VRIJE UNIVERSITEIT BRUSSEL

Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Management

Greening the City Ahead: A Comprehensive Study on the Environmental Impacts of Autonomous Vehicles on Urban Sustainability

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Abbreviations

AVs .... Autonomous Vehicles

CO_2 .... Carbon Dioxide

EU .... European Union

GHG .... Greenhouse Gas

PRISMA............................Preferred Reporting Items for Systematic Reviews and Meta-Analyses

ABSTRACT

This master's study investigates the environmental impacts of autonomous vehicles (AVs) on urban sustainability focusing on emissions, energy consumption, and urban planning. Amid growing concerns about climate change and the need for sustainable urban development, this research aims to answer a crucial question: Will autonomous vehicles serve as a catalyst for environmental sustainability or exacerbate ecological challenges? A systematic literature review was conducted following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to identify, select, and summarize relevant studies which led to the inclusion of forty-two relevant papers published between 2015 – 2024. The results reveal AVs can substantially reduce emissions through enhanced traffic efficiency and operational strategies, with emission reductions ranging from 4.7% to 59%. Additionally, shared autonomous vehicles (SAVs) and autonomous taxi fleets offer considerable potential for reducing the number of vehicles and associated emissions, potentially achieving reductions of up to 94%. Conversely, mixed traffic environments and varying penetration rates of AVs demonstrate complex dynamics, sometimes resulting in increased emissions due to heightened demand and acceleration patterns. The study also explores the broader urban impacts of AVs, revealing potential for both dispersed urban development and increased urban density. Policy measures encouraging the use of SAVs are essential for managing parking demand and optimizing urban mobility. While AVs hold promise for enhancing urban mobility and sustainability, careful planning and consideration is crucial to fully realize their potential.

1.0 Introduction

1.1 Background Information

The topic of autonomous vehicles (AVs) is at the intersection of technological innovation, transportation, and environmental stewardship in a period marked by mounting concerns about climate change and the objective of urban sustainability (Rafael et al., 2022). This master's thesis investigates the environmental implications of incorporating autonomous cars into urban fabric. The goal of this research project, "Greening the City Ahead: A Comprehensive Study on the Environmental Impacts of Autonomous Vehicles on Urban Sustainability," using a systematic literature review approach of AV deployment on urban ecosystems and answer the essential inquiry: Will autonomous vehicles serve as a catalyst for environmental sustainability or inadvertently exacerbate pressing ecological challenges?

The growing relevance of road traffic as a significant contributor to greenhouse gas (GHG) emissions, accounting for more than one-fifth of total world emissions, highlights the importance of this work (Heinold & Meisel, 2018). With 1.3 billion vehicles in the automotive fleet, most of which are passenger cars, an ongoing rise in car ownership in major global cities, and individuals' dependence on personal vehicles has resulted in a cascade of negative consequences (Chen et al., 2020). Increasing carbon emissions, environmental pollution, background noise, traffic congestion, and poor health repercussions are all factors forming the current metropolitan picture. In response to these mounting worries, international organizations have set lofty goals, including the European Union's aim to cut emissions of greenhouse gases by 55% by 2030 and achieve ecological neutrality by 2050 (Cifuentes-Faura, 2022).

Given these ecological imperatives, the transportation sector is increasingly adopting innovation and technological advancements as essential instruments in pursuing sustainable urban expansion (Bibri et al., 2024). Autonomous vehicles (also referred to as self-driving cars), often recognized as a disruptive trend in modern transportation, are emerging as a technological wonder that can potentially change urban and freight transit. According to Jelti et al. (2023), AVs can potentially deliver a greener and more environmentally friendly urban transportation system because they utilize electricity as an engine fuel. In addition, they have the potential to improve general transportation safety while also encouraging automobile sharing, which could ultimately reduce automotive ownership obligations, traffic congestion, energy consumption, and emissions (Onat et al., 2023). Nonetheless, it is vital to recognize the complex discussion surrounding self-driving car adoption. Existing research has highlighted legitimate concerns about the possible repercussions of ubiquitous AV use. These concerns center on the potential for AVs to have severe environmental and societal effects due to changes in travel behavior that might lead to higher consumption of energy, vehicle mile travel (VMT), and pollution (Acheampong et al., 2021).

