Comprehensive Literature Review of Environmental Pros and Cons Impacts of Connected and Automated Vehicles

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Executive Summary

Future motor vehicles are expected to increasingly be connected and automated vehicles (CAVs[1]). While technical understanding of CAV design and performance may be advancing, knowledge of CAV adoption patterns, impacts on urban mobility and the environment, and appropriate regulatory and policy responses, is underdeveloped. This report investigates how transitioning from conventional vehicles to CAVs will impact transport systems and the environment. Based on an extensive literature review and analysis, the report explores the positive and negative environmental impacts of CAVs, synthesising findings from the scholarly literature and technical reports. It includes a discussion and analysis of the environmental impacts of CAVs at vehicle level, transport system level, and urban system level, across the major CAV implementation models. Given there is minimal existing research on the environmental impacts of different CAV technologies, this review attempts to assess these impacts of increased vehicle automation and vehicle connectivity. By critically reviewing and analysing the existing literature, this report aims to provide insights into the complex environmental implications of motor vehicle technology transformation, to explore technological developments, and to inform policymakers, researchers, and stakeholders about the challenges and opportunities associated with widespread adoption of these technologies. It also identifies critical knowledge gaps and under-researched issues and suggests opportunities for future research to better inform government policy and decision-making.

According to the literature, CAVs will have both positive and negative impacts on the environment. And that many of these findings are either heavily caveated or subject to significant penetration of CAVs across the fleet.

For example, at the vehicle level, numerous studies found that CAVS can reduce fuel consumption by 20 per cent and the platooning of vehicles will reduce it by a similar amount. However, the

[1] The report uses the term CAVs (i.e. vehicles that are both connected and automated) as a starting point for discussing the research findings. However. much of the research does not specify whether automation or connectivity or both technologies are in scope so the term CAVs is used as the default descriptor.

benefits are modest when CAV penetration are below 50 per cent. At the same time, the increased travel and speed made possible by CAVs could increase energy use by 40 per cent on highways.

At the transport system level, CAVs could significantly reduce the size of the fleet, with its attendant reductions in energy use and infrastructure impact. However, this is only when the CAVs are shared or used in public transport. Private CAV ownership would not decrease the size of the fleet and may even allow more trips travelled, including by currently under-serviced groups such as people with a disability, the elderly or children. Many of these additional trips may be with no passengers aboard (so-called 'empty trips'). Studies also found that the relevant safety of CAVs could enable travel at faster speeds, but this also increases energy use and a potential increase in fuel use of 40 per cent.

At the urban system level, one study found that CAV-related changes to road design, parking and service stations could lead to positive environmental impacts, however there are likely to be negative impacts in terms of increased noise in urban environments, additional infrastructure requirements and impacts on land and water resources.

The study also found barely any literature in relation to three critical points:

- Identifying the additionality that CAVs will bring to the environment beyond that already expected to be achieved through vehicle electrification.
- Comparing the possible environmental impacts across the different application of CAVs (i.e. private passenger use versus public transport).
- Unpacking the connectivity from automation impacts

See section "Gaps in Knowledge" below for more information.

The main findings of the literature review can be summarised as follows.

Potential positive environmental impacts:

- CAV technologies can foster more streamlined driving behaviours and enable vehicles to operate more efficiently, cooperate with other vehicles, and travel on faster guided routes. These advantages will improve vehicle fuel efficiency and reduce greenhouse gas (GHG) emissions per kilometre travelled.

- Improved vehicle connectivity technologies enable "platooning" of heavy automated vehicles, and the coordinated flow of CAVs can increase traffic efficiency, road capacity, and overall transport network performance, potentially lowering GHG emissions and energy consumption.

- CAVs will enable more on-demand trips with their advanced route planning and automation systems. Expanded car-sharing programs may reduce the need to own a car and allow multiple users to share a single vehicle, thus reducing the number of vehicles on the road and promoting more efficient use of resources.

- The reduced parking demands of CAVs may liberate more land resources in urban areas, which can then be repurposed for residential and commercial development. Such infill development would allow denser urban cores and increase energy-efficient occupancy.

- Studies show different trends in decreasing GHG emissions for different CAV penetration levels. While various scenarios promise reductions in emissions with increasing CAV penetration, the rate and extent of reductions vary.

Potential negative environmental impacts:

- CAVs will bring new forms of mobility that can generate additional vehicle travel on roads, such as more empty trips. These additional travel demands may offset and diminish the potential emission reductions per vehicle facilitated by new technologies.

- Efficient CAV operation can reduce the perceived value of travel time. The reduced driving burden of CAVs and the time saved by mobility gains might then be used for additional distance and time spent on travel. Increased road capacity enabled by CAVs may also attract more vehicle travel, thus increasing transport pollution, noise, and other environmental burdens.

- Increased convenience and mobility gains could potentially shift residential choices and increase sprawl in urban areas. Increased accessibility in urban areas could also disperse land use, activity patterns, and transport patterns, generating second-order environmental impacts over the long term.

- CAVs could reduce public transport (PT) use by providing more convenient and cost-effective transport options. If more PT passengers switch to car use, total vehicle travel will increase, generating higher environmental burdens.

- CAV transportation will likely deploy, operate, and maintain substantial sensors, data processing, storage, and communication devices in transport systems, which will consume more electricity, generate higher emissions, and hinder environmental outcomes.

- Other computational demands of CAV systems, including cybersecurity technology for CAVs, could generate additional energy and environmental costs.

Gaps in the current literature:

- As noted above, there is a notable research gap regarding whether the additional capabilities of CAVs translate into incremental environmental advantages over conventional electric vehicles (EVs). It is essential to quantify the additional benefits these technological advancements may offer beyond those achieved by EVs alone, primarily in relation to GHG reductions.

- Scant research has estimated the distinct effects of particular vehicle connectivity and automation technologies from basic vehicle operations making related investment policies difficult to formulate. More dedicated research is needed, particularly on the transport changes enabled by vehicle connectivity and their environmental outcomes.

- Many research results have been based on theoretical approaches, with few experimental studies focusing on real-world environmental impacts. Future work could include generating, collecting, and analysing real-world data from CAV pilot projects or early deployment areas for more realistic evaluations.

- Commercial vehicles constitute a significant share of total vehicle fleets, but there is a lack of research on the impacts of private vehicles versus shared commercial ownership. Future research needs to address these different impacts.

- Vehicle fleet transition is occurring rapidly. Previous findings on travel behaviour and vehicle adoption patterns at earlier stages of technological development have turned out to be outdated. New research is needed to capture more recent changes and ongoing trends.

- Most research findings were based on studies centred on Europe or the USA. Further research is needed to provide a larger evidence base to inform government policy on implementing CAV transformation and to provide suggestions for mitigation strategies to reduce the negative impacts that may occur in Australia.

In summary, CAVs and AVs present both positive and negative environmental effects. By promoting the use of electric and low-emission car models, better traffic flow, and more intelligent routing, these technologies have the potential to lower GHG emissions and air pollution. By limiting needless accelerations and decelerations, CAVs and AVs can improve fuel efficiency and reduce carbon footprints and energy consumption. In addition, shared automated mobility services may result in fewer cars on the road, easing traffic and lowering overall emissions. On the other hand, the production and use of CAVs and AVs will demand more energy and could cause an accumulation of electronic waste which harms the environment. Even though CAVs and AVs present new possibilities for environmentally friendly transportation, cautious planning, regulation, and innovation are required to minimise potential environmental harm and optimise whatever benefits they may have. Moreover, vehicle adoption patterns, such as vehicle ownership models, are anticipated to significantly impact whether AVs will decrease or augment overall VKT and ensuing GHG emissions. Some studies suggest that the favourable emission outcomes might not materialise at lower AV penetration rates, with the most significant emission reductions probably occurring within the 60–80% range of AV penetration. Further research in the gap areas identified in this study is required to inform policy aimed at increasing the positive impacts while reducing the expected negative impacts.

Glossary of terms

(Excluding proper nouns)

Term	**Acronym**
Adaptive cruise control	ACC
Artificial intelligence	AI
Automated vehicle	AV
Central business district	CBD
Cooperative adaptive cruise control	CACC
Connected Automated vehicle	CAV
Electric Automated vehicle	EAV
Electric vehicle	EV
Greenhouse gases	GHG
Human-driven vehicle	HDV
Intelligent transportation systems	ITS
Linear-quadratic	LQ
Miles per gallon	mpg
Per passenger mile	Ppm
Private Automated vehicle	PAV
Pulse-and-gliding	PnG
Public transportation	PT
Shared Automated vehicle	SAV
Unmanned aerial vehicle	UAV
Vehicle kilometres travelled	VKT
Value of travel time	VTT
Vehicle-to-cloud	V2C
Vehicle-to-infrastructure	V2I
Vehicle-to-vehicle	V2V

1. Introduction

Compared to the residential, industrial, and commercial sectors, the transportation sector is the most dependent on fossil fuels, making it their fastest-growing consumer with an annual growth rate of 1.7% from 1990 to 2021 [1]. In 2021, this sector alone accounted for 37% of total CO_2 emissions across all sectors [1]. New technologies in sustainable transportation are being developed worldwide to reduce air pollution, ease traffic congestion, and improve travel convenience. These technologies aim for intelligent and environmentally friendly urban traffic [2]. As transportation technology advances, many automakers are declaring intentions to launch new models onto the market, including connected and automated vehicles (CAVs), automated vehicles (AVs), and electric vehicles (EVs) [3]. Over the past few decades, there has been a discernible trend in the automotive industry toward incorporating new technologies into vehicle design. The main goals of these technologies – including improvements in connected, automated, and electric vehicles – are to improve road safety and lessen the environmental impact of vehicle traffic. CAVs and AVs could revolutionise the transportation industry with advantages like increased convenience and efficiency. However, these developments also have important environmental ramifications that need careful consideration.

Under the definition provided by the Center for Advanced Automotive Technology, "connected vehicles are defined as vehicles that use any of a number of different communication technologies to communicate with the driver, other cars on the road (vehicle-to-vehicle [V2V]), roadside infrastructure (vehicle-to-infrastructure [V2I]), and the "cloud" [V2C] [4]. One of these options is the use of AVs, which supposedly will open up new possibilities for implementing safe, intelligent, and environmentally friendly mobility initiatives [5]. Scholars, traffic controllers, and city planners are now concentrating more on the effects of this cutting-edge mobility solution [6]. The National Highway Traffic Safety Administration (NHTSA) of the US Department of Transportation defines automated, automated, or "self-driving" vehicles as "those in which at least some aspects of a safety-critical control function (e.g. steering, throttle, or braking) occur without direct driver input." [7]. In 2014, the Society of Automotive Engineers (SAE) divided AVs into six automation levels, from level 0 (incomplete automation, in which no systems replace driving duties) through to level 5 (full automation) [8].

Governments everywhere have been pushed to evaluate the environmental effects of transportation projects before implementation because of growing concerns about the negative environmental externalities of development and road transportation. The development of AVs is the current trend in the automotive industry [9], driven by factors such as increased productivity, decreased fuel consumption, and reduced traffic congestion [10]. The technological advances necessary to realise the level of autonomy capable of positively impacting the environment are still in developmental phases. Generally, it is assumed that the best results would occur at level 5 of automation, as defined by the generally recognised SAE standard [11]. Projections of timelines for availability of this technology vary significantly across studies, although they commonly suggest a horizon around 2030, with a further 10 to 20 years needed before a majority of vehicles are AVs [12].

Much of the literature on the GHG impacts of CAVs fails to apportion an additionally to CAV impacts beyond that already to be achieved through vehicle electrification. Many prior research endeavours have investigated the contribution of CAVs and AVs to enhancing transportation sustainability by curtailing energy consumption and GHG emissions. One estimate regarding complete automation, for example, was proposed by Wadud et al., derived from the "Strong Responses" model [13] and based on the shared-vehicle paradigm. In this framework, the maximum energy reductions from eco-driving, right-sizing, car-sharing, and platooning are in effect counterbalanced by the maximum energy increases from new user cohorts and increased velocities.

Tomás et al. [14] investigated the GHG consequences linked to three AV penetration rates (10%, 20%, and 30%) in an urban freeway corridor in Porto, Portugal. Using a system dynamics approach and a stock-and-flow model, Stasinopoulos et al. [15] evaluated the GHG effects of vehicle automation for a range of scenarios. Both studies suggest that the emissions reduction benefits of switching to AVs might be outweighed by inefficiencies in AV use and by induced demand.

In one of the rare literature reviews focused on environmental consequences, Kopelias et al. [3] highlight energy consumption and emissions as central concerns among researchers. Propulsion type, vehicle design, platooning, eco-driving, route selection, congestion mitigation, vehicle kilometres travelled (VKT), on-demand or shared mobility, penetration levels, use by non-driving populations, and user preferences are some factors the study outlines as contributing to these impacts. Wadud et al. [13] also looked at emissions and consumption, and they agree on several points while adding new ones, i.e. increased speed, the increased weight of improved comfort and entertainment features, and modified speed capabilities. Taiebat et al. [16] broadened the focus to include changes in land use, energy recharging systems, and infrastructure requirements. Interestingly, scholars have recently focused on the latter aspect because it can influence new mobility paradigms in the direction of either increased pollution or sustainability [17].

However, the existing literature overlooks broader environmental impacts, primarily linked to urban sprawl, despite addressing the impacts of land use changes on fuel consumption and emissions. Wilson and Chakraborty [18] and Bicer and Dincer [19] highlight the negative consequences of urban sprawl for land and water resources. These consequences include the loss of agricultural land, disturbance of natural terrains and habitats, flooding, overuse of water, disruption of hydrological balances, rainwater loss, depletion of abiotic resources, acidification, eutrophication, and soil toxicity, among others.

