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The Environmental Sustainability Potential of Autonomous Vehicles: An Overview

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Abstract

The optimization of transportation systems and the integration of autonomous vehicles (AV) are significantly transforming urban mobility and exerting outstanding effects from an environmental perspective. This article examines the possibilities of autonomous vehicles in reducing traffic congestion, emissions, and energy consumption. The optimized driving style of AVs, dynamic route planning, and enhanced intersection systems have a profound impact on emission reduction. The article also delves into current development trends and challenges, encompassing advancements in AV sensing technologies, traffic safety, and cybersecurity. These findings collectively suggest that the deployment of autonomous vehicles brings substantial benefits to sustainable urban mobility; however, further development is necessary to support the widespread adoption of AVs and strengthen societal trust.

Keywords

autonomous vehicle, emission reduction, urban mobility, traffic optimization, sustainable transportation

1 Introduction

Autonomous driving capabilities, such as adaptive cruise control, lane-keeping, and autonomous parking, are already widely adopted on a global scale, foreshadowing the extensive prevalence of autonomous vehicles (AVs) in the near future (Bibri et al., 2024; Cao and Zöldy, 2020; Silva et al., 2022; Törő et al., 2019; Wang et al., 2018). The advent of AVs represents a pivotal moment in road traffic safety and societal transformation, yet numerous technological challenges must be addressed by manufacturers and developers.

Autonomous vehicles refer to vehicles capable of achieving their goals without human intervention, utilizing various technologies such as cameras, radar, or lidar (Szűcs and Hézer, 2022). The tasks of autonomous vehicles, as defined by Bachute and Subhedar (2021), include:

- Perception of the vehicle's entire environment (vehicles, pedestrians, cyclists, etc.).
- Motion planning and control of the vehicle through algorithms.
- Traffic sign detection and road lane recognition.
- Determining the AV's own position.
- Automated parking.
- Fault diagnosis and cybersecurity.

These vehicles can play a crucial role in addressing three main mobility challenges: reducing accident rates, alleviating traffic congestion, and minimizing the environmental impacts caused by vehicles (Salazar-Cabrera et al., 2020).

One of the primary motivations for the widespread adoption of AVs is their potential to reduce accidents by 90%, mitigating damages caused by human factors and eliminating accidents stemming from human errors (Szűcs and Hézer, 2022). Thus, AVs could contribute to achieving "Vision Zero" in transportation, aiming for completely accident-free travel (Wang et al., 2020; Winkle, 2016). Achieving this goal requires the reconstruction of accidents, examining control parameters and environmental factors, as emphasized by Lengyel et al. (2023).

Thanks to the development of autonomous vehicles and vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication, traffic congestion can be effectively reduced (Li et al., 2015).

Recognizing the potential benefits of autonomous vehicles in reducing environmental impact, particularly through optimized and efficient driving and the promotion of shared mobility services, contributes to achieving

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future climate goals (Silva et al., 2022). Thus, AVs represent a significant transformative force striving to achieve common goals of reducing accidents, easing traffic, and lowering emissions.

This article provides an overview of the pivotal role of AVs in reducing emissions, optimizing traffic flow, and shaping sustainable urban mobility, offering insights into current development trends, technological challenges, and the crucial outcomes that can be achieved through the widespread adoption of AVs, including enhanced safety, reduced environmental impact, and the need for ongoing societal trust and technological advancements.

2 Impact of innovative technologies on AV development

New technological innovations, such as artificial intelligence (AI), big data, 5G, blockchain, and intelligent traffic management models, enable the advancement of intelligent global transportation (Lv and Sang, 2023).

Smart cities, employing advanced technologies and data-driven approaches, aim to create a more environmentally friendly and livable environment. Their crucial objectives include minimizing environmental impacts, preserving resources, and achieving energy-efficient and sustainable transportation. Smart eco-cities prioritize environmental well-being and utilize renewable and sustainable technologies (Bibri et al., 2024).

Artificial intelligence (AI) plays a key role in the development of intelligent transportation systems and the design of autonomous vehicles. Companies can address environmental challenges through AI development, enhancing sustainability (Nti et al., 2022). He et al. (2022b) highlights the shortcomings of AV research in urban areas, where spatial expansion and population density pose challenges (e.g. megacities), where AI is expected to play a significant role. Examining the potential applications of Big Data and AI technologies is crucial for smart cities, as AI can assist in optimizing resource distribution (Bibri et al., 2024). Big Data algorithms can be used for tasks such as signal recognition, object detection, traffic forecasting, and travel route planning (Lv and Sang, 2023). Bibri et al. (2024) emphasize the outstanding role of AI in smart eco-cities, stating that AI offers opportunities for greater energy efficiency and safer transportation, which requires AI-controlled systems. According to Bibri et al. (2024), an AI-controlled system consists of five elements (Fig. 1):

- Sensing: collecting data
- Perception: extracting information from the data
- Learning: predicting patterns

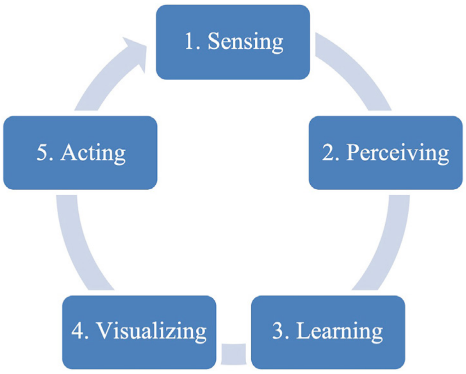

Fig. 1 Five elements of an AI-controlled system. Based on Bibri et al. (2024)

- Visualization: communicating information
- Action: achieving a specific goal.