As a result, an essential issue arises: Will self-driving vehicles be a good factor for the environment or add to the deterioration of environmental challenges? This thesis work examines the existing research and viewpoints on AVs and their ecological consequences to address this vital topic. Finally, it anticipates offering essential suggestions for reducing emissions from transport in the future when self-driving cars are widespread, enabling an environmentally friendly and green urban environment.

1.2 Research Questions

These questions look at essential issues like lowering traffic pollution, how AVs affect shared mobility, how cities change, how environmental noise is reduced, study results that don't agree, and the bigger picture of making urban transportation emission-free. These questions investigate AV integration's possible advantages and limitations, offering a broad view of their role in constructing sustainable urban settings.

1) How do AVs reduce traffic emissions, and what measures are needed to spread the advantages across varied urban environments?
2) How does AV adoption affect shared mobility, including optimized routes and reduced need for private automobile ownership?
3) What impact does AV adoption have on urban form, and what solutions are necessary to adapt to varied metropolitan situations?
4) What comprehensive solutions are needed to effectively integrate AVs into urban areas, considering variables such as energy sources, collaborative transportation, and ethical considerations?

2.0 Methodology

2.1 Introduction

This thesis study will be conducting a systematic review. As a result, the structure of this manuscript will consist of the following components in order: abstract, introduction, methods, results, discussion, conclusion, and references. This chapter presents the methodology that will be used to guide the data collection and analysis. Section 2.2 presents the methodology of literature review. The methods employed for this systematic review adhered to the guidelines outlined in the PRISMA Statement, ensuring rigor and transparency.

2.2 Systematic Literature Review

2.2.1 Scoping Review Approach

The study employed a scoping review approach following the study by Trico et al. (2018), which offers guidelines on the Preferred Reporting Items for Systematic Reviews and Meta Analyses extension for scoping reviews (PRISMA). The PRISMA Statement provides a complete framework for performing systematic reviews (Rethlefsen et al., 2019). PRISMA offers a two-step method that includes a flow diagram and a checklist. The flowchart depicts the processes of study identification, screening, and inclusion. The checklist contains elements and gives a precise strategy for presenting the introduction, methods, results, and discussion parts of a systematic review. Additionally, PRISMA promotes uniformity, openness, and repeatability in systematic review procedures while reducing researcher bias. (Rethlefsen et al., 2019). The approach will entail; (i) identification of the relevant studies, (ii) selection and screening of the studies, and (iii) summarizing and reporting of the findings.

2.2.2 Search Strategy: Databases, Search Terms and Combinations

According to the PRISMA Statement, databases and search keywords are critical components of the systematic review technique (Page et al., 2021). Google Scholar, PubMed Central, and the Directory of Open Access Journals constituted the three primary databases queried as part of the search strategy for this study. The search words, such as "Autonomous Vehicles," "Urban Sustainability," "Emissions," "Environmental Concerns," and "Greening the City," were put together using the "AND" operator in a planned way. This method ensured a thorough review of the literature across the specified databases. Using various databases and particular search criteria increases the study's breadth and depth, allowing for a detailed assessment of the interconnections between autonomous cars, urban sustainability, and environmental concerns.

The study utilized four primary databases: Google Scholar, PubMed Central, Emerald Publishers, Taylor and Francis. Selection criteria for these databases were based on accessibility through the university's study resources, relevance to the research focus on autonomous vehicles and urban sustainability, the volume of publications, and their status as sources of peer-reviewed articles. Anna's archive complemented these databases to retrieve potentially inaccessible articles, contributing to a comprehensive exploration of the environmental impacts of autonomous vehicles on urban sustainability.

Table 2.1 provides a detailed breakdown of the essential features mentioned in this study and the corresponding keywords/search phrases entered into the databases.