Given this apparent neglect of various potential environmental impacts of automated driving despite their potentially far-reaching consequences [20], this report adopts a dual purpose – to scrutinise the positive and negative environmental effects of CAVs and AVs acknowledged among researchers and to highlight under-explored or scarcely mentioned domains as avenues for future investigation. The article thoroughly examines the literature on this topic to achieve this objective, using Boolean searches of databases. The search will identify, select, appraise, and synthesise relevant studies, and find helpful evidence to fill knowledge gaps by:

1. Exploring the literature focused on CAVs and AVs in the last decade
2. Identifying the environmental factors related to energy consumption and GHG emissions
3. Evaluating the positive and negative environmental impacts of CAAs and AVs at vehicle operation, transportation system, and urban system levels.
4. Assessing the effect of the technological development of CAVs and AVs on the environment

5. Discussing research gaps, policy implications, and recommendations for future work.

The following sections of this article are arranged as follows. Section 2 elucidates the methodology for selecting pertinent scientific literature. Section 3 presents the findings from the literature review, divided into six subsections. Section 4 presents critical discussion, limitations, and future directions. Section 5 summarises the conclusions.

2. Methodology

Using search engines, the body of research since 2014 on the effects of CAVs and AVs on the environment has been examined. To find sources for the review, Boolean searches were made on databases using scientific indexes, including Scopus, Google Scholar, and Web of Science, supplemented by searches of grey literature (government and industry publications). A first search included the most commonly used keywords to refer to CAVs and AVs, i.e. "Autonomous" or "Automated" or "Self-driving" or "Driverless", and "Vehicle(s)" or "Car(s)", and "Environmental Impacts", "Emissions", and "Energy consumption", which yielded thousands of results.

There were three stages to the process. The first involved finding scientific journal articles containing the specified keywords. Following identification, a review process was used to remove duplicate articles and those not sufficiently representative of the field. No limitations were placed on studies' locations or their years. Finally, pertinent literature was chosen. This review considers only English-language publications because the researchers could access them. The literature review is structured according to three major levels:

1. Vehicle level (operation efficiency)
2. Transport system level (travel times, VKT, mode share, traffic volume and congestion, accidents)
3. Urban system level (land use, density, infrastructure, parking, urban centres, freight hubs)

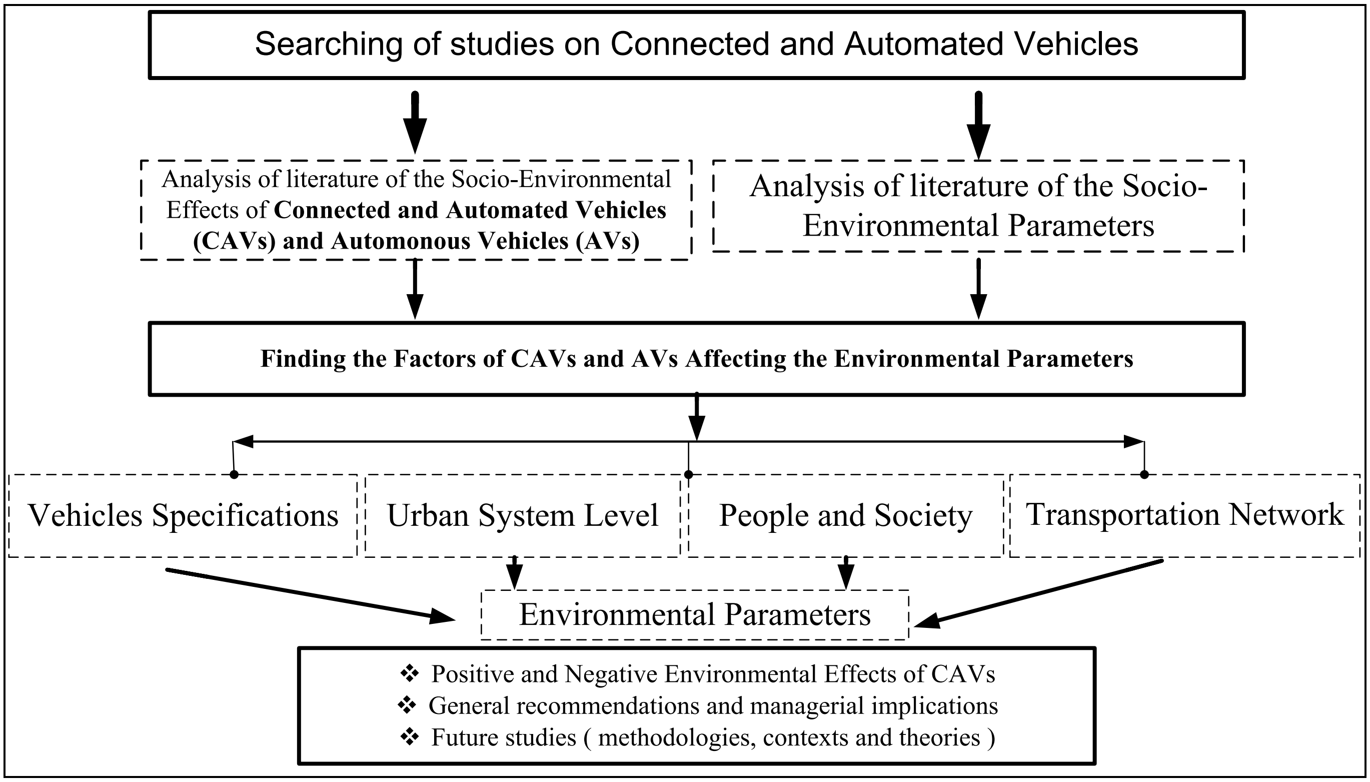

Fig. 1: Summary of the research methodology steps and research objectives

3. Literature review

The existing body of literature on CAVs and AVs predominantly explores their potential ramifications for travel patterns, congestion, and energy consumption. Nevertheless, how full or partial AVs will affect traffic flows and GHG emissions is still unclear. CAVs promise to enhance the overall sustainability of road transportation by curbing emissions and energy use. However, to comprehensively grasp and evaluate the environmental implications of emerging vehicle technologies like CAVs and AVs, it is imperative to consider factors like GHG emission standards, environmental regulations, and the impacts of GHG emissions on the environment. The ensuing sections are a comprehensive review and discussion of environmental factors, the role of emissions, and energy consumption by the CAV and AV industry, outlining both positive and negative impacts.

3.1 Environmental impacts at the vehicle level

3.1.1 Positive impacts

The literature suggests that various vehicle characteristics, including weight, performance, and right-sizing, may impact energy consumption. This section explores the positive effects of CAVs at vehicle level associated with a vehicle's driving and energy performance.

3.1.1.1 Vehicle weight and design

The advent of AVs holds promise for substantial energy and emission reductions. This potential stems from factors like developing lighter and more aerodynamic vehicle designs which use less powerful engines and reduce air resistance and engine idling [24]. These improvements will collectively enhance fuel efficiency and contribute to emissions mitigation. Additionally, the expanded capabilities of AVs to cater to passenger needs for different activities may lead to increased vehicle sizes which could potentially offset and diminish any fuel efficiency gains. A study by Choi and Bae investigated CO_2 emissions during lane-changing manoeuvres, comparing manual vehicles with AVs [25]. Their analysis indicated a 7.1% reduction in CO_2 emissions by AVs, particularly when changing lanes to join slower-moving traffic. Moreover, transitioning from slower to faster lanes by AVs reduced CO_2 emissions by approximately 11.8%.

Because energy consumption and vehicle weight are related, eliminating safety equipment would result in lighter cars and save fuel. Further weight and energy consumption reductions could be provided by the introduction of smaller, purpose-specific vehicles and automatic speed control. The energy use ramifications of light-duty AVs depend on several factors, including consumer acceptability, vehicle performance, and mileage [26]. After a review of the literature, the researchers [16] identified four key factors for optimising outcomes regarding vehicle performance and its environmental impact: (a) Vehicle Operation, which includes eco-routing and eco-driving; (b) Electrification; (c) Vehicle Design; and (d) Platooning.

Fuel consumption is greatly influenced by vehicle design. According to some research [28-30], lighter cars can use less fuel and thereby help cut down on GHG emissions. As AVs are expected to decrease accidents and improve road safety, safety features could become outdated and lighter vehicles which use less fuel could be produced. As automation levels rise, such design changes are expected to become more noticeable. For automation levels 1 through 4, vehicle mass will be significantly reduced, possibly leading to the creation of vehicles which are like "ultralight, aerodynamic pods" [31]. Anderson et al. [31] estimate fuel consumption reductions ranging from 4% to 7%, with a 25% reduction in vehicle weight based on scenario projections. Similarly, the NHTSA [32] proposes that a 10% decrease in weight should lead to a 6–7% decrease in fuel consumption. Switching from gasoline to electricity is another way to lower GHG emissions, as discussed by Wadud et al. and Greenblatt and Saxena [13, 33].

3.1.1.2 Vehicle operation

Eco-driving is becoming more and more popular as a way to reduce environmental impact and maximise vehicle decision-making processes [39]. According to Rojas Rueda et al. [58], eco-driving may reduce fuel consumption by up to 15% for less aggressive drivers and up to 20% for more aggressive drivers. According to Guo et. al [59], adopting eco-driving techniques could improve fuel economy by 4–10%. Numerous studies offer estimates of energy savings. Zhang et al. [60] suggest that fuel consumption could be reduced by 10–20%, while Morrow et al. [61] assert that a 13% reduction in fuel consumption is achievable. On the other hand, other research shows even bigger advantages, with fuel consumption reductions of 30–45% [62]. A controller incorporating cooperative adaptive cruise control (CACC) was developed to optimise vehicle trajectories in urban road intersection networks, as reported by Zohdy and Rakha [40]. Their research compared fuel consumption within various intersection geometries, revealing average fuel savings of 11%, 45%, and 33% more than the conventional control methods of roundabouts, all-way stops, and traffic signals. Furthermore, another study reported that CACC systems using V2I communication to optimise vehicle paths resulted in fuel savings of approximately 47%, 30%, and 19% more than these methods, respectively [41].

It is also expected that “platooning” will improve fuel economy by reducing the air resistance affecting cars that follow the lead vehicle in a platoon, a group of vehicles travelling closely together in a coordinated manner with a lead vehicle dictating speed and direction while the vehicles following autonomously adjust their movements to maintain a safe distance. The advantages of platooning are most significant for vehicles in the middle of the group and much less for those in the front or rear. According to studies like the SARTRE project, platooning may reduce fuel consumption by up to 20% [63]. The energy-saving benefits of platooning are estimated to range from 3–25% by Taiebat et al. [16], with a figure of 10% cited by Timmers et al. [57]. Given the energy-saving advantages offered by platooning, several researchers have started exploring optimal control strategies for platoons [42]. Conversely, some scholars have focused on signalised intersections, devising coordinated control tactics to streamline driving operations at these junctions, reduce vehicle halts, and bolster energy efficiency [34, 43].

3.1.1.3 Acceleration and deceleration systems

The use of automated braking and acceleration systems in AVs, which can drastically reduce fuel consumption, is called "eco-driving." Scholarly research thoroughly examines ways to use vehicle automation to save fuel and energy. Barth et al. [47] identify the broad areas where vehicle automation may have an impact on energy and emissions by using findings from earlier research [48, 49]. The smooth acceleration and deceleration enabled by AVs can provide a 15% reduction in fuel consumption [27]. Wu et al. [50] examined implementing a fuel economy optimisation system, recommending the best deceleration/acceleration profiles for automated systems or human drivers. These guidance factors and variables include current vehicle speed, acceleration, headway spacing, signage, and traffic lights [50]. The authors found that drivers using an urban driving simulator within a network of signalised intersections reduced their fuel consumption by a significant 31%. Similarly, another study looked at the effectiveness of a variable speed limit control algorithm and found that it could save about 16% in fuel compared to scenarios without control measures [51]. The suggested control system integrates real-time information about the driving habits of specific drivers, such as adherence to speed limits and patterns of acceleration/deceleration, within a wholly AV environment. However, the observed fuel savings remain modest when AV penetration rates are below 50%. Li et al. [52] conducted a study demonstrating that in automated-car-following scenarios, using a pulse-and-gliding (PnG) controller instead of a traditional linear-quadratic (LQ) controller, fuel savings of up to 20% may be achieved. Likewise, both simulations and field tests have demonstrated that algorithms for CACC and adaptive cruise control (ACC) can significantly lower fuel consumption [53]. AVs which anticipate the driving decisions of oncoming vehicles and which enable smoother braking and fine speed adjustments show promise for energy savings and emission reductions [54].

3.1.2 Negative impacts

At vehicle level, CAV technologies can potentially contribute to environmental degradation despite their beneficial intentions. This section explores the negative environmental effects of a vehicle's driving performance, energy use, and construction materials.

3.1.2.1 Vehicle operation

One significant issue is the additional energy used by some automated features, like sophisticated sensors and computer systems, which can make cars heavier and consequently less fuel-efficient. Furthermore, even though CAV systems can sometimes optimise driving habits to reduce fuel consumption, they can also promote greater vehicle use by providing increased comfort and convenience, thereby raising overall energy consumption and emissions.

With advanced communication technologies onboard, CAVs are poised to manage the impact associated with a vehicle's driving and energy performance and react more swiftly than human drivers, potentially enabling safer travel at higher speeds. Leveraging V2V and V2I networks, AVs are anticipated to be capable of receiving seamless course instructions, potentially enabling freeway speed limit adjustments [55]. In the USA, speed limits were first implemented to provide safe driving environments by considering variables like driver reaction time, vehicle design, and road limitations. Based on the analysis by Wadud et al. [13], who investigated the possible effects of increased highway speeds enabled by automation technologies, another study of the relationship between speed and fuel consumption for a typical car predicted a 20–40% increase in GHG emissions on highways [56]. Brown et al. [29] underscored this and predicted a potential surge of 40% or more in highway fuel consumption attributable to accelerated travel [29]. Given the higher speeds enabled by CAV onboard communication and sensing technologies, a corresponding elevation of posted speed limits at network level is expected, which is inherently linked to increased fuel consumption rates and GHG emissions.