In recent years, emission models for road traffic have significantly improved in terms of accuracy and proven to be successful estimation tools in assessing the effects of vehicle emissions (Varga et al., 2023). Varga et al. (2023) proposed a mesoscopic traffic model to increase the performance of traffic simulations while maintaining the same modeling accuracy, capable of capturing the fluctuating nature of traffic at the lane level. Wang et al. (2018) states that combining road traffic modeling with emission modeling allows researchers to reproduce vehicle movements and evaluate the data in emission studies.

The Intelligent Transportation System (ITS) enhances traffic safety and reduce environmental impacts through communication between vehicles and road infrastructure. ITS's significant advantage lies in its ability to reduce accidents, improve traffic efficiency, and decrease pollution (Lv and Sang, 2023). Intelligent Transportation Systems play a crucial role in solving transportation problems, including traffic congestion and vehicle carbon dioxide (CO_2) emissions (Lv and Shang, 2023). Integrating communication technologies focused on vehicle emissions and fuel consumption is critical in the development of autonomous vehicles, enabling more efficient decision-making (Salazar-Cabrera et al., 2020).

New technologies, autonomous vehicles, and intelligent infrastructures collectively pave the way for the development of intelligent transportation systems and smart cities (Bibri et al., 2024; Tettamanti et al., 2021).

3 Environmental impacts and possibilities of AVs

The current level of transportation results in significant greenhouse gas emissions (Wang et al., 2018). In 2015, more than 1 billion passenger vehicles were in use worldwide, and due to the current growth in vehicle usage, this number could potentially double by the early 2030s (Silva et al., 2022). Passenger cars contribute to approximately 60% of greenhouse gas emissions within the transportation sector (Silva et al., 2022). Globally, a crucial goal is for governments to achieve low carbon emissions in transportation to preserve our environment (Lv and Sang, 2023). The increasing attention to climate change and sustainable mobility is evident worldwide, with the European Union aiming to become climate-neutral by 2050 (Silva et al., 2022). Given the growth in urbanization and the number of vehicles, addressing transportation development has become an essential step (Fan et al., 2023).

In recent years, numerous companies and research institutions have been exploring autonomous driving, primarily researching its positive effects on urban mobility (Filocamo et al., 2020). Due to the development of autonomous vehicles, vehicle-to-vehicle (V2V), and vehicle-to-infrastructure (V2I) communication technologies, solutions have been developed to reduce vehicle emissions, fuel consumption, and traffic congestion (Li et al., 2015; Filocamo et al., 2020).

3.1 Shared mobility

Ride-sharing services (e.g., Uber, Didi, Lyft) play an increasingly crucial role in meeting mobility needs with the evolution of driverless communication and smartphones. However, it is essential to note that many such platforms suffer from supply shortages in certain regions or during specific periods (e.g., peak hours) due to the number of available drivers. A solution to this could be the widespread adoption of AVs in the travel services market (Qin et al., 2022). The emergence of AV fleets as an alternative transportation option is a significant step in transportation development.

Studies show that a single AV can replace up to 11 traditional vehicles, resulting in a substantial decrease in pollutant emissions (Silva et al., 2022). Liu et al. (2017) state that Shared Autonomous Vehicles (SAVs) can achieve up to 12% energy savings and reduce greenhouse gas emissions by 5.6% in urban environments compared to conventional vehicles. According to Li et al. (2022) under the Californian power grid, shared autonomous electric vehicles (SAEVs) are found to be more than 5 times less carbon-intensive than modern internal combustion vehicles (ICVs) on a per-mile and per-passenger-mile basis. Synergizing SAEV charging with grid operation, particularly with higher levels of renewable integration, can result in substantial emission reductions. Smart charging strategies, when coupled with renewable energy, can achieve up to 95% less emissions compared to other charging methods (Li et al., 2022).

Therefore, the connection between autonomous vehicles and shared mobility services becomes increasingly important for economic and environmental benefits (Qin et al., 2022; Silva et al., 2022).

3.2 Public transportation

One of the most critical measures for reducing private vehicle usage and CO_2 emissions is the development of public transportation networks (Fan et al., 2023). Manzolli et al. (2022) mentions that there are currently few studies on autonomous buses, but they have significant potential for emission reduction. In the future, autonomous buses need to consider various functions such as energy management, battery health and charging scheduling, inter-vehicle safety, and comfort (Manzolli et al., 2022). The Chinese Yutong Bus introduced an intelligent and connected autonomous electric bus project capable of autonomous driving, automatic charging, and unattended station parking (He et al., 2022a). A cloud-controlled platform is responsible for vehicle movement control and traffic regulation. Autonomous buses are expected to play a prominent role in the future as they can revolutionize urban transportation and contribute to reducing emissions (He et al., 2022a).

