickness, a specific form of motion sickness [99–101].

The arena of AV research is rapidly expanding, with a primary focus on crafting AVs that cater to the nuances of human travel requirements. In this context, the comfort experienced by passengers becomes a pivotal benchmark for evaluating the efficacy of these services. Comfort in AVs extends beyond mere physical ease, encompassing a sense of security, convenience, and overall satisfaction with the travel experience. The correlation between the level of comfort offered by AVs and their acceptance by the public is significant and multifaceted. As AVs evolve to become more sophisticated, the emphasis on ensuring a serene and pleasant journey becomes paramount. This not only involves refining the vehicle's internal environment and operational smoothness, but also addressing psychological comfort by enhancing the sense of control and predictability for passengers. Ultimately, the success of AVs in the consumer market hinges on their ability to deliver a travel experience that aligns with the expectations and desires of users for a comfortable, stress-free, and enjoyable journey [102].

The studies on comfort within conventional vehicles have predominantly focused on the driver's behavior, the structural design of the vehicle's framework, and the ambiance of the cabin interior [103,104]. In contrast, AVs represent a paradigm shift where the individual at the wheel transitions from an active controller to a passive occupant, free to engage in activities unrelated to driving. This shift heralds a new era of challenges and opportunities to enhance passenger comfort. The role of comfort in AVs is not just about physical ease but also about creating an environment that caters to the psychological and emotional well-being of passengers. As AVs take over the tasks of navigation and control, the focus intensifies on designing interiors that are not only ergonomically sound but also responsive to the diverse needs of passengers, potentially including customizable seating arrangements, climate control, and interactive entertainment systems. The evolution of AVs thus calls for a holistic approach to comfort, one that seamlessly integrates technology with human-centric design to ensure a tranquil and enjoyable travel experience for all occupants.

As control algorithms advance, the quest for intelligent driving transcends safety to encompass passenger comfort by recognizing it as an essential component of the driving experience. The comfort level within AVs directly influences user acceptance, as discomfort can deter widespread adoption. By gaining a deeper understanding of what causes discomfort for passengers, we can refine the algorithms that govern AV behavior and enhance the interaction between the vehicle and its occupants. This proactive approach aims to minimize the instance and severity of motion sickness, thereby elevating passengers' overall comfort. Enhanced comfort not only improves the immediate experience but also fosters long-term trust and reliance on AVs, paving the way for their integration into daily life. As we move forward, the focus will be on creating a harmonious balance between

technological innovation and human-centric design, ensuring that AVs deliver not just a ride, but a journey that is as pleasant as it is efficient.

4.1. Factors Affecting Passenger Comfort

There are three general factors affecting passenger comfort and the acceptance of AVs, as can be seen in Figure 5.

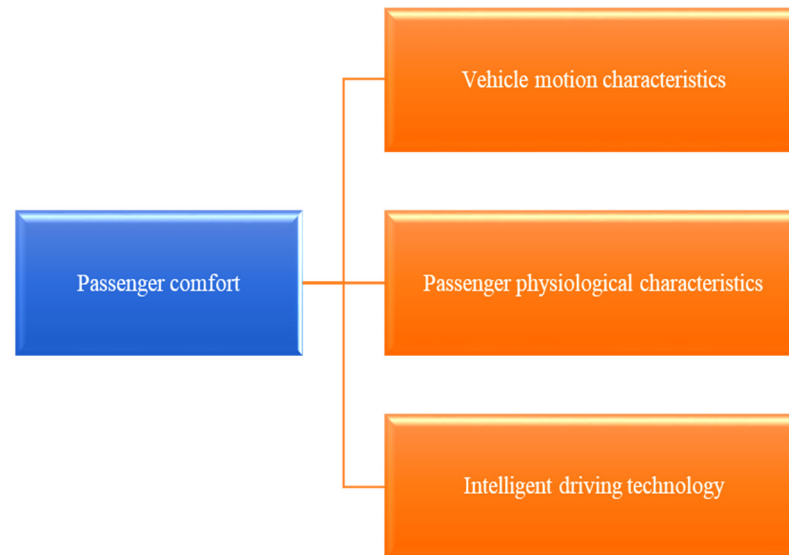


Figure 5. Factors influencing passenger comfort in autonomous driving.

4.1.1. Vehicle Motion Characteristics

To investigate the comfort levels of passengers, researchers typically have individuals undergo trials in various vehicular conditions or using specialized apparatus. Participants then provide their personal assessments of comfort through surveys, which helps establish a link between their subjective comfort experiences and the dynamics of the vehicle's movement. However, these surveys are generally administered only once after the completion of the trip, yielding an aggregate comfort assessment without temporal specificity [105,106]. This means that the comfort ratings do not reflect the comfort experienced at individual moments of the journey, obscuring the connection between comfort and specific vehicular actions. To bridge this gap, digital methods like the fast motion sickness scale (FMS) have been introduced, where passengers rate their comfort level every minute on a scale from 0 (no discomfort) to 20 (severe discomfort) [107]. Despite this advancement, such methods still do not capture the comfort experiences linked to particular instances of vehicle operation. The traditional approach is thus limited, as it does not allow for real-time comfort evaluation, hindering a precise analysis of how vehicle motion affects passenger comfort. Real-time comfort assessments, synchronized with detailed vehicle data, are essential for a more accurate understanding of this relationship.

4.1.2. Passenger Physiological Characteristics

Objective assessments of passenger comfort can incorporate the analysis of physiological responses as indicators of comfort levels. This approach involves monitoring changes in specific physiological metrics, such as heart rate variability, systolic and diastolic blood pressure, and electrodermal activity, which are reflective of a passenger's comfort state [108–110]. Alongside these objective measures, subjective evaluations provide a complementary perspective where passengers personally rate their comfort based on their sensations and experiences. These subjective assessments often consider the physiological predispositions of individuals, acknowledging that personal thresholds for motion-related stimuli, like acceleration, can vary due to unique physiological and psy-

chological profiles [111]. Notably, research has demonstrated that gender can significantly impact susceptibility to motion sickness, suggesting that comfort experiences can differ between genders and may fluctuate in response to diverse vehicular motions [112]. This dual approach, blending objective data with personal feedback, offers a comprehensive view of comfort, accommodating the complex interplay of the physical and psychological factors that contribute to a passenger's overall experience.