Table 2.1 Search Terms and Keywords

Key aspects	Vehicles	Urban	Gas	Green Spaces

Keywords	Autonomous Vehicles	Urban Sustainability Europe	Gas Emissions, Air Quality	Greening the city Europe

Source: Own Compilation

Keyword-Boolean Operators Combinations

1) Autonomous Vehicles AND Urban Sustainability AND Greening the City
2) Urban Sustainability AND Gas Emissions
3) Autonomous Vehicles AND Greening the City
4) Urban Sustainability AND Gas Emissions
5) Gas Emission AND Greening the City AND Europe
6) Autonomous Vehicles AND Gas Emissions
7) Air Quality AND Urban Sustainability AND Europe

2.2.3 Selection of Studies: Inclusion/Exclusion Criteria and Selection Process

Inclusion criteria are predefined conditions or characteristics that research studies or systematic reviews use to determine which participants, articles, or data will be considered for analysis or inclusion in the study (Page et al., 2021). The inclusion criteria for this study involve European-focused journals, studies conducted between 2015 and 2024, the English language, and a thematic focus on keywords related to autonomous vehicles, urban sustainability, gas emissions, and greening the city. This targeted approach ensures a specific and relevant selection of literature that aligns with the study’s objectives and temporal and geographic considerations. The following subsections describe the inclusion criteria in detail.

The study includes article reviews from several European cities. This decision is motivated by the closeness of environmental characteristics among European cities, which have commonalities in climate change consequences caused by gas emissions and urban growth patterns. Additionally, the focus on European cities provides contextual knowledge of the environmental implications of autonomous vehicles, guaranteeing that the findings fit with the unique difficulties and possibilities encountered by metropolitan centers.

2.2.4 The Publications: Type and Language

Exclusively incorporating peer-reviewed journal articles, this study emphasizes the reliability and currency of information. Additionally, articles considered are solely in English to ensure cohesive understanding and consistency in language. This deliberate selection of articles enhances the study’s comprehensiveness and maintains a standardized language, contributing to the clarity of interpretations and conclusions drawn from the gathered literature (Page et al., 2021).

From 2015 to 2024, this research period was carefully chosen to widen the scope and capture the recent achievements and insights pertinent to the study’s core topics—autonomous cars, urban sustainability, emissions, and environmental issues. This timeline allows for examining contemporary literature while also assuring the inclusion of the most recent advances and opinions on the subject. Focusing on 2015–2024, the study aims to provide an up-to-date analysis that aligns with how quickly the studied fields change. It also hopes to add to the current conversation about how self-driving cars affect the sustainability of cities by offering useful new information.

2.2.5 Exclusion Criteria

Exclusion criteria are predefined conditions or characteristics used to identify and exclude certain items, participants, or elements from a study, analysis, or review (Page et al., 2021). Considering the specified criteria and the study’s scope on autonomous vehicles and urban sustainability, articles were excluded if: a) The focus was not on European cities; b) The publication did not undergo peer review; c) The article was not published between 2015 and 2024; d) The article was not written in English; e) The article deviated from the primary topics of autonomous vehicles, urban sustainability, emissions, and environmental concerns; f) Irrelevant content that did not align with the study's research questions identified.

2.2.6 Eligibility Criteria and Selection of Studies

The selection process consisted of several steps, as directed by the PRISMA Statement (Page et al., 2021. The study selection process followed PRISMA guidelines. Google Scholar, PubMed Central, Emerald Publishers, Taylor and Francis were selected as literature databases. The search strategy was categorized into two pointers of the study viz Autonomous Vehicles (AV) in relations to Environmental Impact (EI) and Autonomous Vehicles in relation to Urban Sustainability (US). To begin the search process, search criteria took into consideration the key words in relation to the two pointers as indicated in figure 2. The search was carried out in April, 2024. Only articles published between 2015 and 2024 were filtered. Coarse grained inclusion was conducted as Mualla, et al., (2019) as cited by Li, et al., (2021). Screening was further done by abstract and conclusion, this left 180 articles on EI and 92 articles on US. Fine grained inclusion was then conducted having full manuscripts written in English (Li, et at., (2021) having AV, gas emissions, air quality elements. This left 104 and 19 eligible papers for environmental impact and urban sustainability respectively. Finally, citations were considered for eligible papers screening 31 and 11 publications on environmental impact and urban sustainability respectively. The selection process is showcased in Figure 2.