3.3 Driving style

Optimizing emissions and energy consumption of autonomous vehicles (AVs) depends on various factors. Research by Silva et al. (2022) has demonstrated that the driving profile of AVs can reduce emissions by up to 14% compared to human driving. Furthermore, dynamic routing systems provide additional opportunities for reduction. Silva et al. (2022) showed that AVs programmed with an aggressive driving style increase emissions by 35%, while those programmed with a cautious driving style decrease emissions by 26%. Additionally, reducing vehicle weight and optimizing speed maintenance contribute to emissions reduction (Cao and Zöldy, 2020).

Liu et al. (2017) investigated the effects of connected and autonomous vehicles (CAVs) on fuel consumption and emissions. CAV emissions were estimated using the Motor Vehicle Emission Simulator (MOVES) for various driving cycles, such as FTP (Federal Test Procedure). The FTP cycle simulates low-speed stop-and-go urban traffic, designed by the United States Environmental Protection Agency (EPA). Traditional vehicles are characterized by long reaction times and frequent speed fluctuations. In contrast, CAVs perform fewer stop-and-go movements, and through vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) connectivity, they achieve optimized driving and reduced emissions (Liu et al., 2017).

The results are presented in Table 1, indicating the reduction in individual pollutants in percentage. From the results, it is evident that the gasoline CAV, in the case of Particulate Matter (PM), achieved a reduction of 11.43%, for Carbon Monoxide (CO), 6.41%, for Nitrogen Oxides (NO_X), 13.48%, and for CO_2, a 3.03% decrease was achieved compared to a conventional gasoline vehicle. Gasoline CAV achieved a more significant reduction in PM, while diesel CAV achieved greater reductions in CO and NO_X (Liu et al., 2017).

It is important to note that the movement of CAVs on the road is currently influenced by other vehicles, affecting the possible energy savings. During the early stages of road deployment, CAVs are expected to exhibit similar cycles to traditional vehicles and may not fully realize their potential for energy savings. However, the widespread adoption of CAVs presents an excellent opportunity to reduce environmental impacts. AVs are expected to leverage their emission advantages particularly during rapid acceleration and braking events in urban environments (Liu et al., 2017).

These results highlight that the programmed driving style of AVs can significantly influence pollutant emissions.

3.4 Intersections

In the research by Filocamo et al. (2020), it is illustrated that intersections have a significant impact on emissions and fuel consumption. Therefore, there is a growing need to focus on the development of safe and efficient intersection systems in the future. According to Li et al. (2015), technical solutions are required to reduce congestion and emissions at intersections, especially under high traffic demand. Reducing the number of stops can simultaneously decrease emissions and energy consumption.

Table 1 The impact of gasoline and diesel CAVs on pollutants and CO_2 emissions compared to conventional gasoline and diesel vehicles. Based on Liu et al. (2017)

Emission reduction	Gasoline CAV	Diesel CAV
PM2.5	–11.43%	–10.69%
CO	–6.41%	–7.47%
NO_X	–13.48%	–14.25%
CO_2	–3.03%	–2.69%

Li et al. (2015) utilized ACUTA (Autonomous Control of Urban Traffic) to examine the potential reduction in pollutant emissions by autonomous vehicles at intersections. ACUTA is an intersection control system that regulates the sequence of autonomous vehicles' movements at intersections using a reservation-based control algorithm. In the Single-Tile ACUTA system, only one vehicle can occupy the entire intersection at a time, while in the Multi-Tile ACUTA system, multiple vehicles can.

Li et al. (2015) compared the Multi-Tile ACUTA model with optimized adaptive signal control strategy, which automatically adjusts signal timings based on traffic demands, outperforming pre-timed signal control. They examined the impact on various pollutants under three traffic conditions: low (300 vehicles/h), medium (900 vehicles/h), and high (1,800 vehicles/h) traffic. The ACUTA model achieved a 5.6%, 4.9%, and 3% reduction in CO emissions compared to the signal system under low, medium, and high traffic conditions, respectively (Fig. 2). For NO_X emissions (Fig. 3), the ACUTA model achieved a 5.8%, 5.2%, and 2.6% reduction under low, medium, and high traffic conditions, respectively. Regarding energy consumption

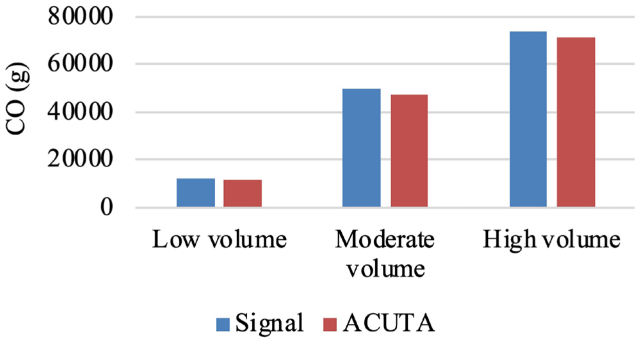

Fig. 2 Comparison of CO emission between signal control and multi-tile ACUTA model. Based on Li et al. (2015)