4.1.3. Intelligent Driving Technology

In the realm of vehicular dynamics, a multitude of management tactics have been conceptualized to cater to diverse operational contexts. These encompass systems for adaptive cruising and automated evasion of impediments, which govern the longitudinal dynamics of acceleration and braking. Additionally, sophisticated algorithms for navigating bends and executing lane transitions address the lateral aspects of vehicular navigation. The overarching objective of these methodologies is bolstering vehicular safety. Nonetheless, as technological advancements unfold, the paradigm has shifted to also embrace the comfort of the occupants in the design of these vehicular management systems. Predominantly, in the domain of autonomous vehicular systems like adaptive cruise control and automated anti-collision mechanisms, the predominant strategy to augment occupant comfort is minimizing the vehicle's peak acceleration and the abruptness of its movements, known as 'jerk'. Furthermore, the formulation of trajectories for lane transitions is a pivotal component of autonomous vehicular technology. Enhancing comfort levels during such maneuvers necessitates the curtailment of both the lateral acceleration and the jerk experienced by the vehicle [113]. This ensures a smoother transition between lanes, contributing to a more pleasant journey for the passengers.

5. Literature Review

5.1. Ecology

Numerous studies have explored the role of ecology in the regulation of AV traffic, suggesting a range of strategies to accomplish this objective.

Li and Shimamoto (2011) presented a scheme for controlling traffic signals in real-time aimed at lowering CO₂ emissions from vehicles. This system utilizes electronic toll collection (ETC) data from equipped vehicles. By employing wireless communications between vehicles and traffic signals (vehicle-to-infrastructure, V2I) via dedicated short range communication (DSRC) technology, it gathers the current traffic conditions. The system then employs a decision tree algorithm to determine the ideal average wait time, which in turn helps calculate the CO₂ emission reductions. Simulation studies have shown that, in comparison to traditional fixed-time traffic controls, this method can cut CO₂ emissions from idling by over 26.9% under heavy traffic conditions. Additionally, it increases the likelihood of vehicles crossing an intersection without stopping by 0.07 when the traffic is sparse [114]. Makarem and Gillet (2011) updated their earlier research [115] and examined how to coordinate intersections using a distributed navigation function for AVs. This method enabled heavier, more energy-intensive vehicles to cross intersections first, with the aim of optimizing energy use. This approach proved to be more energy efficient than conventional traffic light systems [20]. Furthering this concept in a subsequent 2012 study, they incorporated vehicles' inertia and intentions into the communication system. This enhancement aimed to improve system performance in terms of average vehicular speed, intersection capacity, the fluidity of traffic flow, and fuel efficiency [116].

In an effort to diminish the duration of travel, fuel consumption, and the emission of pollutants, Jin et al. (2012) developed a system for the optimal timing of vehicle agents' departures within a multiagent framework. The system's performance was assessed based on the emissions of NO_x, HC, CO, CO₂, and overall fuel consumption. The aggregate emissions of these pollutants and the total energy consumption for all vehicles were calculated from the emission data gathered during simulation trials. The findings demonstrated that the adoption of this system led to a marked decrease in both fuel consumption and

emissions. The reduction percentages varied from 65 to 75 percent for fuel consumption, 63 to 74 percent for NO_x, 55 to 78 percent for HC, 65 to 75 percent for CO₂, and 41 to 71 percent for CO, depending on the traffic volume, which ranged from 54 to 1227 vehicles being introduced over a span of 1000 s. This significant decrease is attributed to the system's improved management of the intersection's temporal and spatial capacity, which eliminates the need for vehicles to engage in inefficient stop-and-go actions [117]. A different analysis by Jin et al. (2012) demonstrated that modest enhancements in CO₂ emissions and fuel efficiency are possible with an optimally scheduled system. Compared to a system based on first-in-first-out (FIFO) principles, this approach did not show significant differences in the emission levels of other pollutants. This could be because the revised system's primary goal was to reduce overall travel time, not necessarily to improve fuel economy. The system utilized a heuristic piece-wise linear function, which did not delve into the detailed trajectory planning that significantly affects fuel usage and emissions [49]. Zohdy et al. (2012) introduced iCACC, an innovative approach to enhancing the navigation of AVs at intersections. The core idea behind iCACC is to manage the paths of vehicles through cooperative adaptive cruise control (CACC) to prevent accidents and reduce the time spent at intersections. Through simulation tests, iCACC was evaluated against traditional traffic signals, focusing on two key performance indicators: time delay and fuel usage. The results showed that iCACC could achieve reductions in both time delays and fuel consumption, with savings of 91% and 82%, respectively, when compared to standard signalized control methods [118].

Saust et al. (2012) developed a collaborative framework utilizing V2I communication, focusing on the integration of signal control with the driving tactics of vehicles. The concept revolves around refining both the lateral and longitudinal control strategies for AVs to lower fuel consumption and emissions and curtail delays. Additionally, the system allows vehicles to adopt a driving strategy that is fine-tuned for fuel efficiency and informed by traffic data from infrastructures. The researchers elaborated on the vehicle optimization process using an enhanced max–min ant system, facilitating real-time optimization of the driving strategy for various driving scenarios. This method was implemented in an AV, enabling the fine-tuning of both forward movement and steering. The preliminary simulation outcomes highlight the potential benefits of this optimized guidance for vehicles [54]. Makarem and Gillet (2012) introduced an innovative decentralized navigation function tailored for the management of AVs at crossroads, with a focus on preventing collisions and optimizing energy consumption. When evaluated against traditional traffic signals, this new system was found to reduce the average energy consumption of vehicles by 13.29% to 73.11%. Moreover, when contrasted with current intersection control methods, their approach demonstrated an improvement in energy savings and peak traffic flow of 24.34 and 7.33 to 94.40 percent, respectively, over centralized management systems. This method indirectly prioritizes heavier vehicles, which typically consume more energy, thereby facilitating more efficient energy use on board. Not only does this technique offer a substantial upgrade over conventional traffic lights in terms of energy conservation, but it also surpasses earlier navigation functions in energy efficiency. The elimination of local minimums within the navigation function is key to this advancement, as it avoids the need for vehicles to decelerate simultaneously when approaching the intersection [115].

In their work, Huang et al. (2012) designed and evaluated a reservation-driven method for managing traffic at intersections, leveraging the extensive connectivity offered by the connected vehicle initiative. They developed a cutting-edge simulation environment tailored for connected vehicle technologies, which amalgamates a detailed traffic simulation with network modeling and emission analysis. This comprehensive simulator was employed to appraise the intelligent intersection system, contrasting it with conventional traffic management techniques across two distinct scenarios. The findings indicated that the intelligent system significantly enhances both traffic flow and environmental outcomes. For instance, in one of the case studies, the smart intersection system achieved an 85 percent reduction in average vehicle wait times, a 50 percent decrease in fuel consumption, and a