3.1.2.2 Vehicle materials

The construction materials of CAVs are also a source of environmental impact. Concerns regarding the environmental sustainability of battery manufacture and disposal processes are raised by the reliance of some CAV systems on battery-powered EVs. Furthermore, tyre pollution is a serious issue raised by the increased use of CAVs. In addition, brake and tyre wear have a higher potential for oxidation than other traffic-related factors, thus affecting the surrounding environment [57]. Tyre wear results from the shedding of tiny particles produced by the friction between the tyres of a moving vehicle and the road surface. Rubber, plasticisers, and other chemicals used in tyre production are mixed together in these particles, which contribute to air and water pollution when they are released into the environment [58]. CAVs may not be as durable or have as long a service life as conventional vehicles, which could result in more waste and pollution in the transportation system [150]. When in continuous use, CAVs may have a shorter service life than conventional vehicles due to their higher mileage and usage rates. If old cars are then disposed of improperly, the batteries and other parts can also produce a lot of waste [150].

3.2 Environmental impact at transport system level

3.2.1 Positive impacts

The literature suggests the potential for CAVs to deliver various positive environmental impacts at transportation system level, including on transportation network and fleet performance, traffic volumes, congestion, transport mode shares, and implementation models. This section explores those impacts.

3.2.1.1 Routes and congestion levels

Increasing routing efficiency offers other indirect positive environmental impacts. Route selection decisions can be informed by real-time data to reduce emissions and traffic congestion if AVs are outfitted with technology that allows them to interact with other vehicles and infrastructure systems. According to research by Guo et al. [59], route selection algorithms that prioritise emissions reduction may reduce fuel consumption by as much as 12%. The overall environmental impact is assumed to be positive, even though choosing green routes may result in longer travel times and a larger fleet of vehicles [60]. Based on this knowledge, researchers pinpoint two possible paths to reductions in energy use and GHG emissions: (a) easing traffic congestion so that cars can run at their optimal speeds and (b) putting traffic-smoothing techniques into practice to minimise stop-and-go driving. Another study by Morrow et al., drawing on prior AV research, compiled a list of eight critical factors influencing the environmental impact of AV integration into traffic, although numerical results were not provided [61]. These factors were divided into two groups based on their spheres of influence: (a) Transportation network and (b) Consumer choice.

3.2.1.2 Road capacity, traffic, car sharing, and driver behaviour

One of the main benefits often mentioned when discussing CAVs and AVs is the possibility of reduced traffic. By allowing closer spacing between cars, CAV and AV use is expected to increase road capacity and reduce traffic, which usually peaks in the morning and afternoon. Iglinski and Babiak [62] claim that fuel consumption can increase by as much as 50% during peak congestion. Reducing traffic congestion may result in 15–60% reductions in fuel consumption, depending on the degree of AV penetration, because both GHG emissions and fuel consumption increase in congested conditions [63]. At low penetration levels, the benefits of AVs are likely to be constrained by the limitations of the existing vehicle fleet, indicating that the degree of AV penetration significantly impacts traffic congestion and flow dynamics [64].

Moreover, combining car sharing and on-demand mobility, especially using autonomous technology, can reduce GHG emissions. Shared mobility effectively reduces vehicle kilometres travelled (VKT) by combining temporally and spatially similar trips, as stressed by Taiebat et al. [16]. Shared mobility also generates many other benefits, including efficiency improvements, fleet downsizing, congestion reduction, energy conservation, and emissions reduction. Because unused time makes up almost 90% of a vehicle's lifespan, car sharing could help reduce fuel consumption and gas emissions by reducing the number of vehicles in use. According to one study, there would be 9–13 fewer vehicles per shared vehicle [65]. In contrast, according to another study, car sharing and appropriately sized vehicles could enable automated taxis to reduce average energy consumption by only 3% [33]. In a larger agent-based study [66], simulations modelled a scenario in which SAVs made up about 3.5% of all daily trips in a mid-sized city.

Understanding and addressing driver behaviour at transportation system level is crucial for improving road safety, reducing congestion, and enhancing overall transportation efficiency. Considering the significant impact of human behaviour on the potential advantages of AVs, particularly those related to fleet reduction, researchers conducted a study which incorporated human driving behaviour as a critical variable [67]. Drawing insights from the responses of 302 participants, the researchers examined user preferences regarding various modes of transportation involving private HDVs, private automated vehicles (PAVs), shared HDVs, SAVs, and public transportation (PT) (i.e. bus, tram, and train) [67]. The findings indicated that private HDV use was the most favoured option, followed by PAV use and PT. Conversely, both shared HDV and SAV options were ranked lowest in preference. Consequently, the researchers questioned the assumption that autonomous driving would reduce the vehicle fleet and the attendant environmental burdens, suggesting that SAV use is the most promising avenue for realising positive environmental outcomes [67].

3.2.1.3 Taxis, public transportation, and delivery services

Alternative AV deployment models cover various industries, including goods delivery, PT, taxi services, and personal transportation [68]. AV taxi services provide one of the most promising uses of autonomous technology, providing on-demand transportation without human drivers. In an investigation into the benefits of automated taxis for reducing GHG emissions in the US, Greenblatt and Shaheen [33] claimed that by 2030, the country would have reduced emissions by 87–94% per VKT by each of these taxis.

A study by Greenblatt and Saxena offered an optimistic perspective on the long-term emissions reduction potential of AVs. Their analysis, focusing on shared electric automated taxis, projected GHG emissions per vehicle per mile in 2030 ranging from 87–94% less than emissions from gasoline-powered internal combustion vehicles in 2014 and from 63–82% less emissions than hybrid-electric cars [33]. Businesses like Uber and Lyft are making significant investments in AV technology to replace their conventional fleets of HDVs with AVs [68].

Lam et al. [70] focused on an all-AV fleet, a ride-sharing PT network. It was demonstrated that operational costs could be reduced, suggesting that AV implementation could result in lower costs. AVs have been considered a feeder service in current PT systems, as well as providing exclusively AV services. To investigate how AVs are integrated with Singapore's bus system, Shen et al. [71] created an agent-based simulation to consider the potential for congestion produced by more people using the roads. A model for analysing the incorporation of AVs as feeders to an established PT network has been formulated by Badia and Jenelius [69].

Businesses like FedEx and Amazon are now testing drones and automated delivery robots, and AVs are increasingly being used for last-mile goods delivery. Benefits include more rapid and effective deliveries, and lower carbon emissions, from optimised routing. Some challenges include unmanned aerial vehicle (UAV) (e.g. drone) regulatory frameworks, navigating urban environments with pedestrians and other vehicles, and guaranteeing safe and responsible delivery practices. The effects of various integration options on established PT networks are not well understood despite the research mentioned above. To sum up, alternative AV implementation models for fleet management, PT, taxi services, and goods delivery present exciting opportunities to apply automated vehicle technology to improving accessibility, safety, and environmental efficiency across a range of industries. However, social, technical, and regulatory issues related to widespread use of AVs must be resolved to fully realise these potential advantages.

3.2.1.4 Traffic patterns

Because CAVs can optimise traffic flow and lessen congestion, they could optimise traffic patterns and have a positive environmental impact. Given the predominant role of the transportation sector in liquid fuel consumption [45], the potential energy consumption benefits of CAVs have garnered increased attention in recent years. Further research is warranted on achieving energy-efficient driving while ensuring the safety and efficacy of mixed traffic systems [72]. Jin et al. [73] introduced a mixed traffic model that accounted for driver reaction delays, information exchange with leading vehicles, and CAV penetration rates. Energy consumption was evaluated using the Advanced Vehicle Simulator (ADVISOR) 2002, which demonstrated the suggested approach's "string stability" and energy efficiency [35]. Simulation findings indicated that, with the assistance of traffic data from leading vehicles, energy consumption and CO_2 emissions within mixed traffic formations would notably diminish when the penetration rate of CAVs surpassed 0.8. Literature suggests that CAVs are a promising technology with the potential to provide a sustainable transportation system and significantly lower energy use and emissions. This potential stems from factors like the promotion of uniform traffic patterns and decreased highway congestion. AVs and CAVs facilitate enhanced vehicle communication, which has been shown to reduce fuel consumption by 15% [74] or even up to 20% [75]. Additionally, using AVs, vehicle-optimal traffic assignment strategies can be implemented to minimise overall travel time and emissions, and maximise fuel efficiency, [28].

3.2.2 Negative impacts

Although CAVs promise significant improvements in mobility and safety, questions have been raised regarding their negative environmental effects at transportation system level. This review looks at various academic works to explore the main issues with CAVs, such as increased energy consumption and GHG emissions associated with traffic volume, congestion, transport mode shares, and network/fleet performance.

3.2.2.1 Easier travel

Improved travel convenience includes lower travel costs and earlier arrival times due to less traffic and accidents. The possibility of faster and more dependable travel may increase demand for travel. Decreased traffic and less delays caused by accidents effectively increase the capacity of roads, although also possibly encouraging increased travel. A study analysed possible changes in travel behaviour in the Puget Sound region of Washington State, USA using scenarios generated by activity-based travel models [76]. These scenarios included one representing a 35% decrease in high-income households' perceived travel-time costs and a 30% increase in roadway capacity, which correlated with a 3.6% increase in emissions. In another scenario, a 30% increase in roadway capacity and a 50% decrease in parking costs resulted in a 19.6% increase in emissions, assuming universal ownership of AVs without sharing. The appeal of driverless cars, especially at peak traffic times, might encourage more people to use them. CAVs have become more appealing as transportation has become more accessible, particularly in situations with heavy traffic. Increased demand combined with more available road space would eventually result in more cars being produced.

3.2.2.2 Faster travel

With advanced communication technologies onboard, CAVs are poised to navigate and react more swiftly than human drivers, potentially enabling safer travel at higher speeds. Studies have shown that speed has a major impact on energy consumption and GHG emissions. In particular, these plateau at average speeds, increase again when vehicles travel at higher speeds, and peak at low speeds, such as during traffic congestion. Leveraging V2V and V2I networks, AVs are anticipated to be capable of receiving seamless course instructions, potentially prompting freeway speed limit adjustments [55].

In the USA, speed limits were first implemented to provide a safe driving environment by considering variables like driver reaction time, vehicle design, and road restrictions. Later, at the federal level, they were also implemented to reduce fuel consumption [77]. Therefore, with AVs in the mix, a national increase in speed limits is anticipated to coincide with a rise in fuel consumption [13]. Based on the analysis by Wadud et al. [13] of the possible effects of increased highway speeds prompted by vehicle automation technologies, another study that examined the relationship between speed and fuel consumption for a typical car predicted a 20–40% increase in GHG emissions on highways [56]. Brown et al. [29] further underscored this, proposing a potential surge of 40% or more in highway fuel consumption due to accelerated travel [29]. Drawing from the observations by Schafer et al. [78] of travellers' time budgets across various societies, Brown et al. speculated that higher travel speeds might incentivise individuals to reside further from their usual destinations, potentially fostering urban sprawl and ultimately a possible 50% emissions increase. Given the higher speeds enabled by AVs' onboard communication and sensing technologies, a corresponding elevation in posted speed limits at network level is expected, inherently linked to higher fuel consumption rates and increased GHG emissions.

3.2.2.3 Empty kilometres travelled

The potential for AVs to alter passenger-free vehicle travel scenarios has not been thoroughly investigated. To cut down on wait times, a car owner could program his driverless AV to pick up family members or send it to locations in advance. One study examined user travel patterns in a shared fleet of self-driving cars using an agent-based model of self-driving cars moving in a square grid that represented an imperial city [66]. The study used some available predefined data from the *2009 National Household Travel Survey* and looked at scenarios involving different trip-generation rates, levels of network congestion, neighbourhood sizes, and vehicle relocation tactics. Ultimately, the research found that a self-driving car could replace nearly 11 conventional vehicles, albeit with a 5–11% increase in emissions generated by repositioning the vehicle.

3.2.2.4 Increased travel by under-served populations

There is speculation that having AVs on the roads could potentially increase VKT due to increased road use by individuals with disabilities and young and elderly populations. While providing CAV mobility services to people with disabilities and elderly populations is socially advantageous, it is also anticipated to result in a general rise in VKT. In the microeconomic model created, under income and time constraints, the elasticity of VKT demand with respect to fuel and time costs was estimated. An average household's expected travel demand was predicted to increase by 2–47% [3]. Numerous possible scenarios that take into account variations in time costs and fuel efficiency have shown an overall increase in energy consumption. There is a chance of a backlash, especially among wealthier individuals whose time costs are reduced less significantly, which could offset any energy savings from CAVs. An improvement in fuel efficiency of 20% attributed to CAVs would then be effectively cancelled out by an average 38% reduction in time costs. Furthermore, academics have drawn attention to concerns that a rise in the use of AVs might paradoxically result in a proliferation of automobiles, worsening GHG emissions [3]. The growth of ride-hailing and attendant on-demand mobility services could lead to a larger fleet, higher VKT, more road traffic, and ultimately higher fuel consumption and GHG emissions. To consolidate findings from prior research, graphical representations could be devised to facilitate a clearer visualisation and understanding of the potential changes in GHG emissions.

A lack of comprehensive data elucidating the reasons for differential travel behaviour among various demographic groups complicates the prediction of travel patterns for currently under-served populations. Analysing data from the *2014 National Household Travel Survey*, MacKenzie et al. [81] noted significantly lower VKT among adults over 62 than those over 42. They hypothesised that fully automated cars might fill this gap in travel demand, thereby increasing emissions by 2–10%. Another investigation hypothesised that, in age groups spanning from 19 to 64, non-drivers might travel in ways similar to drivers and that, in each age group, people with medical conditions would travel in ways similar to those without [82]. It was deduced that under-served populations may contribute to emissions growth of up to 12% with full AV adoption by classifying the sample population into three groups: those aged 19 and above who are not drivers; elderly drivers without medical conditions; and drivers aged 19 and above who have medical conditions. Based on data from the 2003 Bureau of Transportation Statistics report *Freedom to Travel* and the *2009 National Household Travel Survey*, Brown et al. [29] estimated that, if people in all age groups travelled at rates similar to the top decile of each age group, there could be a 40% increase in GHG emissions.

3.2.2.5 Impacts on other transport modes

An important environmental concern of the CAV transition is how it will shift current transport options in the transport systems. Over many years, many cities' transport developments have pursued public transport and active transport options (walking and cycling) with a policy goal to mitigate the energy and climate impacts of private car travel (Newman, 2020). If more advanced

CAV technologies allow people who are on greener transport modes to start using cars, they can increase per capita energy consumption and emissions. However, increased vehicle automation can also generate new modes of transport (such as shared vehicle travel and on-demand services), which can generate a positive environmental effect. This section discusses the literature on the potential impact of CAVs on people's transport choices that have significant environmental implications.