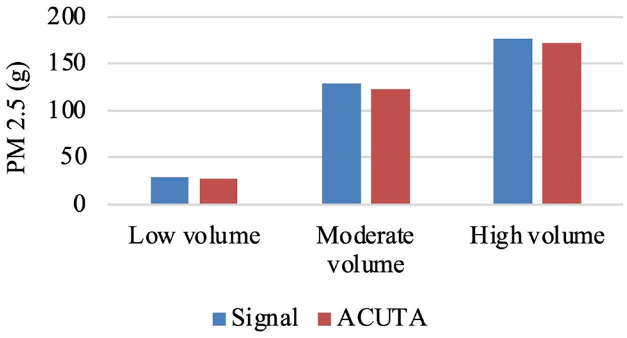

Fig. 3 Comparison of PM2.5 emission between signal control and multi-tile ACUTA model. Based on Li et al. (2015)

(Fig. 4), the ACUTA model achieved a 3.8%, 4.9%, and 11.9% reduction under low, medium, and high traffic conditions, respectively (Li et al., 2015).

Li et al. (2015) compared the Single-Tile ACUTA model with the Four-Way-Stop-Control (4WSC) under three different traffic conditions: low (75 vehicles/h), medium (150 vehicles/h), and high (225 vehicles/h) traffic. The Single-Tile ACUTA model reduces CO emissions (Fig. 5) by 14.3%, 15.2%, and 16.8%, PM emissions (Fig. 6) by 12.2%, 16.5%, and 18.3%, and energy consumption (Fig. 7) by 16.2%, 15.7%, and 14.6% under low, medium, and high traffic conditions, respectively. Filocamo et al. (2020) examined the impact of autonomous vehicles on travel time, emissions, and fuel consumption at intersections. In their research, they assumed vehicle-to-vehicle (V2V) communication, eliminating the need for additional intersection controllers. The methodology followed the principle that the first vehicle to reach the intersection has the right of way to pass (FRFP = first reach, first pass). In this case, priority can be given to the vehicle that is farther away if it is moving faster, reaching the intersection sooner. Another method is the FCFS (first come, first served) system, where the vehicle closest to the intersection gets the right of way, but it does not consider their speed. Thus, a vehicle that is close to the intersection but moving very slowly may also get the right of way (Filocamo et al., 2020).

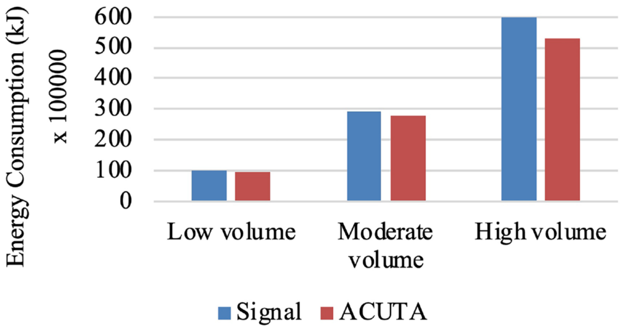

Fig. 4 Comparison of energy consumption emission between signal control and multi-tile ACUTA model. Based on Li et al. (2015)

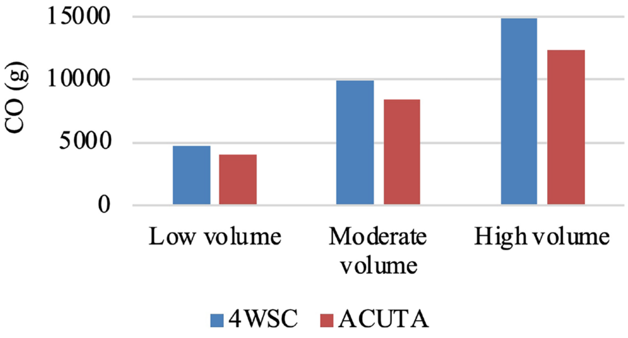

Fig. 5 Comparison of CO emission between 4WSC and single-tile ACUTA model. Based on Li et al. (2015)

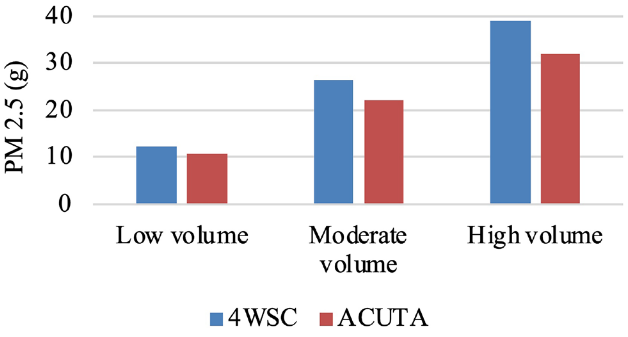

Fig. 6 Comparison of PM2.5 emission between 4WSC and single-tile ACUTA model. Based on Li et al. (2015)