39 to 50 percent drop in pollutant emissions, based on real-world traffic data [119]. Bento et al. (2012) crafted a comprehensive intersection management approach that operated on an agent-based framework and was enhanced by both vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. This system employed a spatiotemporal (ST) reservation strategy designed to reduce ecological effects, prevent accidents, and alleviate traffic jams. They also created a traffic simulation tool to assess the effectiveness of this reservation system in managing both roundabouts and traditional intersections. The system's ST cell reservation was managed by an infrastructure agent, which helped mitigate ecological damage, diminish congestion, and lessen conflicts. Additionally, the system was equipped to handle V2V communications [120]. In a subsequent study, Bento et al. (2013) introduced a centralized version of the ST model that also accounted for older vehicles lacking V2X communication capabilities. The simulations indicated that this model performed well in reducing travel times, conserving energy, and improving traffic flow, and it was adaptable to various types of intersections, including roundabouts [121]. Lee et al. (2013) delved into the environmental and safety benefits of the CVIC system within urban traffic management. They utilized the surrogate safety assessment model (SSAM) and the VT-Micro model to evaluate these impacts. The study involved simulations on a theoretical arterial road with four intersections, examining eight different traffic congestion scenarios ranging from low to high traffic volumes. The findings revealed that the CVIC system significantly outperformed the coordinated actuated control system, reducing overall delays by between 82 and 100 percent across the various traffic volumes. Additionally, the system decreased the incidence of rear-end collisions by 30% to 87%, suggesting enhanced safety conditions. Moreover, the CVIC system was shown to have a positive environmental impact, cutting CO₂ emissions by between 12% and 36% and fuel consumption by between 11% and 37% [122].

Kamal et al. (2014) introduced a novel approach for improving fuel consumption, as well as efficiency and safety, at intersections without traffic signals, termed the vehicle-intersection coordination scheme (VICS). This system is grounded in the model's predictive control paradigm and calculates the most favorable vehicle paths by mitigating the risk of cross-collisions at intersections, taking into account various preferences and constraints. The VICS optimizes the use of the intersection space by ensuring that vehicles with conflicting paths do not reach the potential collision point simultaneously. This is a departure from the traditional method of sequentially allocating the entire intersection space to conflicting vehicles. Moreover, the VICS facilitated the turning maneuvers of vehicles at regulated speeds without the need for additional lanes. Through numerical simulations conducted at a standard intersection setup with multiple and single lanes, including turns, the VICS had demonstrated improvements over conventional signalized intersections in key performance metrics such as fuel consumption, intersection throughput, traffic flow, and vehicle stoppage time [123]. Tlig et al. (2014) introduced a control system for intersections based on synchronization to regulate vehicle speeds and timing, intending to prevent collisions, reduce energy consumption, and enable uninterrupted passage through intersections. This approach decentralizes traffic management by treating each intersection as an independent entity. Control agents are designated to manage the flow of vehicles, alternating the traffic from different directions to maintain synchronization. The research indicated that while the overall delays remained largely unchanged, energy consumption varied with the size of the crossing area [124]. In another study, Tlig et al. (2014) devised a two-tiered decentralized multiagent system that employed strategies to eliminate stops, thereby enhancing the overall traffic flow at the network level and allowing vehicles to traverse intersections without halting. The simulations validated that this system could substantially lower energy consumption at the individual vehicle level [125].

Münst et al. (2015) presented a groundbreaking method for managing traffic in real time using a virtual traffic light control system. This system harnessed mobile communication technologies, cloud computing's robust capabilities, and real-time data processing and decision-making to facilitate its operation. The key technological components of this

system encompassed vehicle identification, precise location tracking, TMP communication protocols, a cloud-driven control framework, and spontaneous group bargaining. The primary objectives of this innovative concept were to enhance the efficiency of traffic circulation, reduce fuel usage, and bolster road safety [126]. In 2016, Wei et al. devised a streamlined model for vehicle following and a dynamic programming (DP) algorithm aimed at reducing overall travel expenses and fuel usage of vehicles, while maintaining a safe distance between them. This was achieved by segmenting time into intervals and space into a grid format. However, the algorithm they proposed is limited in its ability to address problems at the network scale involving a large number of vehicles, owing to the intricate computational demands of their DP algorithm [127]. Zhang et al. (2016) tackled the challenge of orchestrating a seamless stream of connected and autonomous vehicles (CAVs) at two closely situated urban intersections. They introduced a decentralized control system designed to determine the most efficient acceleration or deceleration patterns for each vehicle, aiming to optimize fuel efficiency. This system enabled vehicles to navigate intersections smoothly without the need for traffic signals, preventing road congestion and adhering to stringent safety measures to avoid collisions. The practicality of this approach was confirmed through simulations conducted at two intersections in the heart of Boston, demonstrating that the strategic coordination of CAVs would lead to substantial reductions in both travel times and fuel consumption [128].

Xu et al. (2017) introduced a collaborative strategy termed cooperation between traffic signals and vehicles (CTV). This strategy was designed to determine the most efficient signal timings, the sequence of vehicles, and their respective times of arrival. Concurrently, an optimal control mechanism was employed to refine the acceleration or deceleration patterns, engine power management, and the trajectory of AVs. When benchmarked against traditional actuated signal control techniques, the CTV strategy demonstrated a reduction in the average duration of trips of 19.7 percent and an improvement in fuel efficiency of 23.7 percent. The methodology encouraged vehicles to decelerate in advance to prevent unnecessary stopping and idling at intersections, and it adjusted the timing of green lights to further decrease travel time and fuel usage [56]. Wang et al. (2017) formulated a method known as the cluster-wise cooperative eco-approach and departure application (coop-EAD). This technique encompassed the preliminary grouping of vehicles, the optimization of the order within these clusters, and the management of cluster formation. When evaluated against the conventional ego-EAD approach, the aforementioned method showed enhancements in energy efficiency and traffic flow of 11.01 and 50 percent, respectively. It also resulted in a reduction in harmful emissions ranging from 2.29 to 19.91 percent [129]. Hacıoğlu and Söylemez (2017) introduced an innovative intersection design utilizing a multiagent reservation system. The aim was to reduce overall wait times and energy wastage, as well as to enhance the detection of accidents. This was achieved by segmenting the intersection into three primary communication zones. Implementing this strategy led to a reduction in both the cumulative delay experienced by vehicles and the total energy consumed [130].

Medina et al. (2017) introduced a decentralized approach known as cooperative intersection control (CIC) for the collaborative automation of road intersections. This method enabled AVs to navigate intersections by adhering to their designated paths while preventing crashes. The concept of virtual platooning, an extension of the traditional platooning technique to two dimensions, facilitates the safe and efficient movement of vehicles. This virtual platooning technique permitted vehicles to maintain minimal distances from each other while moving through the intersection, avoiding the need to come to a complete stop, which is common at traffic signals. The advantages of this system are twofold; it not only increased the intersection's capacity but also reduced the fuel consumption by ensuring a more consistent flow of traffic, thereby minimizing instances of acceleration and deceleration [131]. Zheng et al. (2017) introduced a collaborative control system for vehicle intersections in urban settings, which operated independently of traffic lights and was grounded in model predictive control principles. The system presupposed complete

automation of all vehicles and the presence of a control mechanism at the intersection to synchronize vehicle activity. With the aid of the CV application, the system harmonized the movement of vehicles converging from various directions by collectively processing their status. Vehicle paths were forecasted and modified to avoid collisions, adhering to specific preferences and constraints. This control strategy ensured that vehicles on intersecting paths did not enter the intersection simultaneously, thereby reducing the overall risk of collisions. A specialized simulation platform was created to measure the effectiveness of this system quantitatively. The simulations indicated substantial enhancements in the environmental impact, as well as flow and safety, at intersections when compared to traditional traffic signal-based controls [132].