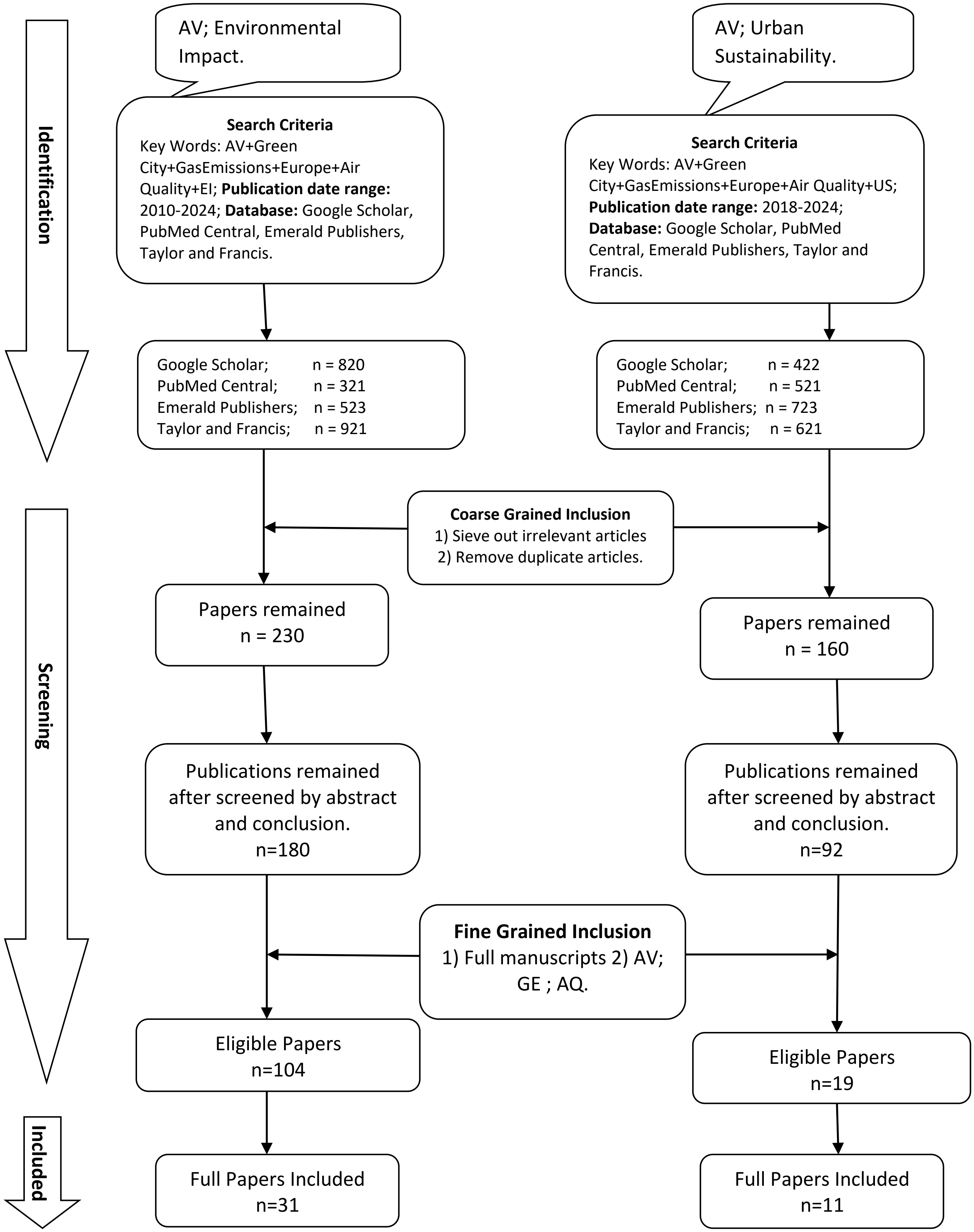

Figure 1: PRISMA Flow Diagram (Reproduced from Page et al., 2021)