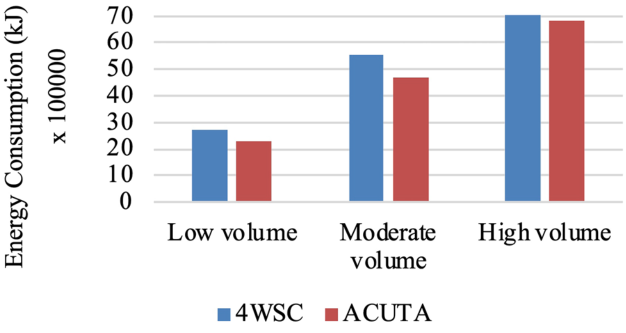

Fig. 7 Comparison of energy consumption emission between 4WSC and single-tile ACUTA model. Based on Li et al. (2015)

Fig. 8 shows a simple intersection examined by Filocamo et al. (2020). The vehicles communicate their position (S), speed (v), and estimated arrival time (t). The vehicle that reaches the intersection first has the right of way. The other vehicle is notified of the necessary deceleration (a). Only one vehicle can be in the intersection at a time, and a safety factor must be used for maximum safety (Filocamo et al., 2020).

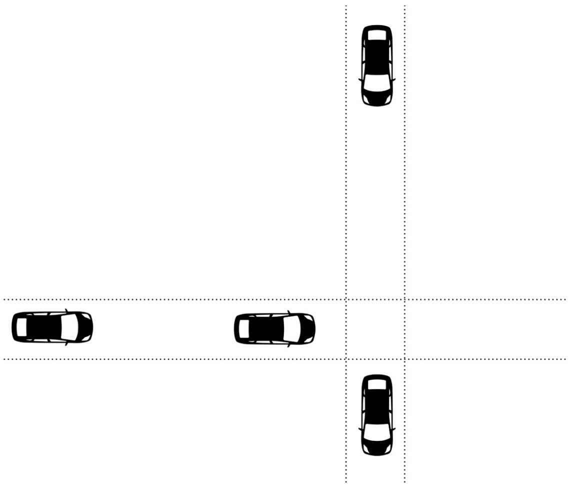

Fig. 8 Two-lane intersection. Based on Filocamo et al. (2020)

Filocamo et al. (2020) compared the developed FRFP method using simulations with the traditional traffic light system and the FCFS system with different intersection types. They examined average speed, CO_2 emissions, and fuel consumption. The results of the study are shown in Table 2 and Fig. 9. The first examined intersection type (Fig. 8), with a traffic flow of 3,450 vehicles per hour, showed that the FCFS method yielded the best results. The FRFP algorithm provided 175.3% higher average speed, 36.7% less CO_2 emissions, and lower fuel consumption compared to the traditional traffic light system. There is no significant difference between the FCFS and FRFP methods.

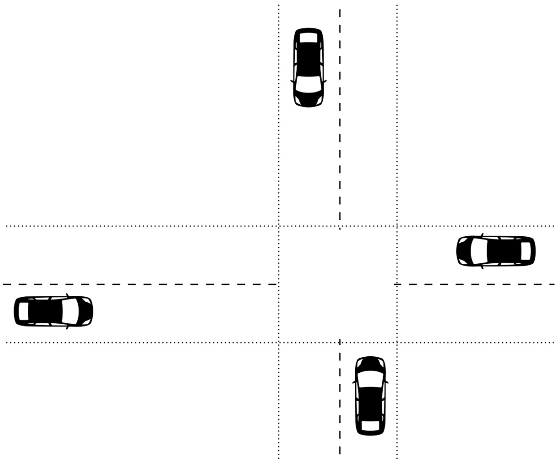

Fig. 11 8-lanes intersection. Based on Filocamo et al. (2020)

The second type of intersection examined is illustrated in Fig. 10. In this intersection, the FRFP algorithm achieved a 38.8% higher average speed, a 12.6% reduction in CO_2 emissions, and lower fuel consumption compared to the traditional traffic light system. The FCFS system resulted in a 1.8% lower CO_2 emission compared to FRFP, but FRFP achieved a faster average speed. The third type of intersection, as illustrated in Fig. 11, had a traffic flow of 2,380 vehicles per hour. In this scenario, the FRFP algorithm demonstrated a remarkable 217.3% higher average speed, a 59.7% reduction in CO_2 emissions, and lower fuel consumption compared to the traditional traffic light system. The FRFP system achieved 22.4% higher average speed and a 14.4% reduction in CO_2 emissions compared to FCFS. This highlights the substantial advantage of the FRFP algorithm, particularly in high-traffic situations.