Existing literature has discussed why CAVs can alter current PT and active transport options. First, although improved CAV technologies would reduce traffic accidents [83, 84], CAVs still pose critical safety problems for pedestrians and cyclists [80]. Increased CAV travel would increase road traffic and make the transport environment less pleasant for walking and cycling [85]. In addition, people without any means of transport may also need quicker transportation if it is available. For these reasons, some people who travel by walking or cycling would switch to CAV [86, 87].

Next, public transport (PT) (bus, tram, and train) is highly efficient and cost-effective for large groups of travellers in urban areas. However, because PT often operates on fixed routes, many travellers must walk to and from a PT location to reach their final destination. Travel time may also be extended if people need to wait to transfer between PT lines on a journey. Supposing AVs could provide more convenient, comfortable, and speedy transport than PT services, many PT users might shift their travel mode to cars [88-90]. If people who used to travel together by PT switched their travel mode to separate and smaller AVs, total traffic volumes and travel distances could quickly increase. A few Australian studies have used social surveys to understand these potential transport changes from a behavioural perspective. For example, Kellett et al. [196] carried out a preference survey of vehicle and travel choices in Adelaide and found that PT commuters were willing to shift to AVs. Using a transport model developed for the Victoria Government, Tajaddini and Vu [198] estimated that 10% of PT and active transport trips would shift to AV.

While many studies are pessimistic about AV impacts on PT use, some authors argue that AVs can solve the PT last-mile problem by seamlessly connecting PT stops with final destinations [92-94]. If the end-to-end connectivity of PT can be improved by effectively integrating PT with AVs, this could increase the attractiveness of PT, especially for those who already use this mode [93].

In addition, reduced need for parking and street space can be repurposed to improve PT facilities, pedestrian paths, and cycle lanes, which could appeal to people who prefer using these greener mobility options [91, 95]. It is noted that PT, especially buses, may also become automated at the same time. However, automated buses often operate with more stops for passengers, making this option less appealing to some travellers [96].

Another obvious issue for AVs is that advanced route planning and automation systems enable more shared trips and on-demand trips [97, 98]. Some people who formerly would have owned a vehicle might consider sharing cars with others to save the cost. Existing studies have found that car sharing is already more attractive than PT and taxi use in many cities as an option that can balance convenience and cost [91, 99]. Although shared AV trips could reduce the number of vehicles on the road, they operate with more limited occupant capacity (maximum 6 passengers per car) than buses and trains. If SAVs take a considerable number of passengers off PT, they will increase the total vehicle volume on the road, and the effect on traffic and the environment could be devastating. Other studies considered that shared mobility preferences may vary among residents in different urban areas [104]. For example, Alessandrini et al. [105] pictured a future city where up to 90% of people in the central urban areas would choose shared transport, while about 70% in inner suburbs and 50% in outer suburbs would choose it. Meyer et al. [90] further suggested that SAVs would be more competitive than public transport in rural and regional areas with low passenger demand. These shifts in transport options would have significant implications for transport energy and emission at the urban system level.

3.3 Environmental impacts of CAVs at urban system level

In this section, we review articles on the potential urban changes induced by CAVs and discuss second-order environmental issues that may arise. Assessing the environmental impacts of CAVs at urban system level is more complex because it involves many human activities and behaviours that are more uncertain than the transport changes linked with new technologies [106]. Other complex changes in regulations and business models associated with the CAV transition are also hard to anticipate. Therefore, many investigations at this level are scenario-based [95] and use question-based surveys or simulation models to estimate likely transport and urban changes [80].

While it is difficult to predict the exact magnitudes of impacts, researchers have identified possible changes based on behavioural or urban economic perspectives. They suggest that a CAV transformation might not be beneficial overall if certain adverse effects at urban system level are not adequately managed [13, 96, 106].

3.3.1 Positive impacts

3.3.1.1 Increase in road capacity and mobility

It is widely recognised that increased vehicle automation and connectivity will increase road capacity in urban areas [3, 90, 118]. Vehicle-to-vehicle communication (V2V) increases vehicles' operating efficiency, safety, and ability to maintain optimally short distances from other vehicles and hence use road space more efficiently [13, 119]. Communication between vehicles and road infrastructure (V2I) can supply real-time navigation and routing guides, helping vehicles avoid accidents and traffic congestion [120]. For these reasons, vehicle travel distances and time on the road will decrease compared to those of conventional vehicles if all other factors (e.g., total travel demand and volume) stay unchanged. These improved technologies can in aggregate optimise traffic distribution over the urban transport network, thereby increasing road capacity and travel efficiency. These more efficient transport movements can reduce vehicle energy consumption and emissions in a city [118] [121].

While it is difficult to measure the effects of vehicle connectivity and vehicle automation on transport systems at the same time, some recent studies have attempted to understand these effects separately by using models to compare scenarios both with and without specific CAV technology, e.g. vehicle connectivity [122]. These studies found that CAVs can improve the overall transport network performance more than AVs alone or conventional vehicles [123]. Table 3 in the Appendix categorises the studies investigating the impacts of vehicle connectivity on road capacity and transport efficiency.

3.3.1.2 Shifting urban built environments

Many researchers believe that the transport transition to CAVs will shift the physical environment in urban areas. When AVs, CAVs, and SAVs become more prevalent, inner-city areas will become denser due to changes in land use and design to meet the characteristics of CAV operation [12, 131]. For example, SAVs will be more efficient when passengers are closer and activities are more connected [130, 132]. In addition, a decline in vehicle parking and street space demand could liberate more land resources in the city centre, which can then be repurposed for residential and commercial development [106, 133]. Infill development would also foster energy-efficient housing occupancy, more mixed activities, and closer interactions, which could create denser urban cores [134].

While CAVs can reduce parking demand in the city centre [145], they will also require more land on the periphery for parking, which may have environmental consequences [130, 152]. However, some studies suggested that more intensive use of AVs on the road may not require a number of parking spaces exceeding the number of vehicles that must be stored in a neighbourhood [144]. This trend will be particularly stark if many travellers move to a vehicle-sharing model in which they own fewer cars and use shared vehicles more [190]. In addition to changes in commercial parking locations, residential parking use may change for households willing to switch to CAVs and SAVs, which could lead to less parking and garage space required per newly developed dwelling [192]. If future dwelling constructions consume less land, they will be more energy-efficient and environmentally sustainable [144].

3.3.2 Negative impacts

Many studies at the urban scale have addressed the long-term impacts of CAVs on the environment. In general, the key concerns about the environmental impacts at the urban scale are whether CAVs will 1) increase total vehicle travel demand and 2) lead to urban structural change in a way that consumes more energy and generates emissions. It is noted that the energy transformation from carbon fuels to electricity currently underway will mitigate some of these environmental issues. However, other environmental impacts – like air pollution, noise, infrastructure emissions, land and water resources etc. – are also related to vehicle travel and structural changes in urban areas [107, 108].

3.3.2.1 Travel demand changes due to operational characteristics of CAVs

Many studies have suggested that the characteristics of CAVs generate new forms of mobility that could change vehicle travel demand in cities. These include:

- More empty trips – Users take advantage of CAV capabilities to reposition their vehicles for other users or park in lower-cost locations [90]. More empty vehicles cruising for such purposes will increase the total distance travelled.
- More re-pick-up – Re-pick-up can increase the number of people using the same vehicle at different times and expanded activity schedules can increase vehicle travel distances [109].
- More linked trips – People using a CAV can easily add multiple activities to a trip chain [110]. Total trip distances could be increased if more people adopt this sort of mobility pattern.
- New car users – People using other transport modes or having minimal driving capability (e.g. very young or old people) could switch to car use if CAVs could increase their mobility at low cost [91].
- Changes in car parking and cost – CAVs will free up parking in the city centre but generate additional round-trips between users and parking locations [111]. Zero parking costs at destinations can also incentivise vehicle travel.
- More shared trips – CAVs can increase shared mobility by combining multiple users on a similar trip, generating total trip reductions [80].
- On-demand trips – On-demand services ensure that vehicle trips exactly match users' travel demand and reduce the time spent on empty trips.
- Changes in car ownership and fleet size – Increased car sharing and on-demand services could reduce the need to own a car [112]. However, this does not guarantee a decline in total vehicle fleet size because ownership could rise in response to lower operational costs [95].

Table 2 in the Appendix lists selected research and findings about the likely change in travel demand induced by CAVs. While the magnitudes of change vary somewhat among different case studies, they all suggest similar trends and directions of change. It is noted that other CAV-induced factors could also influence vehicle travel demand, such as changes in parking costs, road capacity, and land uses. These effects will be more explicitly discussed in later sections.

3.3.2.2 Increased travel demand with changes in the perceived value of travel time

Studies broadly recognise that vehicle travel demand will increase as CAVs change the value of travel time [106]. Because CAVs will free users from driving, a significant reduction in the value of travel time perceived by their users is generally expected [113]. Many studies have proposed that users could work, read, or communicate in an AV or shared AV while travelling, making their use of time more productive than if they had to drive [114, 115]. Some studies have considered that these changes in in-vehicle behaviour and time value could vary with different circumstances. For example, passengers' adoption of travel time can differ according to their employment and family type [106]. Some studies have also argued that passengers may not be able to use their travel time productively in complex traffic situations requiring frequent speed, direction, and lane changes, and that more significant changes in time use could be found on longer and smoother journeys in outer urban and regional areas [116].

Although changes in the value of travel time are accepted conceptually in the literature, evidence to justify these hypothetical changes is not particularly strong (see Table 2 in the Appendix). Some stated-preference survey results suggested no statistically significant differences between the value of travel time for conventional and for fully automated vehicles [117]. In Australia, the potential impacts of AVs on travel behaviour have been investigated in Sydney [116, 165], with results showing no significant changes in the perceived value of travel time when people shift to AVs for transport.

3.3.2.3 Potential impacts on urban structure

In urban settings, changes in the value of travel time and road capacity induced by CAVs can change the accessibility of local areas [124]. Researchers consider that the reduced driving burden of CAVs and the time saved by mobility gains will cause additional distances to be travelled [129, 130]. Examples from the past show that changing transport costs would motivate people to relocate to more affordable areas with more housing options, with the result that suburban sprawl would increase [109, 125, 126, 127]. Such sprawl necessitates the construction of new housing and infrastructure, and consumes more energy and resources [108]. Other researchers have argued that future residential changes would mainly be an outcome of changes in commuting times and accessibility, rather than the more productive use of time which a personal CAV would allow [123]. In this reading, urban sprawl would thus stagnate because of limits on time spent commuting [91, 128]. Australian studies of the impacts of AVs on residential land use and structure have been very recent, based on some preliminary research regarding conceptual and analytical frameworks [112, 145]. A recent study by Feng et al. [199] tested the urban impacts of CAVs using an agent-based simulation model. They found that the movement of residents would be limited by spatiotemporal accessibility constraints, e.g. commuting time thresholds. As a result, the predicted increases in trip lengths and impacts on traffic congestion are modest.

3.3.2.4 Other environmental impacts

Transportation switching to CAVs will require significant changes in road infrastructure [45, 109, 137-139]. The transport literature about road infrastructure changes has rarely addressed underlying environmental issues. Some useful information is found in a study by Liu et al. [140] which comprehensively assessed potential changes in road infrastructure and its likely impacts on energy and emissions (Table 1). The main finding was that changes associated with road design, parking, and service stations could lead to positive outcomes for the environment. New construction and upgrades, and the deployment of new devices would however have negative energy and environmental implications.

Table 1: Road Infrastructure Requirement for CAVs and the Environmental Implications

Infrastructure change	Description	Environmental implication
Signage and road markings	Increase the recognition of road signs via standardisation, maintenance, and roadside light and vegetation control	3
Digital communication	Deployment of a substantial number of sensors and digital communication devices on the roadside	1
Pavement structurea	Substrata beneath CAV operation tracks need to be strengthened	2

Road surfaces	Reduce the stop distance design standard – the requirement for friction can be relaxed with the more predictive speed adjustment/braking of CAVs	5
Safe harbour areas	Set up safe harbour areas on roads for emergency parking if travellers need to take control of their vehicles	1
Parking	Decline in parking demand and increased parking capacity (reduced parking space per car)	5
Service stations	Increased charging machines at service stations and service stations are replaced by charging roads	5
Roundabouts	Due to improved vehicle-to-vehicle interactions, less roundabouts in lower-traffic areas will reduce queuing and waiting times	5
Bridges/tunnels	Bridges and tunnels will require upgrade or redesign to cater to heavy vehicles' platooning needs	1
Road geometry design	Simplify road/street geometry design standards, e.g. lane width reduction	5

Notes: Score 1 = disadvantage; 2 = possible disadvantage; 3 = neutral; 4 = possible advantage; 5 = advantage.

Not only can CAVs alter urban road capacity and mobility, they will also impact transport in rural and regional areas, with environmental implications. An apparent benefit of CAVs is that they can better service areas with low passenger demand, which will increase the mobility of rural residents [90] and reduce GHG emissions [141]. It has been suggested that changes in driving cost and travel time value can increase transport interactions between regional and metropolitan areas [90]. Some studies also believe increased accessibility can contribute to population and economic growth in regional cities [141] [126]. However, the long-term environmental impacts of these shifts are still uncertain.

The transport literature has considered the use of CAVs in ports [142]. The advantage of automated freight vehicles in ports is that they can improve traffic conditions, increase the number of service vehicles, and reduce transport waiting times in terminal areas, leading to more efficient energy use and better environmental outcomes [143, 144]. Some studies have suggested that CAVs may not impact port cities as a whole because they often operate in closed automation environments, e.g. terminal areas. Other researchers believe that CAV operation could expand service zones outside terminal areas, increasing pollution and noise [142]. Researchers have also suggested that infrastructure and road capacity upgraded for automated freight vehicles could also be used for other urban activities, thus increasing travel demand and environmental burden [142, 143]. Similar transportation environmental issues may also apply to mining, production, and exporting cities with solid industrial and residential settings.