Mirheli et al. (2018) advanced the concept of a signal-head-free intersection control logic (SICL) designed to determine nearly optimal paths for CAVs that prevent any intersection conflicts. They introduced a probabilistic forecasting method to enhance the efficiency of intersections utilizing the Monte Carlo tree search technique. This method aimed to increase the capacity of intersections, minimize travel durations, eliminate vehicle stops, and lower fuel consumption [133]. Malikopoulos et al. (2018) developed a decentralized framework for optimal energy control that aimed to reduce the consumption of energy and fuel, as well as travel time, while also enhancing the capacity of intersections without traffic signals and ensuring safety. Their findings indicated that the maximization of intersection throughput is solely reliant on stringent safety measures, and the framework's design facilitated a decentralized approach to formulating optimal control problems with a focus on minimizing energy. They provided a thorough analytical resolution for these decentralized issues and established conditions that guaranteed the existence of viable solutions that comply with all safety requirements. The simulations demonstrated the significant advantages of this framework, which enabled vehicles to maintain momentum and save fuel, thereby reducing travel times. When compared to conventional traffic signal controls, this innovative method has been shown to decrease fuel usage by 46.6 percent and travel duration by 30.9 percent [134]. Bashiri et al. (2018) unveiled a centralized control system for vehicle platoons at intersections, known as platoon-based autonomous intersection management (PAIM). This system was structured around a reservation policy and a cost function, aiming to reduce both the average wait time and its inconsistency. The system's design ensured safety by preventing vehicles with intersecting paths from entering the conflict zone simultaneously. Additionally, the system incorporated a greedy algorithm that sifts through all scheduling options to find the most efficient one, balancing the overall delay against its variability. To evaluate the PAIM's effectiveness, simulation software was developed to measure the average delay per vehicle and the variability of these delays, comparing them to the performance of a conventional four-phase traffic signal. The simulation results demonstrated that PAIM surpasses traditional traffic lights in terms of reducing delay and fuel consumption [24].

Bichiou and Rakha (2018) introduced an innovative algorithm for managing traffic at intersections, which took into account the complex dynamics of vehicle movement and varying weather conditions. This model was framed as an optimization challenge, constrained by the equations of motion for vehicles and the maximum speeds they can achieve. Utilizing Pontryagin's minimum principle, the algorithm seeks to find a solution that minimizes travel time. The expected outcome was an optimal solution that provides the least amount of delay while meeting the outlined constraints. When tested through simulations and compared with traditional traffic management systems like roundabouts, stop signs and signal-controlled intersections, the new method showed potential reductions in fuel consumption, CO₂ emissions, and delays of up to 42.5, 40, and 80 percent, respectively [3]. Philip et al. (2018) explored an intelligent traffic management system where AVs autonomously determine their speed in coordination with roadside units to optimize intersection use, thereby reducing their environmental impact and fuel usage. The evaluation of this system was based on metrics such as the average wait time for trips, the general speed of traffic, and the surplus fuel consumption. The efficiency of the

system was assessed by comparing the actual fuel consumption to the minimum possible, as well as a comparison of the fuel used near the intersection to the optimal amount for that area. The study found that a fixed iteration approach yielded the highest fuel savings. However, the introduction of quantization led to a minor increase in fuel usage due to less-than-ideal vehicle cluster scheduling. The study also noted that methods involving switching traffic lights and self-organising traffic lights (SOTLs) were less efficient in terms of fuel consumption, possibly because they cause vehicles to bunch up at intersections, leading to prolonged idling and a lack of control over the group's speed for the remainder of the trip [135].

Xu et al. (2018) developed a dual-layered approach for managing traffic signals and optimizing vehicle speeds for CAVs. This approach simultaneously fine-tuned traffic signal schedules and the speed patterns of vehicles and involved a two-tier system; the first tier focused on optimizing traffic signal timings and scheduling vehicle arrivals to reduce the collective travel time, while the second tier adjusted the engine output and braking to cut down on fuel use for each vehicle. The optimization at the roadside used an enumeration method, whereas the onboard vehicle control employed a pseudospectral method. Through simulations, this method was benchmarked against existing methods, demonstrating notable enhancements in both transport efficiency and fuel savings [136]. Zhao et al. (2018) developed CoDrive, a system designed to provide cooperative speed guidance to vehicles. This system aimed to optimize fuel efficiency by aligning vehicle speeds with the timing of traffic signals at intersections. They identified that vehicles with different post-intersection routes require distinct speeds for optimal fuel usage. To address the issue of the slower vehicles impeding the faster ones, especially in dense traffic or on single-lane roads, they created an algorithm that negotiates a mutually agreeable speed for all affected vehicles. This cooperative speed advisory system effectively reduced the collective fuel consumption to an optimal level. Additionally, they introduced an incentive mechanism to balance the fuel savings among all vehicles. The effectiveness of CoDrive was validated using the SUMO simulation software (<https://eclipse.dev/sumo/>), which demonstrated fuel savings of up to 38.2 percent over the standard approach without speed advice, and an improvement of 7.9 percent over the GreenDrive system [137]. Meng and Cassandras (2018) presented a strategy for determining the ideal acceleration and velocity for AVs that approach traffic signals in a manner that allows for continuous movement. The primary goals of this design were to minimize travel duration, reduce energy consumption, and prevent the need for vehicles to be idle at red lights. This was accomplished by fully utilizing the data transmitted from traffic signals to vehicles. They employed a direct adjoining method to address optimal control issues with both variable and fixed end times, within the bounds of state constraints. This approach was notable for its ability to produce a solution in real time through analytical means, setting it apart from other methods that rely on numerical computations. Through comprehensive simulations, the performance of AVs using this speed profile was assessed against that of manually driven vehicles, demonstrating the algorithm's superiority in reducing travel time and energy consumption [138].

Zhao et al. (2018) explored the benefits of strategically synchronizing wirelessly interconnected vehicles within roundabouts to enhance traffic fluidity. They implemented an optimization structure coupled with an analytical resolution to facilitate the ideal integration of vehicles in this context. Simulations were conducted to assess the efficacy of their method, revealing that vehicles operating in complete coordination can achieve a reduction in overall travel duration of 51 percent and a decrease in fuel consumption of 35 percent [139]. Zhang et al. (2018) explored the management of CAVs within a multi-scenario corridor. They developed an analytical solution in a definitive form, incorporating internal boundary conditions. The solution's efficacy was assessed using VISSIM simulations. Their method markedly decreased the journey duration and fuel consumption of CAVs when contrasted with a standard scenario that involves conventional vehicles operated by humans without any form of control [140].