2.3 Analysis Strategy and Data Extraction

Following a review of relevant materials, the data extraction procedure for this study delves into many aspects of European cities dealing with the influence of autonomous cars on urban sustainability, emissions, and greening programs. Each case study’s findings provide distinct narratives highlighting the numerous problems and possibilities that urban areas confront while integrating autonomous vehicles. The qualitative examination of these case study results allows for a more in-depth knowledge of complex dynamics. By carefully looking at each result and putting them together, this study shows how European cities have had different experiences. It adds to the larger conversation about how self-driving cars and the sustainable growth of urban landscapes can work together.

2.4 Limitations

Despite the depth of the study, several limitations must be acknowledged in any study (Salameh et al., 2020). First, the explicit focus on European cities may bring regional biases, limiting the findings’ applicability to other global contexts. Furthermore, the study’s focus on English-language papers may ignore relevant contributions in other languages. The timeline of 2015 to 2024 may ignore crucial previous studies or fail to convey the long-term effects of self-driving cars. Also, leaving out articles other researchers haven’t reviewed could mean missing out on helpful information from other sources. Another limitation is the heterogeneity in methodology and quality of included research, which may influence the consistency of the synthesis findings. The study’s thematic emphasis on individual keywords may overlook related variables critical to a more comprehensive understanding of autonomous vehicles’ environmental implications. Although attempts were made to alleviate these limitations, they must be addressed when interpreting and implementing the study’s findings.

3.0 Key Findings and Discussion

The majority of research findings predominantly discuss the environmental impacts of energy consumption and emissions. Conversely, there is a nascent body of literature addressing the impacts on land use, with fewer references focusing on direct environmental effects and instead emphasizing urban planning implications.

3.1 Impact of AVs on Air Quality: Atmospheric Pollution and Emission

The environmental impact of autonomous vehicles (AVs) is predominantly examined through emissions variation, with results falling into three distinct categories. The first category comprises studies exploring operational concepts within fully autonomous traffic environments. The second category investigates mixed traffic scenarios with varying levels of AV penetration across different cases. Lastly, the third category focuses on the impacts of AV fleets and shared mobility. Furthermore, this section discusses the wider impacts of autonomous vehicles (AVs) on the entire transportation system and their compatibility with other modes of transportation. However, these features are not specifically categorized within the aforementioned groups.

3.1.1 Effects Arising from the Design, Integration, and Mobility of Autonomous Vehicles

When examining the factors influencing the energy use and emissions of autonomous vehicles (AVs), it's pertinent to first consider variables stemming from their design, driving systems, and other necessary parts. C. Zhang et al. (2019) estimates that more than half (53.4%) of the total energy use of an electric vehicle is attributed to accelerating and overcoming frictional resistance. Therefore, any enhancements in driving efficiency can lead to reduced consumption and subsequently lower emissions. Indeed, calculations derived from the MOVES (Motor Vehicle Emission Simulator of Europe Environmental Protection Agency) model, suggest that replacing human-driven vehicles with autonomous vehicles (AVs) might lead to emission savings of up to 14% (Liu et al., 2019). In a realistic urban environment, Conlon et al. (2018) found a decrease in emissions ranging from 4.7% to 14.5%. A substantial proportion of these efficiency benefits could be achieved through enhancements in traffic flow assisted by different cooperative driving technologies. Out of these options, Platooning and Cooperative Eco-driving at Signalized Intersections and Cooperative Adaptive Cruise Control (CACC) are emphasized for their significant environmental advantages. (Z. Wang et al., 2020a).