3.4 Analysis of positive and negative effects of CAVs

The earlier sections have discussed the positive and negative environmental impacts of CAVS at vehicle, transport system, and urban system levels. This section synthesises the complex interactions between CAVs and the environment using data extracted from the recent literature.

First, the causal-loop diagram in Fig. 2 visually depicts the advantages and disadvantages of CAVs for the environment according to their relation to vehicles, the transportation network, and user behaviours. It shows that, by optimising routing and platooning, CAVs can reduce traffic congestion, enhance air quality, and reduce GHG emissions. The effective use of energy and the possibility of electrification of CAV fleets present opportunities for reducing dependence on fossil fuels, thus supporting the shift to environmentally friendly transportation. Increased energy consumption induced by the power requirements of complex sensor arrays and computational systems would be one adverse environmental effect. This causal-loop diagram highlights the need for comprehensive approaches to sustainable transportation planning and policymaking by graphically capturing the complex interplay between the positive and negative environmental effects of CAVs.

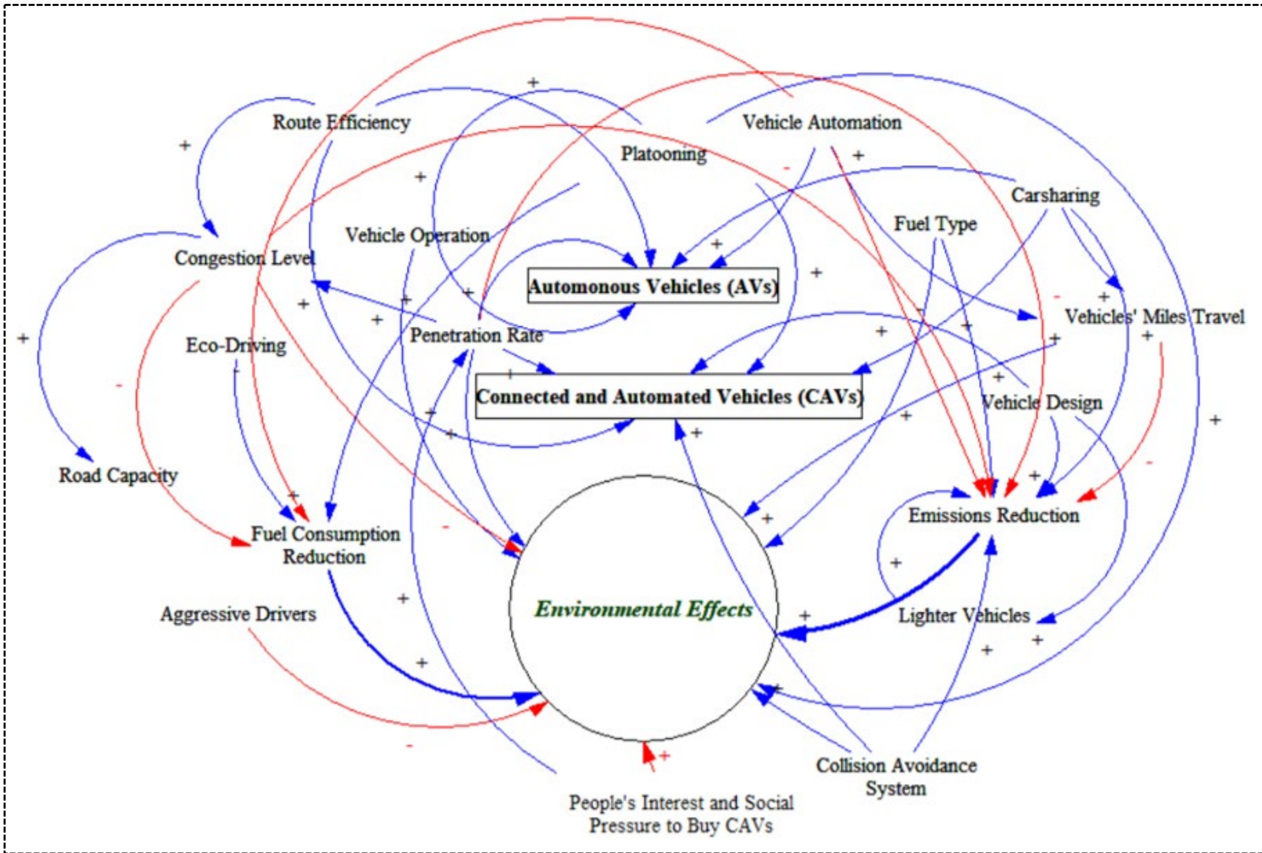

Fig. 2: Causal loop diagram of positive (blue) and negative (red) effects of CAVs and AVs

Figure 3 (a-d) compares the parameters collectively representing various strategies and technologies to reduce GHG emissions, highlighting the multifaceted approach required to address environmental impacts. It shows that platooning and eco-driving practices account for 35% of GHG reduction potential (Fig. 3b). The type of fuel that vehicles use contributes 50% to the GHG reduction potential, reflecting the significant impact that transitioning to low-carbon or alternative fuels can have on reducing GHG emissions. Fig. 3(a) shows that minimising the time spent searching for parking spaces represents 19% of the GHG reduction potential. Implementing eco-friendly signal operation systems to manage traffic represents 9% of the GHG reduction potential. The use of collision avoidance systems which enhance safety accounts for 2% of the GHG reduction potential.

Fig. 3(c) highlights that vehicle design could reduce energy consumption by 7%. Factors such as aerodynamics, weight, and drive-train efficiency influence how efficiently vehicles use energy. Advanced routing algorithms and real-time traffic information could reduce fuel consumption by 12% by minimising distances travelled and maximising fuel efficiency. Efficient routing would also help to minimise congestion and delays, contributing to energy savings. Car-sharing programs can lead to modest reductions in energy consumption of 3%. However, the impact of car sharing on energy consumption may vary, depending on factors like vehicle occupancy rates, trip distances, and vehicle types.

Fig 3(d) illustrates that transport mode shifts account for 17% of the increase in GHG emissions associated with CAVs. It indicates that shifting towards CAVs as a dominant transportation mode could result in higher overall GHG emissions if people reduce the use of more sustainable modes like PT or active unpowered transportation. Empty miles travel contribute 2% of the increase in GHG emissions for CAVs. While CAVs have the potential to optimise routing and reduce empty miles through improved coordination and scheduling, there is still a risk of empty mile travel due to factors such as "deadheading" (returning empty after completing a trip) or inefficient vehicle allocation. "Easier miles" travel accounts for 41% of the increase in GHG emissions for CAVs. This means that while using CAVs may lead to efficiency gains and reduced emissions per kilometre travelled, it could also induce travel demand and overall increased VKT if CAVs encourage more frequent or longer trips.

"Faster miles" travel occurs because CAVs enable greater travel distances in less time, and this parameter contributes 24% of the increase in GHG emissions for CAVs. "Highest congestion level" represents the severity of traffic congestion experienced by CAVs. This parameter accounts for 50% of the increase in GHG emissions for CAVs. Fig 3(d) further shows that vehicle automation contributes 16% of the increasing GHG emissions for CAVs. Vehicle automation may boost efficiency and safety on the road, but it may also result in more people using their cars and driving more, thus increasing GHG emissions. Compared to conventional vehicles, CAV energy requirements for their electric propulsion systems, sensors, and computing hardware could result in higher overall energy consumption and GHG emissions. To guarantee a sustainable and effective transportation system, efforts to reduce GHG emissions from CAVs must consider elements like travel behaviour, infrastructure, and technology adoption.

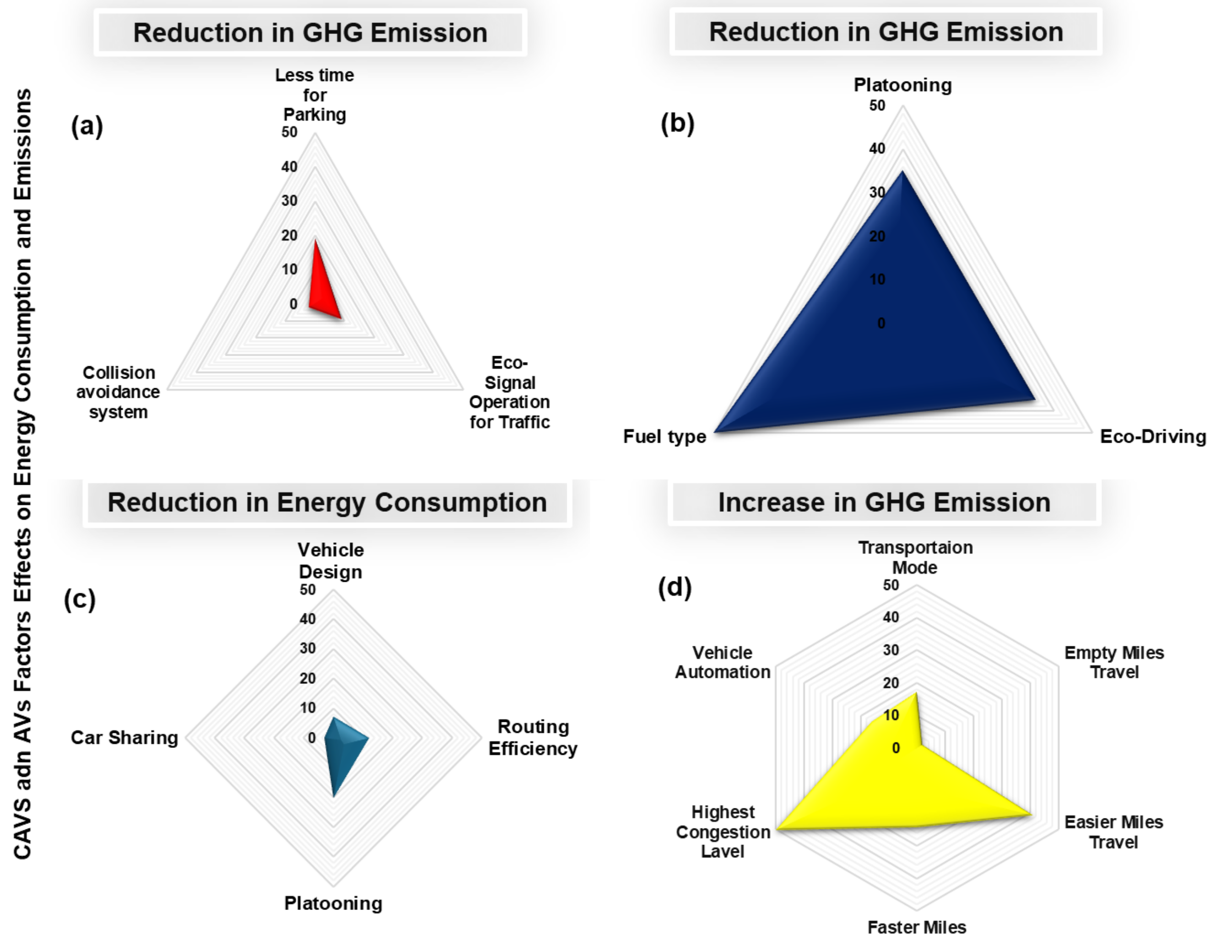

Fig. 3(a-b): CAV and AV factors and their effects on reducing GHG emissions

Next, Fig. 4 reports the number of papers for each area of study of CAVs. These papers collectively contribute to advancing knowledge and understanding of the environmental, technological, and social implications of CAVs, offering insights into possible strategies for promoting sustainable and efficient transportation systems in the era of connected and automated mobility.

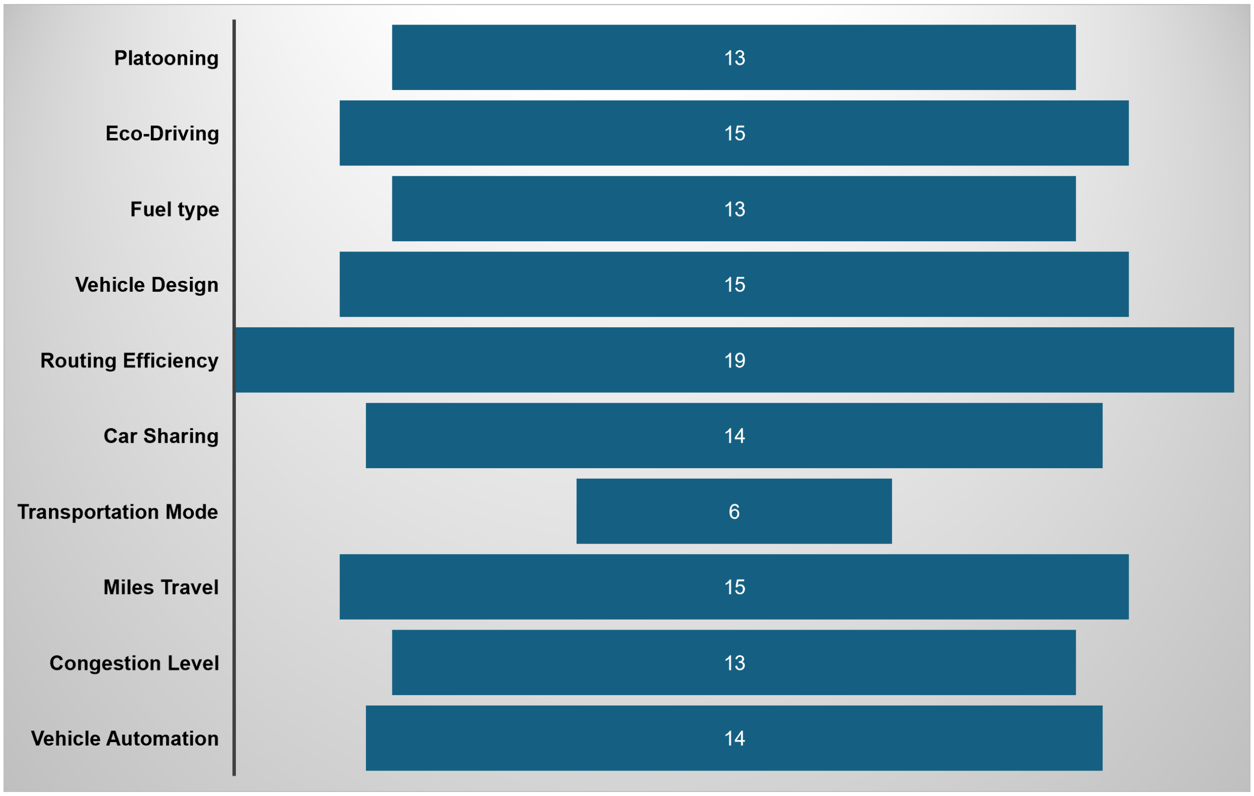

Fig. 4 Number of papers for each area of study of CAVs

To show the changes in factors due to technological developments, Fig. 5 shows the increase in VKT for CAVs across various papers and years. Each percentage value represents the increase in VKT compared to a reference point mentioned in each paper. These percentages indicate the growth or expansion of VKT attributed to adopting and using CAV technology over the specified years. Notably, the percentage increases vary across papers and years, indicating differences in methodologies, data sources, and possibly the advances and adoption rates of CAV technology over time. Moreover, Fig. 6 shows the energy consumption and emission reduction trends (unrelated to the VKT factor) for different scenarios and simulation modelling results in papers since 2014, with each study's reference point or baseline year included. The data overall shows that adopting CAVs has a positive environmental impact, with projections of notable reductions in various studies from 2014 to 2020. It is clear in Fig. 6 that the advantages in terms of energy and GHG emissions reductions should increase with advances in, and widespread use of, CAV technology.