Table 2 The algorithms' impact on average speed, emissions, and fuel consumption in various intersections. Based on Filocamo et al. (2020)

	Vehicles/hour	Method	Average speed (m/sec)	Emission CO_2 (mg)	Fuel Consumption (mL)
2 lane intersection	3450	Traffic Light	3.83	258,094,493	110,946
		FCFS	10.46	164,779,985	70,831
		FRFP	10.54	163,263,697	70,180
On-ramp intersection	1773	Traffic Light	4.91	60,569,184	26,037
		FCFS	6.7	51,981,274	22,345
		FRFP	6.81	52,912,280	22,745
8 lanes intersection	2380	Traffic Light	2.56	155,409,183	66,807
		FCFS	6.64	73,131,010	31,436
		FRFP	8.23	62,571,993	26,897

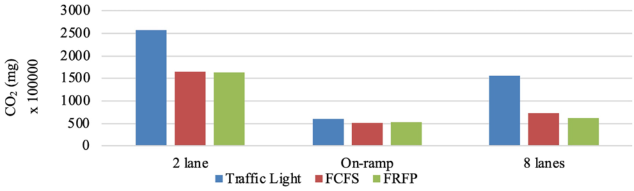

Fig. 9 The algorithms' impact on CO_2 in various intersections. Based on Filocamo et al. (2020)

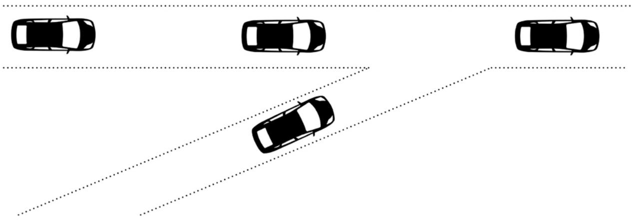

Fig. 10 On-ramp intersection. Based on Filocamo et al. (2020)

Filocamo et al. (2020) demonstrates that the FRFP method has a substantial impact on improving average speed, reducing emissions, and minimizing fuel consumption in various intersection scenarios. These findings underscore the potential benefits of advanced algorithms in optimizing traffic management for environmental and efficiency gains.

In general, it can be concluded that optimized intersection systems significantly contribute to sustainable transportation development and the reduction of environmental impacts associated with autonomous vehicles (AVs).

3.5 Alternative propulsion system

Alternative fuels and propulsion systems, such as compressed and liquefied natural gas, as well as electric propulsion, play a crucial role in sustainable transportation solutions (Manzolli et al., 2022; Wang et al., 2018). Electric propulsion has become prevalent in various manufacturer models; however, it is imperative to emphasize the use of renewable energy sources for electric vehicles. In this context, employing electric propulsion in autonomous vehicles (AVs) can positively impact vehicle emissions (Wang et al., 2018).

3.6 Parking

In many cities, there are areas where there is insufficient parking space during peak hours, leading to increased traffic congestion, delays, and emissions. According to Estepa et al. (2017) in a 15-block business district in Los Angeles, it takes an average of 3.3 minutes for drivers to find available parking spaces, resulting in the daily emission of 47,000 gallons of gasoline and 730 tons of carbon dioxide. Estepa et al. (2017) proposed the concept of dual parking (Fig. 12) for autonomous vehicles to temporarily increase parking capacity, simultaneously reducing travel time, fuel consumption, and emissions. Double parking involves an organized double row formed by autonomous vehicles. Introducing dual parking in metropolitan areas holds significant potential for reducing fuel consumption and emissions associated with AVs (Estepa et al., 2017).

3.7 Dynamic route planning

Liu et al. (2019) proposed a dynamic route planning algorithm to enhance the energy efficiency of connected and autonomous vehicles (CAVs). The algorithm takes real-time traffic data into account to minimize both time and energy requirements for the route. The advantage of dynamic routing over static routing lies in its ability to formulate an optimal path based on the current traffic conditions of the road network. Various scenarios were examined, showing that CAVs achieved energy consumption reductions ranging from 5% to 16% compared to conventional vehicles. Therefore, dynamic route planning in CAVs can significantly contribute to reducing energy consumption.

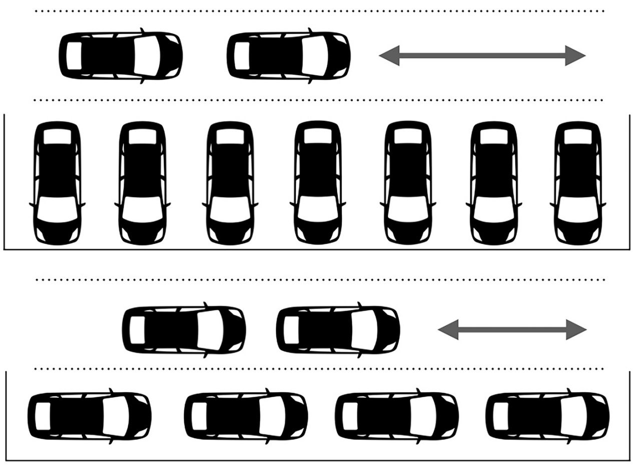

Fig. 12 Double parking examples. Based on Estepa et al. (2017)

3.8 Lane-drop

Lane-drop, indicating a reduction in the number of lanes, is a common occurrence on highways due to construction, accidents, or lane closures (Fig. 13). This phenomenon often leads to traffic congestion, resulting in increased emissions and fuel consumption. Guo et al. (2020) proposed an integrated Variable Speed Limit (VSL) and Lane Change (LC) control for CAVs in response to lane-drop events. The suggested method was examined in three environments through simulation. The first environment involved a lane-closure event lasting 10 minutes (small event) (Table 3), the second lasted 30 minutes (normal event) (Table 4), and the third simulated a scenario (Table 5) where the incident does not cease (e.g., construction) (Guo et al., 2020).