Mahbub et al. (2019) developed a decentralized framework aimed at optimizing energy for two connected intersections, taking into account interior boundary conditions. They introduced an analytical solution in a definitive format that accounted for these conditions and offered trajectories that were both fuel-efficient and safe for CAVs along their set paths. This new framework demonstrated notable enhancements in fuel economy, mean power requirements, and average journey times relative to a conventional scenario featuring manually operated vehicles without any control mechanisms [141]. In the research conducted by Hadjigeorgiou and Timotheou (2019), the focus was on the coordination of CAVs at intersections without traffic signals. The objective was to determine the CAV trajectories that reduced travel time and optimized fuel efficiency. However, a direct relationship was observed where less travel time often resulted in higher fuel consumption, and the inverse was also true. Consequently, the study aimed to balance the fuel consumption and travel time for CAVs expected to cross the intersection within a predetermined time frame. Due to the non-convex nature of the problem, a mixed-integer programming model was formulated to establish stringent lower and upper bounds. Additionally, a heuristic method that alternated between convex and concave strategies was designed to quickly generate solutions of superior quality. The simulations confirmed the effectiveness of these methods and underscored the significance of balancing fuel consumption with travel time, as minor increases in travel time can lead to substantial fuel savings [142]. Filocamo et al. (2019) introduced an innovative algorithm tailored for the control of road intersections and specifically designed for operation with AVs. This novel approach is adaptable to various intersection designs and was put to the test against contemporary algorithms in scenarios involving roundabout, on-ramp, eight-lane, and two-lane intersections. The findings revealed that, in comparison to the first-come-first-served (FCFS) method, there was a 59.7 percent decrease when set against traditional traffic signal systems and a 14.4 percent decrease in CO₂ emissions and fuel usage. Moreover, the study found that roundabouts were less efficient than standard intersection types. However, with the implementation of the proposed system (FRFP), there was a significant reduction in travel times, CO₂ emissions, and fuel consumption [143].

Chen et al. (2020) tackled the challenge of orchestrating the movement of CAVs at intersections lacking traffic control. They employed an optimal control framework designed to minimize a combined measure of the CAVs' energy use and travel time by determining each vehicle's ideal speed trajectory. The process began with a detailed definition of the problem of autonomous intersection navigation for CAVs, considering different scenarios of the energy recuperation abilities of the vehicles. This also included an examination of how the electrification of the powertrain affects the issue. To guarantee a swift search for solutions and a singular global optimum, the optimal control problem (OCP) was redefined using convex modeling methods. The numerical results confirmed the proposed methods' validity and demonstrated the balance between energy consumption and travel time through Pareto optimal outcomes [144]. In a 2022 study by Vrbanić et al., the focus was on mitigating the adverse environmental effects of traffic, such as by easing congestion and lowering fuel and energy use, as well as exhaust emissions. They implemented a dynamic speed limit system (VSL) informed by Q-Learning, which employed CAVs as the agents for setting speed limits within the control system. The study evaluated two optimization goals, the cumulative time all vehicles spent in the traffic network and the overall energy consumption. Real-world data regarding the emission classifications of vehicles and the proportion of gasoline- and diesel-powered vehicles were sourced from the Croatian Bureau of Statistics. The findings indicated that the VSL system guided by Q-Learning could effectively adapt its control policy, leading to enhanced traffic flow metrics, reduced energy usage, and lower exhaust emissions across various rates of electric CAV integration [17].

Heiberg et al. (2023) conducted a comprehensive life cycle assessment on autonomous electric vehicles (A-EVs) to evaluate their environmental footprint in comparison to electric vehicles (EVs) and vehicles with internal combustion engines (ICEVs). The assessment

covered both the manufacturing and operational phases, with a benchmark of 150,000 passenger miles. The findings indicated that during the manufacturing stage, A-EVs generally had a greater environmental impact than the other systems across most categories, such as the carcinogenic effects on humans, ozone layer impact, and global warming potential. However, when considering the operational phase, A-EVs demonstrated superior performance over EVs and ICEVs in several key areas, including reduced smog creation, acid rain, and contributions to global warming [145]. Research by Zong and Yue (2023) delved into how various disturbance attributes and the composition of mixed vehicle platoons influence CO₂ emissions amidst different types of disturbances. Their findings suggested that integrating CAVs can lead to a reduction in carbon emissions under certain disturbance conditions. They also pinpointed the specific disturbance types that result in increased carbon emissions in mixed traffic scenarios. The study highlighted the significant, varying roles that different disturbance characteristics have on the environmental impact of CAVs. Factors such as the placement of CAVs within a platoon and the diversity of human-driven factors were found to influence the degree of carbon emission reduction. Drawing from these insights, the study offered strategic recommendations for optimizing CAV-based cooperative eco-driving and the implementation of environmentally friendly traffic management practices [146]. A study by Wei and Shao in 2024 focused on measuring the variations in the driving behavior of human-driven vehicles (HDVs) when trailing a CAV as opposed to another HDV. The research aimed to explore the effects of these variations on road safety and environmental factors. To evaluate safety, metrics such as variability in speed and acceleration, along with time-to-collision (TTC), were employed. Environmental impacts were gauged using emission and fuel consumption models, which were adjusted based on specific parameters. The findings revealed that HDVs demonstrate more stable driving patterns in terms of speed and acceleration when following CAVs, leading to significant improvements in TTCs. Additionally, these HDVs were found to be more fuel-efficient and to emit fewer pollutants on average [147].

5.2. Passenger Comfort

In the realm of traffic management, passenger comfort is a pivotal factor. This section delves into research that has prioritized this aspect.

In 2010, Wang et al. introduced an innovative intersection driving assistance system (IDAS), which leveraged vehicle-to-infrastructure (V2I) communication to achieve multiple goals. The IDAS was composed of three key elements: (1) passing support (PS), offering guidance on optimal speeds; (2) an alert system for impending traffic light changes to prevent violations, and (3) a warning mechanism to avoid rear-end collisions. The study's outcomes demonstrated that the IDAS effectively harnessed the potential of infrastructure-vehicle communication systems, enhancing not just the safety of driving but also boosting passenger comfort and the overall flow of traffic at intersections [148]. Mladenović and Abbas (2013) introduced a novel approach centered on a self-organizing and cooperative control framework. This method utilized distributed intelligence across vehicles to determine the speed of approach for each vehicle. The control system was crafted within an agent-based framework, where agents autonomously adjusted their trajectories based on a newly devised priority principle. System tests confirmed its adherence to safety, comfort, and efficiency standards [149]. In their other research, Mladenović and Abbas (2014) expanded on this concept with a self-organizing, priority-driven, agent-based system for managing intersections for AVs, employing vehicle-to-vehicle (V2V) communication. The system strategically planned vehicle trajectories by integrating social priority considerations and speed calculations, leading to enhanced passenger comfort, safety, and system efficiency [150].