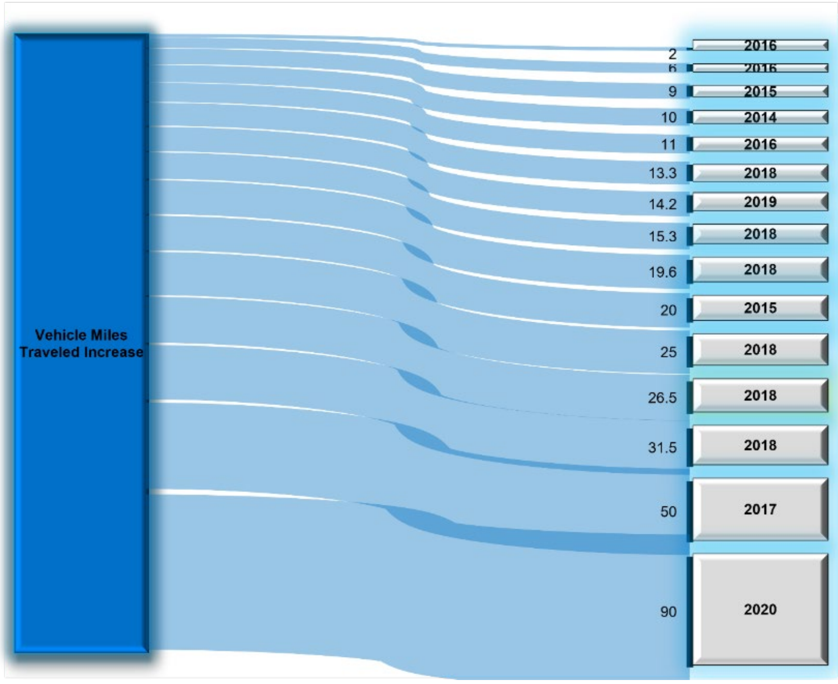

Fig. 5: VKT increase percentages vs. papers and years

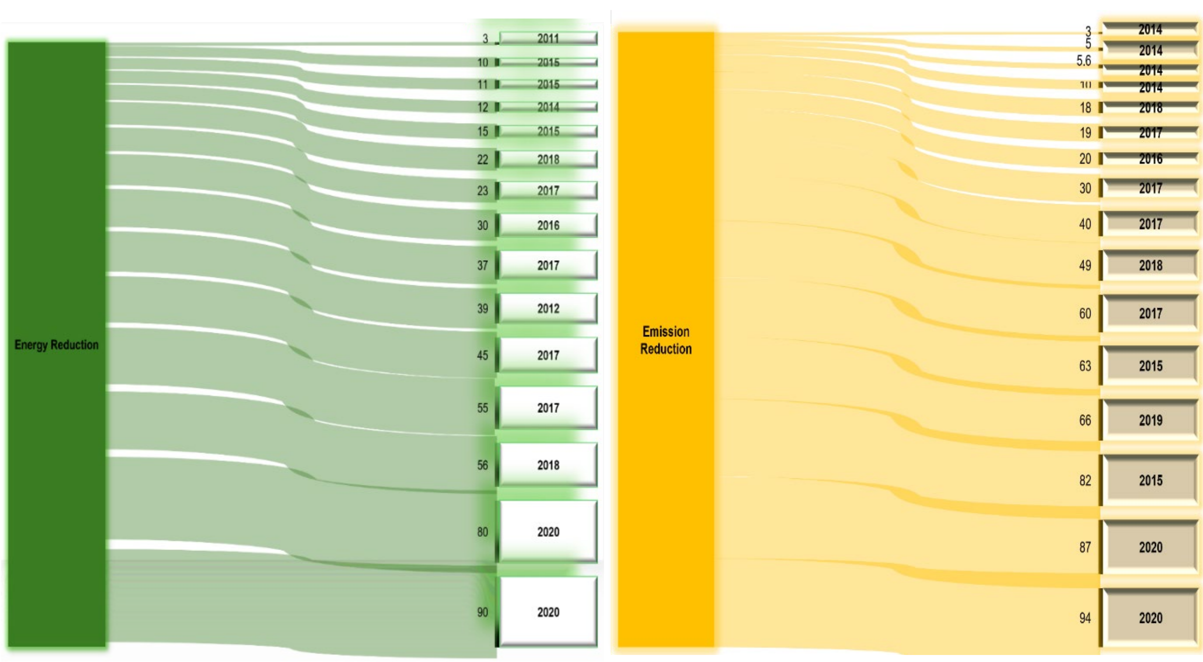

Fig. 6: Energy and emission reduction percentages vs. papers and years

In summary, CAVs and AVs present both positive and negative environmental effects. By promoting the use of electric and low-emission car models, better traffic flow, and more intelligent routing, these technologies have the potential to lower GHG emissions and air pollution. By limiting needless accelerations and decelerations, CAVs and AVs can improve fuel efficiency and reduce carbon footprints and energy consumption. In addition, shared automated mobility services may result in fewer cars on the road, easing traffic and lowering overall emissions. On the other hand, the production and use of CAVs and AVs will demand more energy and could cause an accumulation of electronic waste which harms the environment. Even though CAVs and AVs present new possibilities for environmentally friendly transportation, cautious planning, regulation, and innovation are required to minimise potential environmental harm and optimise whatever benefits they may have. Moreover, vehicle adoption patterns, such as vehicle ownership models, are anticipated to significantly impact whether AVs will decrease or augment overall VKT and ensuing GHG emissions. Some studies suggest that the favourable emission outcomes might not materialise at lower AV penetration rates, with the most significant emission reductions probably occurring within the 60–80% range of AV penetration. Table 1 in the Appendix summarises the important literature focused on the positive and negative environmental effects of CAVs and AVs.

3.5 Knowledge gaps and suggestions for future research

The existing literature has discussed various environmental issues that may occur with CAV transformation, there are still gaps in the existing body of research that call for additional investigation. While studies have provided quantitative estimates of the extent to which specific changes would happen, comparing which impacts outweigh other impacts is complex. For example, to what level can the increase in travel demand which CAVs may induce offset and diminish the positive effects of CAVs, and how effectively can post-deployment policies mitigate negative outcomes? Policymakers need better information and more advanced research to support technology and infrastructure investment decisions.

Most studies have bundled vehicle automation and connectivity technologies together when addressing transport and its environmental outcomes. Scant research has estimated the separate effects of different CAV technologies, e.g. connectivity vs. automation, which makes investment policies difficult to formulate. More dedicated research is therefore needed, including developing methods and collecting valid data to quantify these separate transport effects. Further, to distinguish between the short-term and long-term environmental impacts of different CAV technologies, e.g. connectivity vs. automation. Identifying and quantifying relevant environmental metrics, such as CO2 emissions and energy consumption, over these different time periods will provide a comprehensive understanding of how CAV technologies will impact the environment over time.

While various types of international evidence were collected, results were very case-specific. Many studies used quite different assumptions, models, and indicators, making direct comparisons problematic. Local empirical research is therefore needed to reflect local social responses, infrastructure and transport conditions, and development needs.

Next, many research results were based on theoretical approaches and it is thus necessary to perform more empirical studies to understand the extent of environmental effects and their significance. Future work could include collecting and analysing real-world data from CAV pilot projects or early deployment areas to validate and refine modelled estimates of environmental impacts and provide a more realistic evaluation [3]. Further, since commercial vehicles constitute a significant share of total vehicle fleets, future research needs to address commercial vs. private vehicle ownership models and their different impacts.

Broad externalities beyond transport systems (e.g. communication, energy production, manufacturing, and new materials) may also have environmental implications. This will require policymakers, economists, industry experts, and infrastructure providers to work together to identify development issues and responses. Other disruptive changes in regulations, business models, and urban activities may also arise along with a CAV transformation. These will require government planners and policymakers to be aware of and proactive about potential environmental outcomes.

Finally, although studies have addressed the negative effects of CAVs that may occur at both transport and urban system levels, suggestions for mitigating strategies are still limited in the current literature. More research is therefore needed to focus on potential solutions and policy issues to better inform government decision-making.

4 Environmental impacts of CAV technologies: Summary of findings

As noted earlier, many environmental discussions in the existing literature still mix the effect of vehicle automation and connectivity technologies. Based on a more comprehensive review of the literature, this section summarises the effects of different CAV technologies on the environment to better inform government policy and investment inquiries.

4.1 Vehicle automation

The introduction of AV automation technology has the potential to yield both positive and negative environmental effects. Automation technologies like predictive analytics and ACC can optimise driving habits, resulting in more seamless acceleration and deceleration, which increases fuel economy and decreases emissions. Automated safety features like lane-keeping assistance and collision avoidance systems can decrease the frequency and severity of collisions. This would lessen the environmental damage caused by vehicle collisions, including fuel spills and emissions from emergency response vehicles. By maximising the charging infrastructure, offering real-time range information, and coordinating charging schedules, automation and connectivity can help EVs become more widely adopted. However, as more people use personal vehicles due to the convenience of automated driving, automation may result in a rise in VKT. Thus, higher overall emissions and energy consumption may offset some of the efficiency gains. Furthermore, the manufacture and upkeep of automation and connectivity technologies like processors, data centres, and sensors demand a lot of energy and resources, which could have an adverse effect on the environment, particularly if those resources are derived from fossil fuels. The first benefits of AVs, like better mobility options for wealthy non-drivers, are expected to appear in the 2030s and 2040s, according to a study by Litman [145]. It is anticipated that the full benefits of lessened parking problems, increased safety regulations, lessened traffic congestion, affordability for those on low incomes, energy efficiency, and emissions reductions will materialise in the late 2050s or early 2060s [145]. Integrating AVs into urban traffic systems is poised to instigate major shifts in traffic dynamics and urban planning [146].

Numerous automakers have expressed optimism regarding AV technology, envisioning its widespread adoption in the United States. Moreover, they highlight potential synergies between AV and EV technologies, suggesting that AV deployment could accelerate as governments globally phase out fossil fuel-powered vehicles. Nonetheless, several challenges persist and some experts caution that achieving reliable, safe, and affordable AVs may require considerably more time than proponents anticipate [147]. Most current AVs operate at "level 3," meaning human intervention is required in certain traffic scenarios [147]. Only a handful of AVs are classified as "level 4," meaning they can autonomously complete trips along predetermined, mapped routes.

Numerous automakers and tech firms are presently in the process of developing electric and hybrid AVs. It is anticipated that commercially available AVs will predominantly be EVs for several compelling reasons: the preference for emission-free and quieter modes of transportation, particularly in densely populated urban areas and amidst global efforts to curtail carbon emissions; the considerable electricity needed by AV sensors and computing systems, which batteries can more effectively accommodate than internal combustion engines can; and the heightened responsiveness of EVs which renders them safer and more manageable for AI algorithms to govern. Moreover, electric AVs may have an advantage in self-recharging capabilities, potentially eliminating the need for human intervention in the refuelling process, unlike gasoline-powered vehicles.

EVs, including electric AVs, boast emission-free operation at the tailpipe. Leveraging the efficiency of electric motors, these vehicles exhibit lower emissions compared to their gasoline-powered counterparts, even when drawing electricity from a grid primarily fuelled by fossil fuels. In the USA, EVs emit carbon equivalent to a gasoline-fuelled vehicle achieving 88 miles per gallon (mpg), surpassing the efficiency of the most fuel-efficient gasoline cars at approximately 58 mpg and the average new gasoline vehicle at 31 mpg. Despite a considerable portion of US electricity currently being generated from fossil fuels – predominantly natural gas, which fuelled 63% of electricity generation in 2019 – an increasing integration of renewable energy sources into the grid promises a continued reduction in GHG emissions per EV. However, a surge in overall vehicle emissions could accompany an escalation in car production and use, even with predominantly electric fleets.

Moreover, extended travel distances and prolonged vehicle occupancy may contribute to an uptick in emissions. In the event of widespread adoption of, and advances in, AV technology, driving may undergo a significant safety transformation which renders many conventional vehicle safety features redundant. According to estimates by the National Renewable Energy Laboratory, eliminating unnecessary safety components could make AVs up to 75% lighter than traditional vehicles, consequently enhancing their energy efficiency substantially.

According to insights from the National Renewable Energy Laboratory [147], adopting CAVs/AVs could foster more streamlined driving behaviours and route optimisation, resulting in smoother acceleration and deceleration as well as enhanced traffic avoidance strategies, ultimately enhancing energy efficiency. Leveraging their sensors and AI arrays, AVs could capitalise on platooning or “flocking” techniques, substantially reducing inter-vehicle distances to exploit slipstream effects which diminish air resistance and bolster overall operational efficiency.