The study evaluates a proposed control method (VSL+LC control) across these three scenarios in a two-lane freeway

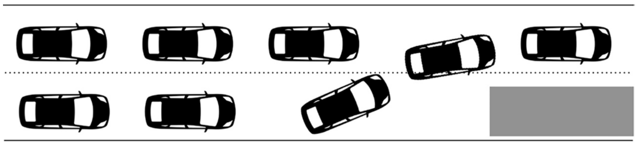

Fig. 13 Lane closure example. Based on Guo et al. (2020)

Table 3 The small event's impact on travel time, travel distance, pollutants, and CO_2 emissions. Based on Guo et al. (2020)

Change rate	VSL-only control	VSL + LC control
Travel time	–9.16%	–23.86%
Travel distance	0%	+13.56%
CO_2	–4.45%	–11.23%
PM_X	–4.84%	–10.29%
NO_X	–4.85%	–12.32%

Table 4 The normal event's impact on travel time, travel distance, pollutants, and CO_2 emissions. Based on Guo et al. (2020)

Change rate	VSL-only control	VSL + LC control
Travel time	–13.84%	–44.62%
Travel distance	–0.27%	–0.20%
CO_2	–8.78%	–25.03%
PM_X	–10.13%	–23.91%
NO_X	–9.75%	–26.65%

Table 5 The big event's impact on travel time, travel distance, pollutants, and CO_2 emissions. Based on Guo et al. (2020)

Change rate	VSL-only control	VSL + LC control
Travel time	–13.84%	–44.62%
Travel distance	–0.27%	–0.20%
CO_2	–8.78%	–25.03%
PM_X	–10.13%	–23.91%
NO_X	–9.75%	–26.65%

under constant high traffic demand. The method is compared with no control and Variable Speed Limit control (VSL-only), with significant improvements observed in travel time and average emissions. In each scenario, travel time shows notable improvement percentages compared to the no control case. The integrated control method distributes lane change maneuvers, reducing congestion and waiting times, resulting in environmental benefits. Emissions of CO_2, PM_X, NO_X decrease considerably under the proposed control, outperforming VSL-only control. The reduction in emissions is attributed to decreased waiting times and harmonized vehicle speeds, minimizing acceleration and deceleration-related emissions. Longer incident durations correlate with greater reductions in emissions (Guo et al., 2020).

4 Current development trends and directions

AVs have reached a significant technological level, yet there remain numerous problems and challenges that manufacturers and researchers need to address.

AVs are now much more capable of perceiving their surroundings even in adverse weather conditions compared to traditional vehicle drivers. However, there are still development opportunities in this area (Winkle, 2016). AVs employ various sensors for information gathering, such as radars, lidars, infrared, ultrasonic sensors, and cameras. Szalay et al. (2021) emphasizes the importance of cooperative perception system in autonomous vehicles, covering a broader range of traffic conditions. Using the approach proposed by Rozsa et al. (2022), estimating the position, speed, and 3D shape of moving objects is twice as fast with a mono camera using two frames compared to a method using three frames. According to Zhang et al. (2023), adverse weather perception can be significantly improved through various machine learning and image processing methods, including noise reduction techniques. During rainy night driving, where raindrops blur the camera lens and make it challenging to detect pedestrians and cyclists, active learning can provide more than three times more accurate detection.

Aldoski and Koren (2023) draw attention to the diversity problem of traffic signs in the context of AVs. Traffic signs can visually differ from country to country, complicating the implementation of recognition techniques. Cybersecurity is an essential aspect of AV safety. Particularly, GPS, image recognition, and light sensing systems pose security risks (Szűcs and Hézer, 2022). It is also crucial to examine the impact of AVs on noise pollution, as urban noise pollution can decrease by up to 24% due to reduced traffic, considering only the presence of autonomous vehicles (Silva et al., 2022).

These findings collectively demonstrate that intelligent transportation systems and autonomous vehicles offer numerous benefits for environmental protection and sustainable transportation solutions. However, further development is required, particularly in areas such as infrastructure adaptation, regulatory frameworks, public awareness, safety measures, cybersecurity protocols, and enhancement of perception systems. Addressing these aspects is crucial to fully realize their potential and overcome existing challenges.