Schoettle and Sivak (2014) examined the behavior of drivers and passengers from five different nations: the United States, China, the UK, Japan, and India. They investigated the potential activities passengers might engage in while not driving, such as watching television or socializing, and assessed how these activities might affect passenger comfort. The

study forecasted that in China, between 6% and 10% of passengers might encounter some level of motion sickness in fully automated AVs, with 6% to 13% potentially experiencing moderate to severe symptoms. This was in contrast to the UK, where the predicted range was slightly lower at rates of 4% to 7% for any motion sickness and 4% to 9% for moderate to severe symptoms [105]. Elbanhawi et al. (2015) scrutinized the established comfort metrics used for the advantage of passengers and introduced factors for autonomous passenger consciousness. They highlighted the necessity of evaluating comfort levels in AVs. They also noted that relinquishing control could heighten the likelihood of motion sickness, whereas uninterrupted trajectory paths could help avert motion sickness and provide a more intuitive travel experience. Furthermore, they emphasized the importance of extensive consumer trials to pinpoint optimal vehicle responses and the need for research into empirical human factors to confirm the accuracy of behavioral models and strategic planning algorithms [96]. Siebert et al. (2015) formulated a 14-point scale specifically designed to evaluate driver discomfort. The research posited that discomfort is more readily perceived by individuals, thus it was employed as a proxy for the lack of comfort. This scale was tested within a driving simulator experiment and demonstrated robust internal reliability. The findings also indicated that the scale could serve as an effective instrument for gauging discomfort in automated interactions between humans and machines [78].

In 2016, Krajewski et al. introduced a novel method that was both separate and distributed, utilizing graph-based techniques to refine the longitudinal movement of various vehicles at city crossroads. This method facilitated collaborative vehicle behavior, collision avoidance, and accounted for varying elements such as traffic signals, all while optimizing a predefined cost metric. The team also implemented multiple heuristics to diminish the computational demands required to address these intricate challenges. Through simulations employing the Monte Carlo technique in an intersection model, they demonstrated a 28 percent decrease in overall costs—encompassing travel duration, operational efficiency, and passenger comfort—when compared to a traditional driver model, and a 2.6 percent improvement over a non-collaborative approach [151]. Heil et al. (2016) conducted a study where they utilized acceleration and jerk as metrics to assess comfort levels. They formulated a model for planning lane-change trajectories using a quintic polynomial, tailored for autonomous driving systems. The significant advancements of this research included the analytical methods used to assess certain characteristics of paths based on quintic polynomials, such as peak acceleration, jerk, and potential overshooting tendencies. These methodologies were scrutinized for their computational efficiency and practicality in actual vehicle testing. The findings suggested that the model was capable of creating asymmetrical, human-like lane-change trajectories, potentially enhancing the comfort of passengers [152].

Dai et al. (2016) developed a system for managing autonomous intersections (AICs) aimed at enhancing safety, fairness, overall throughput, travel efficiency, and passenger experience. They introduced a quality of experience-based algorithm (QEOIC) for scheduling vehicle passage through intersections in a manner that is both effective and fluid. By establishing a predefined decision zone and segmenting the intersection into various collision zones, they formulated a scheduling principle that assigned vehicle priority across these zones, simplifying the collision constraints. The researchers also suggested that this method was suitable for real-time traffic management. The system's design adjusts the discretization of position dimensions based on lateral trajectory influences. In regions where boundary conditions are largely uniform, greater spacing between adjacent positions is favored, reducing the computational load by minimizing the number of states. This approach also has the potential to increase comfort by maintaining consistent acceleration over longer stretches [153]. Artunedo et al. (2017) devised a strategy to enhance the comfort of passengers in AVs navigating bends. They utilized the open-source navigational framework of OpenStreetMap to transform standard navigation data into a format suitable for driving. These data were then integrated with a mixed-integer nonlinear programming optimization algorithm. The algorithm factored the vehicle's side-to-side acceleration and

abrupt movements into its loss function, intending to create a trajectory that was as smooth as possible, thereby maximizing passenger comfort [154].

In 2018, Bellem et al. undertook research to establish guidelines for the operation of self-driving vehicles to maximize passenger comfort. This research involved a simulation study to pinpoint optimal driving techniques. The study assessed three different types of driving maneuvers—lane changes, accelerations, and decelerations—by varying the levels of acceleration and jerk to alter the trajectory of each maneuver. Additionally, the study examined how personality characteristics and individuals' own descriptions of their driving habits might influence their preferences for various automated driving maneuvers. The findings indicated that for acceleration maneuvers, it was preferable to minimize both acceleration and jerk. When it came to changing lanes, it was recommended to maintain minimal acceleration and to provide early feedback about the movement. Notably, participants favored two synthetic deceleration options over deceleration in the manner of a human driver. Furthermore, personality traits appeared to have no significant impact on the preference for certain maneuvers, whereas the reported driving style of the participants had a slight influence on their choices [106]. Wang et al. (2020) executed an experiment that simulated the driving conditions anticipated in the AVs of the future. The experiment gathered data on the vehicle's dynamic parameters and the comfort levels reported by passengers of varying physiological profiles. Analytical methods, including a single-factor approach and a binary logistic regression model, were employed to identify the elements influencing passengers' comfort assessments. They developed a predictive model for passenger comfort utilizing bidirectional long short-term memory (LSTM) networks. The findings revealed that this model achieved an accuracy rate of 84 percent, offering a solid theoretical foundation for refining the control algorithms and navigational paths of self-driving vehicles [94].

Sever et al. (2021) introduced an optimal control strategy aimed at reducing a numerical index of motion sickness. This metric focused on the motion detected by the vestibular system rather than the actual movement of the vehicle. Consequently, the vestibular system's mathematical model was integrated into the controller's design. The performance metric considered both jerk and acceleration. A control-oriented, linear parameter-varying vehicle model was formulated for the path-following controller's design. Through simulation studies that applied path-following control, the motion sickness dose values for the controlled vehicle were scrutinized. The findings from a standard lane-change test at different speeds demonstrated that the newly designed controller, which targets the reduction of the motion sickness dose value, successfully decreased the acceleration and jerk experienced by passengers, ensuring that the vehicle adhered to the intended path [155]. Mims et al. (2022) sought to understand the discomfort factors for passengers in current vehicles to guide the design of forthcoming AVs. The study involved interviewing 75 individuals across three distinct demographic groups. The findings highlighted the specific discomfort triggers for each group and the differences among them. Common sources of significant discomfort included riding with a distracted driver, being in or near a vehicle that maintains a minimal following distance, and navigating through fog. Moreover, the study indicated that passenger discomfort stems from a wide array of influences, including the conduct of the driver and the vehicle they are in, the actions of nearby vehicles, environmental conditions, and the vehicle's interior design, with these factors varying across different passenger demographics [156].