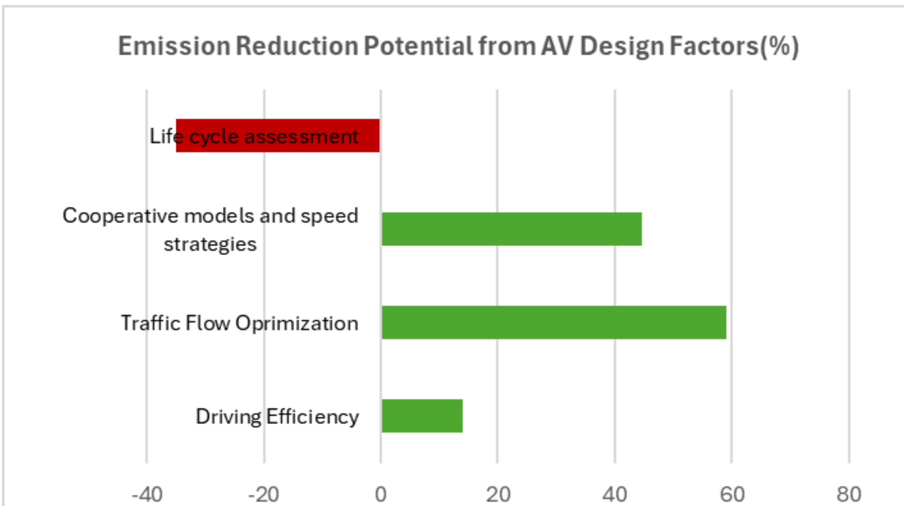

Figure 2 Emission Reductions from Different Strategies

A significant amount of literature presents models employing diverse operational concepts in various scenarios. Numerous studies focus on enhancing traffic flow at intersections with the integration of autonomous vehicles (AVs), facilitated by vehicle-to-vehicle and vehicle-to-infrastructure connections. The measures implemented have resulted in emission reductions between 13.8% and 59% (Bento et al., 2019; Bichiou and Rakha, 2019; Chen and Liu, 2019; Feng et al., 2018; Filocamo et al., 2020; C. Wang et al., 2020; Z. Wang et al., 2020b). In addition, other researchers support enhancements via various cooperative models (F. Ma et al., 2019) and variable speed strategies (Guo et al., 2020), which may achieve emission reduction of as high as 42.62%. Moreover, certain studies highlight the importance of considering the entire life cycle of a vehicle rather than solely concentrating on its operational period. For instance, Patella et al. (2019a) underscore that electric autonomous vehicles (e-AVs) may actually see a 35% increase in emissions at the vehicle level (including construction, maintenance, and end-of-life phases) compared to a conventional internal combustion vehicle, despite the potential for AVs to achieve operational savings of up to 60% in a scenario where 100% of vehicles are autonomous. This emphasizes the necessity of a comprehensive approach when assessing the environmental impact of AVs.

3.1.2. Effects due integration of both autonomous vehicles and conventional vehicles in traffic, as well as varying market penetration rates

The gradual adoption of autonomous vehicles (AVs) implies a prolonged period during which conventional and autonomous vehicles will coexist on roads. In field experiments conducted in closed-loop environments, even with low percentages of AVs (as low as 5%), there is evidence that they contribute to stabilizing traffic and levelling stop-stop intervals, resulting in a considerable decrease in emissions (Stern et al., 2019). Talebpour and Mahmassani (2018) performed an examination of mixed traffic situations that included traditional human-operated cars, connected human-operated vehicles, and autonomous vehicles (AVs). Their research indicates that the inclusion of linked vehicles improves the stability of traffic flow, much like autonomous vehicles. Nevertheless, automation demonstrates greater efficacy than connectivity alone in mitigating traffic shockwaves. Furthermore, autonomous vehicles exhibit greater efficiency when compared to connected vehicles that have similar degrees of market adoption.