Additionally, platooning offers the prospect of accommodating more vehicles on existing road infrastructure without exacerbating congestion issues, although an accident could precipitate a domino effect. Despite the potential environmental advantages, widespread deployment of single-occupancy CAVs might yield a net adverse environmental impact. Increased opportunities for occupants to engage in work or leisure activities during travel could incentivise greater mobility, leading to a surge in VKT attributable to CAV usage which escalates pollution levels. Furthermore, empirical evidence suggests that a substantial portion of an EV's battery capacity could be diverted to cabin amenities and the computational demands of CAV systems, thus potentially compromising energy efficiency and raising electricity consumption.

Regulatory authorities might elevate speed limits on selected roadways, deeming AVs capable of safe operation at higher velocities, and thereby increase energy consumption over equivalent distances. At the same time, automakers may pivot towards designing larger, albeit less energy-efficient, EVs which include onboard amenities such as mobile offices or sleeping quarters. The resulting increase in vehicle size and battery capacity could precipitate higher carbon emissions during manufacture. When evaluating the holistic lifecycle of these vehicles from production to disposal, projections suggest that widespread use of private electric CAVs/AVs could cause a possible surge in carbon emissions of up to 200% [147].

4.2 Vehicle connectivity

Connectivity makes coordinated traffic flow management possible by enabling vehicles to communicate with infrastructure and with one another. This may lessen traffic congestion and cut down on engine idling and emissions. Concerns about data privacy and security are raised by vehicle connectivity because the gathering and exchange of driver and vehicle data may result in misuse or illegal access, requiring the use of more energy-intensive cybersecurity and encryption measures. Through better traffic flow and optimised driving habits, AV connectivity technology can reduce emissions and increase fuel efficiency. Congestion and idling time can be reduced by using AVs to more quickly anticipate and respond to traffic conditions by using real-time data from other vehicles, infrastructure sensors, and traffic management systems. This reduces air pollution and GHG emissions as well as saving fuel. Additionally, AVs can facilitate the adoption of electric and alternative fuel vehicles by providing infrastructure support such as charging stations and incentives for cleaner transportation options. AVs can facilitate ride-sharing and shared mobility services which lower the overall number of vehicles on the road and consequently reduce emissions and traffic.

Communication among various entities, including infrastructure, neighbouring vehicles, pedestrians, sensors, and smart devices, is imperative for the operation of AVs. Given the heavy reliance of AVs on inter-vehicle and infrastructure communication, advances in ITS have significantly bolstered technological progress with highway and in-vehicle systems, particularly for AVs. ITS, as defined by ITS Canada, encompasses using advanced technologies such as computers, sensors, control mechanisms, communication systems, and electronic devices in transportation to enhance safety, efficiency, and environmental sustainability [148]. Currently, a broad range of ITS applications are implemented for automated highways. These applications include traffic signal synchronisation, active traffic management, smartphone applications, on-board navigation systems like Google Maps, and other connected vehicle technologies [149]. The fundamental objective of ITS deployment is to enhance network efficiency, thereby reducing traffic congestion and enhancing driver safety and security.

However, there are also negative environmental effects associated with AV connectivity technology. The possible rise in VKT as a result of factors like improved accessibility and convenience of transportation is one cause for concern, improper management of which could result in increases in emissions and overall energy consumption, negating the advantages of increased fuel efficiency. Furthermore, the use of electric AVs raises concerns regarding the environmental sustainability of battery production and disposal, as well as the effects of electricity generation on the environment. It is essential to put policies and strategies in place that give priority to energy efficiency, sustainable manufacturing practices, and the integration of AVs with larger transportation and urban planning initiatives so as to maximise the positive environmental impacts of AV connectivity technology and minimise the negative ones. This entails investing in renewable energy sources, encouraging the use of cleaner modes of transportation, boosting shared mobility services, and ensuring that resources are managed responsibly throughout the AV lifecycle. AV connectivity technology can significantly contribute to the development of more environmentally friendly and sustainable transportation systems by proactively addressing these issues.

4.3 Summary of technological development of CAVs

In summary, the rapid advances in CAV technology hold significant promise for revolutionising the transportation landscape, but also pose consequential environmental problems. Fig. 7 summarises the positive and negative environmental effects, research gaps, and future technological development projected for CAVs by 2060. Advances in CAV technology can potentially improve the safety, efficiency, and convenience of urban transportation. CAVs are projected to maximise traffic flow, lessen congestion, and minimise accidents, supported by sophisticated machine-learning algorithms and advanced sensor systems which enable real-time data collection and autonomous decision-making. But amid these technological advancements, there are environmental nuances to consider. Through enhanced traffic management, route optimisation, and the proliferation of electric and low-emission vehicles, CAVs do offer the potential to reduce GHG emissions but, if not carefully managed, widespread adoption of CAVs could also result in increased energy consumption and VKT. Furthermore, the production and implementation of CAVs require significant resource inputs and could produce significant electronic waste, underscoring the importance of lifecycle environmental assessments and sustainable manufacturing techniques. Environmental sustainability must therefore be prioritised in the holistic development of CAVs with lifecycle assessments, emission reduction plans, and legislative frameworks that reward environmentally friendly behaviour. The development of

CAVs could then help create more resilient and environmentally friendly transportation systems for future generations and strike a balance between technical innovation and environmental stewardship.

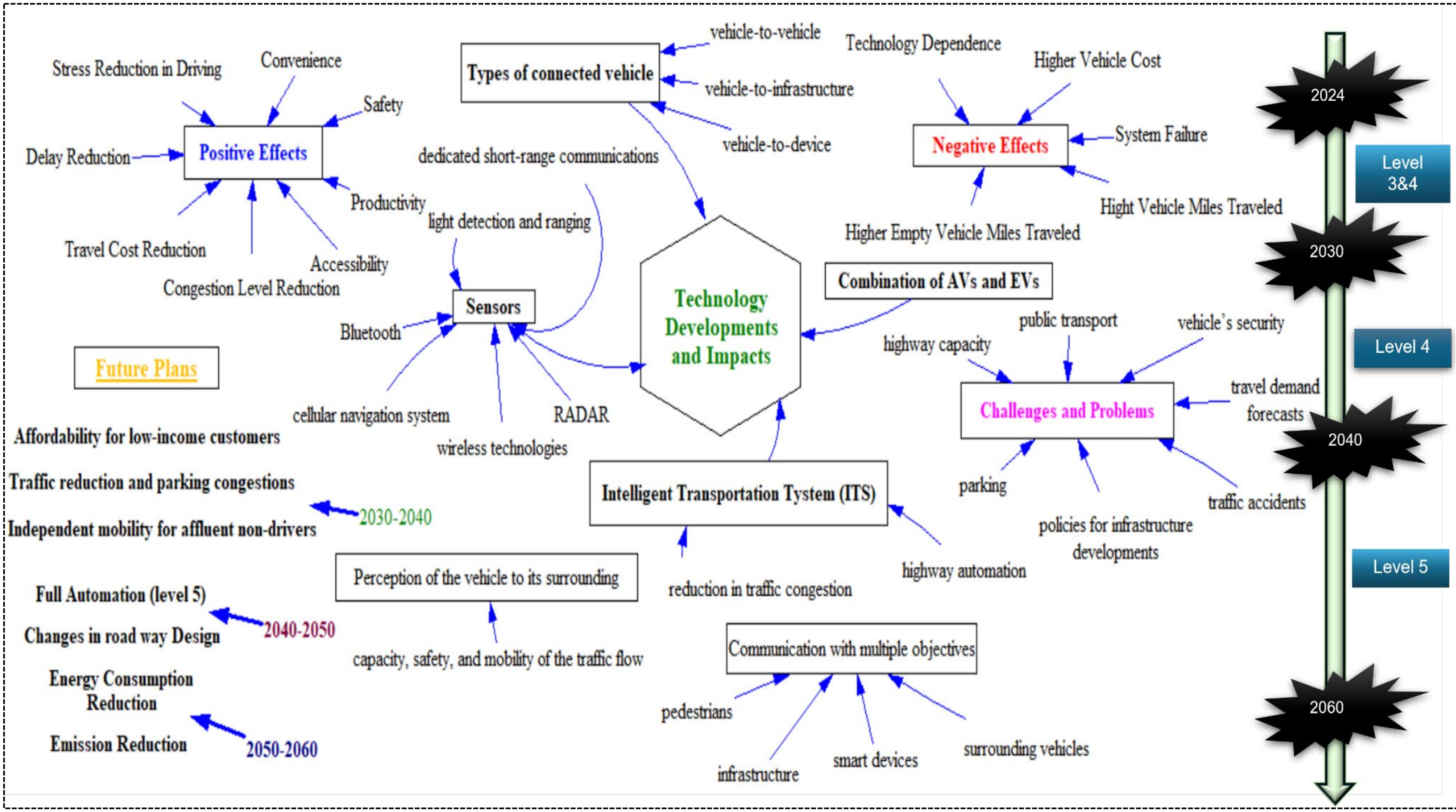

Fig. 7 Summary of CAV technological developments vs environmental effects and future projections

5. Conclusion

This study synthesises findings from the literature regarding the anticipated environmental ramifications of CAVs. The objective was to collate and classify researchers' projections concerning how Connected and Automated Vehicles will impact greenhouse gas emissions and fuel consumption. It was found that integrating CAVs into traffic will both directly and indirectly influence the environment. The magnitude of these effects hinges on various factors stemming from the vehicles themselves, the transportation network, or user responses. Despite substantial research efforts aimed at addressing environmental concerns arising from new vehicle and engine technologies, numerous questions remain unresolved. Given that many research outcomes are rooted in theoretical frameworks only, there is a recognised need for further empirical investigations to fully comprehend the real-world scope and significance of environmental impacts. Using available real-world data is imperative for a more pragmatic assessment of the prospective positive outcomes.

Despite their potential benefits, the connectivity aspect of CAVs may produce several negative environmental impacts because constant data exchange between vehicles, infrastructure, and servers requires substantial energy for data processing, storage, and transmission. The sophisticated onboard systems necessary for connectivity are energy-intensive, potentially reducing the overall energy efficiency of the vehicles. The production of advanced electronic components needed for CAVs, such as sensors and communication modules, requires rare earth metals and other materials with high environmental costs of extraction and processing. This also increases the demand for more powerful batteries, leading to greater consumption of materials like lithium, cobalt, and nickel. Rapid technological advances can cause earlier obsolescence of electronic components, resulting in shorter vehicle lifecycles and increased electronic waste. Electricity production also has non-negligible effects on total emissions, a fact not fully explored in the literature. The lifecycle perspective makes for an intriguing research topic and requires in-depth examination at system level. CAVs could induce travel demand, because their convenience encourages more travel and thus greater VKT. CAVs will also operate more frequently without passengers, thus further increasing VKT and associated emissions which offset efficiency gains. The need for extensive upgrades to existing infrastructure, such as communication networks and sensors, also adds to the environmental burden through their manufacture, installation, and maintenance.

Addressing these issues requires a comprehensive approach, including the development of energy-efficient technologies, the development of simulation tools to provide insights into the medium- and long-term environmental impacts of automated vehicle adoption with a focus on the connectivity impacts, effective urban planning, and policies promoting sustainable travel behaviours. For broad externalities beyond transport systems, policymakers, economists, industry experts, and infrastructure providers need to work together to identify development issues.

In forthcoming studies, researchers must scrutinise various factors like novel designs and driving capabilities, potential communication with other vehicles and infrastructure, using electric motors, and the capacity for efficient management of shared and on-demand mobility across diverse settings. Cooperative driving systems facilitating optimal management of vehicle movements in traffic environments are poised to diminish emissions and energy consumption. Nevertheless, the effects of automated vehicles on GHG emissions will depend on ongoing technological developments, consumer reactions, and government regulations. For this reason, it is difficult to predict with certainty the total beneficial impacts of automated vehicles on GHG emissions from transportation systems. Projecting the long-term effects on GHG emissions with confidence is unlikely to be possible due to the need for long-term land-use adjustments, the unexplored roles of policy, welfare, and equity, and uncertainty about the potential effects of AVs. Moreover, the COVID-19 pandemic has presented challenges for current mode-choice models, which may encourage policymakers to adopt appropriate mobility options that prioritise public health and safety. Therefore, a proper systemic approach is required to develop appropriate methodologies, tools, and techniques to fully understand the impact on GHG emissions of the adoption of CAVs across various levels. Subsequent initiatives should focus on policy aspects like parking regulations, management plans, and congestion pricing models. Validating and identifying potential policy measures through case studies is crucial. This involves comparing ideal driverless cities globally and considering various policy procedures, measures, and acceptability levels. Given that vehicle automation technologies are still in an immature developmental phase, studies addressing uncertainties around future technological trajectories have suggested many avenues for future research.

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Appendix

Table 1: Literature Summary of Positive and Negative Environmental Effects of CAVS and AVs.