In a 2023 study by Aledhari et al., the focus was on delineating the structure of self-driving vehicle systems and the supplementary frameworks that prioritize human comfort. The discussion extended to the intricacies of AV comfort systems, the reaction times of AV drivers, the comfort ratings of AVs, motion sickness concerns, and the optimization technologies involved. The research also delved into the effects of autonomous driving on users' physical and mental well-being, as well as the influence of AV comfort factors on the car industry. The aim was to provide a comprehensive review of critical technical aspects to aid researchers and app developers in understanding the various comfort factors

and systems associated with autonomous driving. To cap it off, they presented specific use cases concerning the comfort issues posed by autonomous driving [157]. Finally, Su et al. (2023) conducted a user study that developed two methods of assessing comfort: one based on continuous pressure input and the other on discrete smartphone interactions. Participants employed these methods to gauge their comfort levels during a study using a high-fidelity simulator for autonomous driving. The effectiveness of these methods in measuring comfort was scrutinized and compared. Overall, the discrete method was found to be more reliable in its measurements and exhibited less bias than the continuous method [158].

5.3. Ecology and Passenger Comfort

Several studies have highlighted the importance of ecological sustainability and passenger comfort in traffic control. A traffic management system that simultaneously addresses these objectives and achieves a satisfactory equilibrium between them could represent an optimal strategy for future implementation.

In 2014, Azimi et al. introduced the concept of spatiotemporal intersection protocol (STIP), leveraging vehicle-to-vehicle (V2V) communication and speed optimization to enhance traffic flow and prevent collisions. The method aimed to reduce delays caused by vehicles coming to a complete stop, improve fuel efficiency, and increase passenger comfort by minimizing frequent stops. The high concurrency protocols with slowdown (HCPS) were designed to allow vehicles with lower priority to decelerate as they approach an intersection, giving way to higher-priority vehicles and reducing the need for complete stops [159]. In 2015, Qian et al. tackled the challenge of directing AVs at intersections lacking traffic signals. They employed a priority-based coordination system that divided the issue into assigning priority and controlling vehicles under set priorities. Their decentralized model predictive control (MPC) strategy allowed vehicles to independently resolve optimization problems, facilitating smooth intersection crossing. This method prioritized efficiency, comfort, and fuel economy while upholding safety across the system. The decentralized MPC was found to be 4% more fuel-efficient compared to the standard MPC, and it achieved a 10% improvement in energy savings over the bang-bang (BB) control law [160].

Zhang et al. (2017) addressed the optimization problem of reducing passenger discomfort during vehicle turns at intersections. They explored the balance between lowering fuel consumption and enhancing passenger comfort. The optimal solution they developed did not necessitate extra computational resources, as the end conditions were set by another group of collision-avoidance constraints, allowing for real-time application. The solution effectively reduced passenger discomfort without compromising fuel efficiency [161]. Ding et al. (2017) introduced a centralized cooperative intersection control (CCIC) method for intersections without traffic signals in an AV setting. This method transformed the intersection control challenge into a nonlinear optimization problem that took into account factors such as vehicle delays, fuel usage, emissions, and driver comfort. A simulation study was conducted at a four-way, two-lane intersection under various traffic conditions to evaluate the CCIC against the traditional AIC systems. The findings showed that the CCIC could significantly enhance traffic flow by approximately 14%, reduce travel time by nearly 90%, cut CO₂ emissions by about 60%, and improve driver comfort by roughly 2% [162]. In 2017, Cao et al. developed a semi-decentralized, multiagent-based vehicle routing strategy to enhance punctuality, travel time, driver satisfaction, safety, fuel efficiency, and emissions. This approach involved two types of agents: vehicle agents that adhered to local route instructions from infrastructure agents at intersections, and infrastructure agents that provided route guidance by solving route assignment problems. Tests on actual road networks demonstrated their effectiveness in increasing punctuality, decreasing overall travel time, and improving routing performance, outperforming existing methods in reducing travel time, fuel consumption, and emissions, thereby contributing to intelligent transport systems and sustainable urban development [163].

In 2018, Zhao et al. explored the cooperative scheduling of CAVs at intersections without traffic lights. They created a hierarchical mathematical model of the intersection and proposed an analytical control algorithm based on Pontryagin's minimum principle for CAVs. This algorithm aimed to optimize multiple objectives while considering vehicle constraints, prioritizing safety, reducing congestion, and enhancing fuel efficiency and comfort. The low computational demand of the algorithm allowed for quick and stable optimal solutions. The simulations with high-speed CAVs at intersections confirmed the algorithm's ability to coordinate CAVs effectively, resulting in improved safety, mobility, comfort, and fuel efficiency [164]. Zhao et al. (2019) introduced a cooperative driving algorithm utilizing MPC for CAVs at intersections without traffic signals. This comprehensive model encompassed conflict points, longitudinal vehicle dynamics, and vehicular and traffic constraints. A decentralized MPC was crafted to navigate each CAV through the intersection, with objectives that included avoiding rear-end collisions, preventing intersection conflicts, boosting traffic flow, conserving fuel, and increasing comfort. The simulations demonstrated enhancements in safety, efficiency, fuel economy, and comfort for all CAVs within the intersection zone [165]. In 2020, Wang et al. devised a method for managing the traffic of CAVs across multiple intersections autonomously. Their framework was tripartite, including an autonomous strategy for crossing unsignalized intersections, the optimization of trajectories for multiple objectives along road segments, and a composite route planning approach that accounted for the varied decision-making behaviors of CAVs. They identified potential conflict points for CAV trajectories, established safe time intervals for conflict resolution, and proposed a multi-objective control model that balanced safety, energy efficiency, and comfort. This model yielded a closed-form solution for trajectory optimization. Additionally, they developed a composite strategy for route planning to accommodate dynamic traffic conditions, and simulations confirmed the method's superiority in enhancing overall traffic efficiency [166].

Zhang et al. (2021) explored traffic management at intersections for CAVs, proposing a decentralized and flexible intersection management system. This system included a novel model for assessing vehicle interactions and a priority-based rule for collision avoidance, which aimed to optimize traffic flow and reduce delays for emergency vehicles. They also designed a multi-objective function to determine the best CAV trajectories, considering comfort, speed, fuel efficiency, and safety. The simulations showed promising results in terms of traffic efficiency and reduced delays for emergency CAVs [167]. Duz et al. (2022) developed a global speed planning algorithm for AVs, prioritizing comfort alongside computational efficiency. The algorithm optimized a cost function that considered both energy consumption and comfort, with trip time as a user-defined constraint. They introduced a comfort model that accounted for various accelerations and frequency components, and their tests on a realistic scenario assessed the balance between energy use and comfort [168]. Malik et al. (2023) conducted research on convoy driving for AVs in urban settings, aiming to enhance fuel efficiency and comfort. They applied a coalitional game framework to model convoy driving as a game of coalition formation. Through extensive numerical experiments, they demonstrated that convoy driving can lead to significant fuel savings and improved comfort for passengers [169].