5 Public perception of AVs

The acceptance of autonomous vehicles (AVs) and the societal impacts of AV fleets are influenced by various factors. The ethical and moral considerations surrounding AVs currently stand as one of the most crucial aspects for their widespread adoption (Bachute and Subhedar, 2021).

Alongside the technical challenges in the development of autonomous vehicles, numerous legal and ethical dilemmas await resolution. Highlighting the significance of "death algorithms" and questions of responsibility in AV-related accidents underscore the need for clarity on the accountable parties and the ethical principles guiding such situations (Szűcs and Hézer, 2022; Tettemanti et al., 2021). An essential question revolves around whether occupants of AVs can benefit in a potentially fatal accident or if the principle of minimizing casualties will prevail. According to a survey, people tend to view AVs more positively if they save more lives but might refrain from purchasing them if the vehicle can sacrifice occupants (Rhim et al., 2021). It is crucial to clarify whether AVs may violate traffic rules when necessary and, if so, under what circumstances (Szűcs and Hézer, 2022).

Research by Krizsik and Sipos (2023) indicates that factors such as age, income, and fuel costs influence the acceptance of AVs. Younger generations generally show greater acceptance of autonomous vehicles, while acceptance among older individuals increases, especially after successful test drives.

In general, fear and negative perceptions of AVs can hinder their widespread adoption globally.

6 Evaluation of sources

In this analysis, a total of 32 articles were examined, contributing insights into various facets of autonomous vehicles (AVs). The sources were categorized into distinct themes (Table 6) to facilitate a comprehensive evaluation.

Ten articles cover a wide spectrum of environmental considerations related to AVs. Eleven sources collectively provide insights into the optimization and challenges associated with traffic systems. Ten articles contribute to understanding the latest advancements, challenges, and future trends in AV technology. Two sources shed light on the achievements and challenges within the realm of battery electric vehicles. Two articles delve into the ethical considerations and societal implications associated with autonomous vehicle technologies. Five articles offer valuable insights into simulating critical vehicular functions or conducting accident reconstructions.

7 Summary and outlook

In response to the escalating challenges of urban transportation, the development of autonomous vehicles (AV) and optimized traffic systems becomes a key factor in shaping sustainable and efficient urban mobility. The integrated approach, considering driving profiles, vehicle mass, alternative propulsion, and the role of Intelligent Transportation Systems (ITS), is crucial for designing eco-friendly transportation systems and combating climate change. Innovative technologies, such as AI and Big Data, play a pivotal role in this development.

This article meticulously examines the possibilities of autonomous vehicles in reducing traffic congestion, emissions, and energy consumption, emphasizing the role of alternative propulsion, shared mobility, and public transportation. The evolution of smart cities and transportation systems can pave the way for a more sustainable future, with autonomous vehicles playing a pivotal role in reducing emissions and enhancing traffic efficiency. Future potentials include dynamic route planning, the effects of lane closures, and optimizing driving styles during the integration of autonomous vehicles. Based on comparisons and results, the research indicates that ACUTA models effectively reduce pollutant emissions and energy consumption under various traffic conditions. In the development of environmentally conscious transportation, researchers and industry stakeholders need to collaborate to address new challenges.

Table 6 Overview of utilized literature

Research Topics	Literature
Emission Reduction and Environmental Impact of AVs	Estepa et al., 2017 Fan et al., 2023 Filocamo et al., 2020 Guo et al., 2020 Li et al., 2015 Liu et al., 2017 Lv and Shang, 2023 Nti et al., 2022 Salazar-Cabrera et al., 2020 Silva et al., 2022
Traffic Systems and Traffic Management	Aldoski and Koren, 2023 Törő et al., 2019 Cao and Zöldy, 2020 Estapa et al., 2017 Filocamo et al., 2020 Guo et al., 2020 Liu et. al., 2019 Tettamanti et al., 2021 Szalay et al., 2021 Varga et al., 2023 Wang et al., 2018
Autonomous Vehicle Technology Advancements and Development Trends	Bachute and Subhedar, 2021 Bibri et al., 2024 He et al., 2022b Lv and Shang, 2023 Qin et al., 2022 Rozsa et al., 2022 Szűcs and Hézer, 2022 Wang et al., 2020 Winkle, 2016 Zhang et al., 2023
Battery Electric Vehicles	He et al., 2022a He et al., 2022b Manzolli et al., 2022
Ethics and Social Perception	Krizsik and Sipos, 2023 Rhim et al., 2021
Simulation and Modeling	Lengyel et al., 2023 Li et al., 2015 Liu et al., 2017 Tettamanti et al., 2021 Varga et al., 2023

Reviewing current development trends, the article explores the advancement of AV sensing technologies and cybersecurity challenges. Furthermore, it emphasizes the significance of societal acceptance and ethical considerations related to AVs, including responsibility in accident scenarios and the ethical guidelines applied by AVs. Based on these findings, it can be concluded that the application of AVs, optimized intersections, and new technologies can promote sustainable urban mobility. However, further research and development are needed to enhance technological efficiency, cybersecurity, and societal acceptance, fully realizing the potential of these innovations in shaping the future of urban transportation.

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