Author	Environmental Effects					Type of Vehicle	Effects		Case study
	Emissions	Energy	Noise	Land use	Others		Negative	Positive	
Barth et al. [73]	✓	✓	×	×	×	AVs	×	• 10–15% energy saving • 15% reduction in fuel consumption	Numerical Example
Fagnant and Kockelman [90]	✓	×	×	×	×	AVs	×	• Up to 94% less GHG in long term	Numerical Example
Fagnant and Kockelman [80]	×	×	×	✓	×	AVs	×	• Reduction of parking space (each AV reduced 11 parking spaces)	US
Brown et al., [50]	×	✓	×	×	×	AVs	×	• Energy savings 90% in the long term	Numerical Example
Zhang et al. [84]	×	×	×	✓	×	AVs	×	• 90% reduction in parking demand	US
Li et al. [109]	✓	×	×	×	×	AVs	×	• 5% reductions	Numerical

								of carbon monoxide and particulate matter emissions	Example
Greenblatt and Saxena [17]	✓	✗	✗	✗	✗	AVs	✗	• Up to 94% less GHG in long term	Numerical Example
Wadud et al. [16]	✓	✗	✗	✗	✗		✗	• Up to 94% less GHG in long term	Numerical Example
Miller and Heard [48]	✓	✗	✗	✗	✗	AVs	✓ Higher emissi ons	➢ Reduces total travel time ➢ Reduction in collisions and congestion ➢ Increases in travel speeds	Numerical Example
Wadud, and Anable [110]	✗	✓	✗	✗	✗	AVs	✗	➢ Up to 45% reduction in energy	Numerical Example
Clements and Kockelman [51]	✗	✗	✗	✓	• Economic effects	AVs	✗	➢ 40% reduction in parking spaces	US
Clark et al. [111]	✗	✗	✗	✓	• Social impacts	AVs	✗	✓ 90% reduction in parking spaces	US
Zhang and Guhathakurta [84]	✗	✗	✗	✓	✗	AVs	✗	✓ 4.5% reduction in parking demand	US

Ross and Guhathakurta, [112]	×	✓	×	×	×	AVs	×	✓ 50% of energy savings by ride-sharing of full AVs	Numerical example
Metz [49]	×	×	×	✓	• Increasing the demand for sharing trips	AVs	×	✓ Reducing the number of parking places, especially in CBD areas	Numerical example
Zhang et al. [113]	✓	✓	×	×	×	AVs	×	✓ Lower energy consumption ✓ Lower emissions	Numerical example
Liu et al. [114]	✓	✓	×	×	×	AVs	×	✓ 14% reduction of emissions	US
Vahidi and Sciarretta [115]	×	✓	×	×	×	AVs	×	✓ 2-50% energy savings	Numerical example
Conlon et al. [116]	✓	✓	×	×	• Improving traffic flow	AVs	×	✓ Reductions between 4.7% and 14.5%	Numerical example
Feng et al. [117]	✓	×	×	×	• 24% reduction in vehicle delay	CAVs	×	✓ 13.8% reduction of CO2 emissions	Numerical example
Bento et al. [118]	✓	×	×	×	×	AVs	×	✓ Significant reduction of CO2 emissions	Numerical example
Bichiou and Rakha [119]	✓	✓	×	×	• 80% reduction in delay	CAVs	×	✓ 42.5% reduction of fuel	Numerical example

								consumption ✓ 40% reduction of CO_2 emissions	
Chen and Liu [120]	✓	×	×	×	• Minimising travel times	AVs	×	✓ Minimising fuel consumption ✓ Minimising emissions of vehicles	Numerical example
Patella et al. [121]	×	×	✓	×	×	AVS	×	✓ 24% noise pollution reduction	Numerical example
Chehri and Mouftah [122]	×	×	✓	×	×	AVs	×	✓ 2-4% reduction of fuel consumption	Numerical example
Guo et al. [71]	✓	×	×	×	×	AVs	×	✓ Reduction of emissions up to 44.62%	Numerical example
Wang et al. [123]	×	✓	×	×	• Enhancing traffic efficiency	CAVs	×	✓ Increasing energy efficiency with ensured safety	Numerical example
Wang et al. [124]	✓	×	×	×	×	CAVs	×	✓ More than 7% reduction of energy consumption ✓ Up to 59% reduction of pollutant emissions	Numerical example
Kopelias et al. [3]	×	✓	×	×	×	CAVs	×	✓ 30-90% reduction of fuel use	Numerical example

Rafael et al. [125]	✓	×	×	×	×	AVs	×	✓ 30% reduction of both NOx and CO2 emissions	Numerical example
Fakhrmoosavi et al. [126]	✓	×	×	×	×	CAVs	×	✓ Improvements in travel time and emissions	Numerical example
Jia Et al. [127]	✓	×	×	×	×	AVs	✓ Increase in GHG	×	Seattle and Kansas
May et al. [128]	✓	×	×	×	×	AVs	✓ Increase in GHG (56% and 42%)	×	Numerical example
Winter et al. [129]	✓	×	×	×	×	AVs	✓ Increase in GHG	×	Amsterdam
Harper et al. [130]	✓	×	×	×	×	AVs	✓ Increase in GHG (2.5% and 2.1%)	×	US
Gawron et al. [131]	✓	✓	×	×	×	AVs (Taxis)	×	✓ 60% reduction in cumulative energy and GHG emissions	Numerical example
SAE [132]	✓	✓	×	×	×	AVs (Trucks)	×	✓ GHG reduction ✓ 10% reduction in fuel consumption	US
Poinsignon et al. [133]	✓	×	×	×	×	AVs (Buses)	×	✓ Significant emissions reduction	Numerical example

Table 2: Estimated Impacts of CAVs on Travel Demand and Vehicle Ownership

Author	Estimation/Finding
Fagnant and Kockelman [80]	An up to 26% increase in vehicle kilometres travelled (VKT) was estimated after a 90% adoption of CAVs.
Guerra [154]	5-20% increase in VKT after wide AV adoption.
Wadud et al. [16]	A VKT increase of 4-13% with partial vehicle automation and 30-60% for full automation.
Milakis e al. [142]	AV will increase VKT between 1-23% by 2030 and 10-71% by 2050.
Cavoli et al. [155]	The use of AV can lead to an increase in the VKT and a reduction in PT shares.
Arbib and Seba [156]	The number of vehicles would drop from 247 million in 2020 to 44 million in 2030 in the US due to the popularity of CAVs.
Soteropoulos et al. [43]	A reduction of KVT of about 10-25% if travellers chose car sharing.
Soteropouls et al. [43]	VKT increases 35-60% for lower cost and more empty trips. It can rise up to 90% if SAVs replace PT and all private vehicles.
Zhang and Guhathakurta [147]	A distinct change in VKT according to family types from 7% to 12%.
Loeb and Kocklman [157]	SAVs generate 19-31% more vacant trips
Loeb and Kockelman [158]	14.2% increase in empty VKT per SAV.
Patella et al. [121]	In a scenario with 100% presence of AVs, inner urban roads would benefit from a 24% reduction in noise pollution due to a 5% decrease in traffic volume.
Narayanan et al. [153]	Vehicle occupancy increases from 1.2 to 3; A SAV replaces 10 vehicles on road.

Table 3: Estimated Impacts of Vehicle Connectivity on Road Capacity and Travel Demand

Author	Estimation/finding
Hymel et al. [172]	Increasing road capacity by vehicle connectivity and automation without increasing network connectivity would induce a small VKT increase.
Van den Berg and Verhoef [160]	Road capacity will increase by 7% if the Automated adaptive cruise control (AACC) rate is between 40% and 60%. Cooperative adaptive cruise control (CACC) will increment the capacity to nearly 102% when all cars are communicated.
Shladover et al. [87]	10%, 50%, and 90% penetration of adaptive cruise control can increase capacity by 1%, 21%, and 80%, respectively. 20%, 30% and 50% penetration of vehicles with awareness devices can increase capacity by 7%, 10%, and 15%.
Fernandes and Nunes [164]	Platooning can increase road capacity by 5 times and the saved road space can be reallocated to other travel modes.
Guo et al. [83]	Fuel consumption can be reduced by up to 12% through dynamic route guidance (V2I).
Gucwa [173]	Up to 14.5% increase in VKT if a zero-cost travel time is assumed for travelling in a CAV
Minelli et al. [165]	CAV will initially reduce but then increase travel time due to increased market penetration. This increase is significant for market penetration of between 60% and 100%.
Childress et al. [102]	CAV will increase road capacity by 30%, resulting in a 3.6% increase in VKT.
Childress et al. [102]	A decrease in the perceived value of travel time cost of 35% plus a 30% increase in road capacity would increase 5% VKT.
Wadud et al. [16]	Vehicle platooning (V2V) can reduce energy consumption between 3% and 25%
Farmer [174]	If all vehicles on roads are fully automated, highway capacity can increase by around 100%.

Auld et al. [175]	If CAVs increase 80% of road capacity, VKT will increase by 4%. The elasticity of VKT to road capacity is low. The change in the value of travel time can increase VKT by 59%.
Milakis et al. [142]	40% penetration of CAVs can increase road capacity by over 10%. 100% penetration of CAVs can increase road capacity by over 200%.
Mattas et al. [176]	In high-density traffic conditions, AVs without connections will slow down and generate 11% more emissions, but if AVs are connected CO2 emissions can be reduced by 5%.
Hwang and Song [177]	As CAVs increase, road capacity improves and emissions can be reduced by up to 30%.
Narayana et al. [153]	CAVs would increase capacity by 9.4% with 100% penetration without connectivity and by 39.2% with connectivity.
Cordera et al. [141]	An increase in road capacity will increase travel demand, including empty trips that offset the positive effect.

Table 4: Estimated Impacts of CAVs on Household Residential Relocation and Urban Sprawl

Author	Estimation/Finding
Litman [136]	CAVs can increase urban sprawl between 10% and 30%.
Auld et al. [175]	If CAVs increase 80% of road capacity, VKT will increase by 4%. The elasticity of VKT to road capacity is low. The change in the value of travel time can increase VKT by 59%.
Hymel et al. [172]	Increasing road capacity by vehicle connectivity and automation without increasing network connectivity would induce a slight VKT increase.
Childress et al. [102]	A decrease in the value of travel time and an increase in road capacity would increase VKT by up to 20%.
Gelauff et al. [180]	CAVs can lead to urban expansion in large cities and decline in smaller regional cities.
Carrese et al. [186]	40% of respondents would move to the suburbs under the AV regime in Rome.
Wellik and Kockelman [187]	5.3 to 5.5% reduction in the number of households living in the metropolitan region of Austin in a 100% AV scenario.
Moore et al. [179]	25.8% of respondents would be willing to move and increase their commute time by more than 10 minutes if they owned a CAV. CAVs can save trip time value by 30%, which could result in 68% urban sprawl predicted.
Guan et al. [188]	30% of respondents reported willingness to move further from the city centre, if level 4 AVs become available.
Liu et al. [22]	With increased CAV levels, land rent will decline, resulting in the expansion of suburban areas.
Zhang and Guhathakurta [147]	SAVs can increase the household distance to the CBD by up to 13.8%.
Hasnat et al. [171]	Extensive adoption of private CAVs improves network conditions and encourages households to live further from work, leading to up to a 5.6% increase in suburban households.

Table 5: Estimated Impacts of CAVs on Parking and Travel Demand

Author	Estimation/Finding
Zakharenko [193]	Outside the city centre, parking areas could accommodate around 97% of daily parking demand.

Milakis et al. [142]	SAVs will reduce parking demand by between 67 and 90%.
Zhang and Guhathakurta [147]	5% more shift from conventional vehicles to SAV could save 4.5% parking space.
Simon et al. [194]	20% to 60% SAV adoption would reduce CBD parking by 20% to 64%.
Kondor et al. [195]	Parking demand will decrease by 50% if SAVs serve 100% of travel demand.
Zhang and Wang [152]	By the year 2040, a scenario with PAVs (37.35%), SAVs (37.35%), and conventional vehicles (12.65% shared and 12.65% private) can reduce CBD parking by 75% and increase suburban parking by 100%.
Narayanan et al. [153]	CAVs can reduce parking areas by 48% to 90%.
Azevedo et al. [191]	Car park space can be reduced by 50% due to a more efficient layout for AVs.
Silva et al. [145]	City parking would be reduced by 83% if AVs served 90% of travel demand, among which SAVs served 40%.
Kang et al. [196]	25-32% of current parking areas could be repurposed, owing to CAV's capability of parking at their origins.

Table 6: Estimated impacts of CAVs on transport mode changes

Author	Estimation/Finding
Impacts on other transport modes	
Childress et al. [102]	PT and walking share will reduce by 9% and 12% respectively, with a 30% increase in road capacity, 35% reduction in the perceived value of travel time, and a 50% reduction in parking cost induced by CAVs.
Davidson and Spnoulas [215]	PT and active modes will decline by 14% and 11% if the car operation cost decreases by 50% and the perceived value of travel time is reduced by 10-50%. 10% of PT trips made by members of no-car households are likely to switch to AVs given the availability of affordable SAVs.
Rodier et al. [216]	100% CAV penetration could reduce the cost of travel by 20% per mile, which can increase 6% drive alone, reduce 12% PT mode and 4% active mode.
Booth et al. [218]	Minorities of respondents indicated that they would be likely to use AVs instead of walking (18%), cycling (32%), and public transport (48%).
May et al. [128]	Shifting to AVs could increase VKT by 50%, the use of active transport could decrease by 13%, and the use of PT could decrease by 18%, by year 2050.
Hamadneh and Esztergár-Kiss [219]	AVs strongly affect public transport when the value of travel time (VOT) of AVs gets close to the VOT of public transport.
Sun et al. [63]	CAVs will reduce PT share and increase VKT. Applying congestion pricing and deployment of SAVs could help reduce vehicle travel demand and emissions.
Impacts of SAVs	
Martin et al. [89]	A reduction of 9 to 13 vehicle travels per vehicle sharing.
Fagnant and Kockelman [90]	Each SAV can replace around 11 conventional vehicles but adds up to 10% more travel distance than comparable non-SAV trips, resulting in overall beneficial emissions impacts.
Soteropoulos et al. [43]	SAV could reduce PT share by 16 and 12% and more significant reductions (26-20%) in non-motorised transport.
Lokhandwala and Cai [217]	A fleet of shared Automated taxis can maintain the same service level as the traditional taxi system in New York with 59% fewer vehicles and 750 tons of CO2 per day of emissions reduction.

Table 7: Estimated Impacts of CAVs on Land Use and Built Environment

Hawkins and Nuruak Habib [229]	Current parking spaces may be transformed into commercial, residential, and mixed-use hubs.
Gelauff et al. [180]	CAVs can increase population density in non-urban areas by 1% and adoption of SAVs would increase population density in urban areas by 3%.
Wellik and Kockelman [187]	20-62% increase in developable land at 100% AVs scenario over 0% AV scenario due to reduction in parking.
Kumakoshi et al. [230]	Commercial land use area may increase by 35%, owing to the parking reduction after the introduction of SAVs.
Bridgelall and Stubbing [231]	The trip rate for commercial land use may triple by 2050 and land use may shift to lower-density suburbs.
Cordera et al. [141]	CAVs will increase the capacity of inter-urban roads by 80% and urban roads by 40%. As a result, the population density will decrease by 1.3% in suburban areas.
Hiramatsu [232]	SAVs can increase population density in the CBD by 0.8% and decrease suburban population density by up to 19.3%.