6. Challenges and Opportunities

Integrating AVs into current traffic systems presents a multifaceted landscape of challenges and opportunities, particularly when considering the ecological impact and passenger comfort. [170,171]. In the following, we delve into the challenges associated with the integration of AVs into road networks:

- **Technological limitations:** AVs face challenges in navigating complex urban environments due to the need for advanced AI algorithms to interpret real-time scenarios accurately, especially in congested areas and at intersections;

- **Common sense reasoning:** AVs require further developments in common sense reasoning to effectively handle unpredictable situations involving pedestrians, cyclists, and other road users, ensuring passenger safety and comfort;
- **Infrastructure and connectivity:** The absence of clear lane markings and traffic signs in some locations, along with the need for reliable communication systems like 5G technology, pose challenges for AVs to operate seamlessly in all environments;
- **Mapping and adaptability:** Developing comprehensive and adaptable three-dimensional maps for AVs to navigate accurately in diverse locations is crucial but time-consuming, requiring broad coverage and high accuracy;
- **Public perception and acceptance:** Overcoming public skepticism and building trust in AV technology is crucial for widespread adoption, as concerns about safety, cyber-attacks, and malfunctioning software can impact passenger comfort and the acceptance of AVs.

In the following, we explore the opportunities presented by the integration of AVs into road networks:

- **Safety and efficiency:** AVs offer the potential to significantly enhance road safety, reduce accidents, and improve overall transportation efficiency, benefiting both ecologically and in terms of passenger comfort;
- **Environmental impact:** The adoption of eco-friendly technologies in AVs can lead to reduced carbon emissions, improved energy efficiency, and sustainable transportation practices, aligning with ecological considerations;
- **Passenger comfort:** Improving passenger comfort is a key consideration for AV development, with advancements in motion characteristics, intelligent control algorithms, and passenger acceptance contributing to a more comfortable and enjoyable ride experience;
- **Traffic flow optimization:** AVs can optimize traffic flow, reduce congestion, and improve traffic management through intelligent routing systems and efficient navigation models, contributing to passenger comfort and ecological sustainability;
- **Economic benefits:** The integration of AVs into traffic networks can lead to economic benefits, increased mobility, and enhanced urban space utilization, offering opportunities for sustainable transportation solutions that prioritize passenger comfort and environmental well-being.

By addressing these challenges and leveraging the opportunities presented by AV technology, stakeholders can work towards a future where AVs contribute positively to both the ecological sustainability of transportation systems and the comfort and well-being of passengers.

7. Future Research Directions

In the following, some future research directions associated with integrating AVs into traffic networks, while considering ecology and passenger comfort, are presented:

- **Ecological impact assessment:**
 - Conduct in-depth studies to evaluate the long-term ecological impact of AV integration, focusing on factors such as energy efficiency, emission reduction, and sustainability practices;
 - Explore the life cycle and environmental footprint of AVs, including manufacturing, maintenance, and disposal processes, to understand the overall ecological implications of widespread AV adoption.
- **Passenger comfort optimization:**
 - Investigate innovative approaches to enhance passenger comfort in AVs, considering factors like motion characteristics, intelligent control algorithms, and passenger acceptance;
 - Explore the integration of sensory interactions and feedback mechanisms in AV design to create a more comfortable and enjoyable ride experience for passengers.

- **Traffic management strategies:**
 - Develop advanced traffic management techniques tailored to handle the challenges and opportunities presented by AVs, with a focus on enhancing overall transportation efficiency, reducing congestion, and optimizing traffic flow;
 - Explore the use of real-time data dissemination and communication systems to improve traffic management in AV-dominated networks, ensuring seamless integration and operation.
- **Accessibility and connectivity studies:**
 - Investigate the impact of AVs on accessibility within transportation networks, considering ease of approach, interaction with destinations, and overall connectivity between origins and destinations;
 - Explore the potential for AVs to enhance accessibility for diverse user groups, including the disabled, the elderly, and young individuals without driving licenses, to various destinations, including administrative, medical, and service locations, while improving transportation system efficiency and connectivity.
- **Human factors and behavioral studies:**
 - Conduct research on human factors and behavioral aspects related to AV adoption, focusing on public perception, trust, and acceptance of autonomous technology;
 - Explore how passenger behavior and preferences influence the design and implementation of AV systems to ensure a seamless and comfortable travel experience for users.

By delving into these future research directions with a focus on ecological sustainability, passenger comfort, traffic management, accessibility, and human factors, researchers can contribute valuable insights to the ongoing discourse on integrating AVs into traffic networks while prioritizing environmental well-being and passenger satisfaction.

8. Conclusions

The integration of AVs into existing traffic networks presents a complex challenge that necessitates a sustainable approach, balancing both ecological sustainability and passenger comfort. This review aimed to bridge the gap in the literature by providing a comprehensive evaluation of the ecological and passenger comfort implications of AVs' integration into traffic systems. The research highlighted the array of sustainable advantages that AV technology could offer in terms of diminishing air contamination and curbing greenhouse gas emissions. These advantages are rooted in environmentally conscious practices which include sustainable streamlined parking, eco-conscious driving behaviors, environmentally optimized traffic signals, the prevention of collisions, vehicular platooning, appropriate sizing of vehicles, alleviation of traffic congestion, strategic routing for efficiency, shared vehicle journeys, and strict compliance with traffic regulations. Additionally, the review emphasized the importance of understanding the factors affecting passenger comfort, such as vehicle motion characteristics, passengers' physiological traits, and intelligent driving technology, in enhancing the overall passenger experience within AVs.

Despite the promising sustainability aspects of AV technology, the review also identified challenges in the sustainable integration of AVs into existing traffic systems. These challenges include the need for a deeper understanding of the interconnected ecological and passenger comfort-related factors, the development of effective control algorithms to optimize AV performance, and the seamless integration of AVs into current infrastructure. However, amidst these challenges, this review highlighted numerous opportunities for innovation in the field of autonomous transportation. These opportunities include the potential for AVs to improve traffic flow efficiency, reduce emissions, and enhance passenger comfort through advanced technologies and intelligent driving systems.

Looking ahead, this review proposes future research directions to sustainably advance the field of autonomous transportation. These directions include the refinement of control algorithms, the integration of AVs into existing infrastructure, and long-term evalu-

ations of the ecological and passenger comfort implications of AV technology. The study underscored the importance of a collaborative, multidisciplinary approach involving policymakers, researchers, and industry stakeholders to navigate the challenges and leverage the opportunities presented by AV integration. By addressing these key areas, policymakers can make informed decisions and develop effective policies to maximize the sustainability of the benefits of AV technology while mitigating the potential drawbacks related to ecology and passenger comfort in the evolving landscape of transportation systems.

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