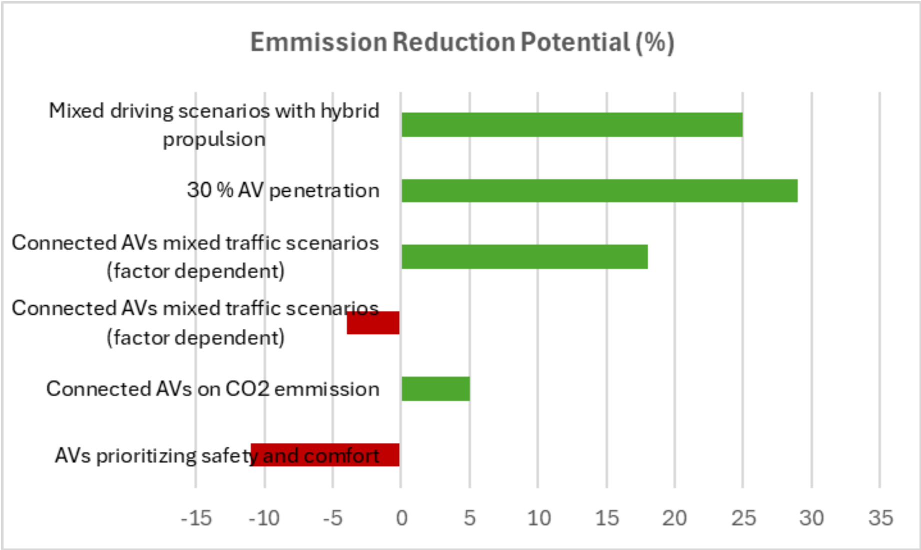

Figure 3 Integration of both autonomous vehicles and conventional vehicles in traffic, at varying market penetration rates

Autonomous vehicles (AVs) typically prioritize safety and comfort parameters, which can result in a tendency to slow down and generate approximately 11% more emissions. However, research suggests that if AVs were connected, carbon dioxide (CO2) emissions could be reduced by up to 5% (Mattas et al., 2018). Conversely, findings from Bandeira et al. (2021) indicate that the introduction of connected autonomous vehicles in mixed traffic scenarios could result to a 4% increase or an 18% decrease in CO2 emissions, depending on factors such as road type, driving conditions, and adoption rate.

The introduction of autonomous in an urban environment at a 30% adoption rate resulted in small 0.7% increase in the emission of CO2 and nitrogen oxides (NOx) due to heightened demand and acceleration after coming to a halt as seen in a study by Rafael et al. (2020). However, this can be countered with an AV scenario that includes 30% which may result in a 29% decrease in emissions. Similarly, a 20% adoption rate of electric AVs in a mixed fleet with electric human-driven vehicles and various collaborative strategies has been suggested to be the most energy efficient (C.R. Lu et al., 2019a). This may be attributed to the decrease in the regenerative energy of vehicles at higher adoption rates. However, when taking into account the inclusion of manually operated internal combustion vehicles, higher levels of electric vehicle use (whether autonomous or human-driven) are advantageous. In mixed driving circumstances, the use of hybrid propulsion in eco-driving methods has shown acceptable results, with more than 25% decrease in exhaust emmission (S. Wang and Lin, 2020).

3.1.3 Impact of Ride Sharing: Shared Autonomous Vehicles (SAVs)

Ride sharing platforms provide users i.e., passengers and drivers, with the chance to maximize the efficiency of supply and demand, resulting in possible economic advantages. Shared mobility services have the potential to save European households up to USD 6000 compared to owning a car, according to estimates by Anderson et al. (2018). The possibility of platforms like autonomous vehicle (AV) fleets, such as Shared Autonomous Vehicles (SAVs) or Autonomous Taxis (aTaxis), is being examined as viable replacements to traditional car ownership.

Various studies suggest that a single AV could replace from 7 to 11 traditional vehicles depending on factors such as waiting time and cost considerations (Iacobucci et al., 2018). These findings hold promise for substantial reductions in emissions. For example, autonomous electric taxis could potentially achieve emission reductions of 87–94% compared to human-driven traditional vehicles (Greenblatt and Saxena, 2019). Such transitions could lead to significant environmental benefits and contribute to the overall sustainability of transportation systems.

According to Lokhandwala and Cai (2018), a group of self-driving taxis that are shared among users may provide the same level of service as the regular taxi system while using 59% fewer vehicles. This would lead to a daily decrease of 725 tons of CO_2 emissions. Further, other studies have shown the possibility of reducing emissions by as much as 73%. This estimate considers the existing energy supply mix and the implementation of an efficient infrastructure for charging batteries Bauer et al. (2018). The magnitude of emission reductions can be influenced by variables such as the fleet size and the guidelines for recharging (H. Zhang et al., 2020). Along these lines, Miao et al. (2019) suggest that emissions from an autonomous taxi platoon can be reduced by 42% by accurately forecasting service coverage in different geographic areas and maintaining an optimal proportion of vehicles to charging points.

Multiple studies have analyzed the possible efficacy of implementing pollution fees as an incentive for the adoption of shared mobility. In fact, there is evidence to show that the implementation of these fees might result in a significant reduction of emissions, potentially leading to their complete elimination (Jones and Leibowicz, 2019).

Several studies have examined the potential effectiveness of introducing pollutant fees to incentivize shared mobility. Jones and Leibowicz (2019) demonstrate that emissions could nearly be eliminated with the application of such fees. However, when focusing exclusively on commuting trips, some models yield less promising environmental outcomes. For instance, M. Lu et al. (2018) revealed that 20% of autonomous taxis had the potential to replace all privately owned automobiles used for commuting. However, they also discovered that greenhouse gas emissions increased by 25% as a result of these autonomous taxis making additional trips to find their next passenger.

In their study, F. Yao et al. (2020) found that the adoption of autonomous vehicles (AVs) in large-scale mobility services might lead to a reduction in emissions of up to 12.3% when conventional vehicles are phased out. This suggests that while AV adoption holds promise for emissions reduction, careful consideration of factors such as trip types and passenger occupancy rates is essential to maximize environmental benefits.

3.1.4. Impact on Transportation System and Compatibility with other Infrastructure

The modeling of actual urban transport infrastructure has generally supported the reduction of emissions due to the adoption of autonomous vehicles. However, these findings may not be universally applicable to all cities. Oke et al. (2020) conducted a broader analysis by categorizing cities into different groups. The study found out that the impact of introducing mobility services with AVs varies depending on the characteristics of the city. In cities with extensive public transport networks, the introduction of AV-based mobility services may exacerbate congestion. Nevertheless, in more populated urban areas where public transportation is moderately used, the utilization of autonomous vehicles (AVs) for shared mobility holds potential for reducing traffic congestion.

For instance, in a metropolis, where private vehicles contribute to 96% of daily transport emissions, the introduction of AVs could potentially lead to increased kilometers traveled and emissions. Nonetheless, regional emission reductions of up to 5% can be achieved with electric AVs (A. Wang et al., 2018).

Studies reviewing transportation infrastructure, such as the EU-28, predict favorable outcomes by the year 2050. Nevertheless, the self-centered utilization of AV technology has the potential to undermine these results (Noussan and Tagliapietra, 2020). Similarly, China is projected to achieve substantial reductions in global emissions starting from 2045, as a result of improved consumption characteristics and growing adoption of autonomous vehicles (F. Liu et al., 2019). Numerous studies delving into the dynamics between different modes of transportation, project that by 2050, the distance travelled by vehicles could surge by 50%, while the utilization of public transport and active modes like cycling and walking could decline by 18% and 13%, respectively (May et al., 2020).

For instance, a study by Booth et al. (2019) revealed that 48% of the participants expressed their willingness to substitute public transportation with a self-driving vehicle, along with 32% of cyclists and 18% of pedestrians. However, concerns persist regarding safety and the coexistence of AVs and cyclists in urban spaces (Blau et al., 2018; Latham and Nattrass, 2019). Furthermore, research on the acceptance of autonomous vehicles suggests that having a favorable attitude towards environmental conservation and technological advancements does not always correspond to a desire for autonomous vehicles (Potoglou et al., 2020; Müller, 2019; Lang and Mohnen, 2019). Studies investigating the use of shared transportation in a situation where all vehicles are autonomous show that most participants prefer Shared Autonomous Vehicles (SAVs) (Stoiber et al., 2019).

The consequence of autonomous vehicles in urbans environments has received skepticism as seen from surveys of experts in the field conducted by Nogués et al. (2020). To mitigate potential sustainability challenges in the future, the study advocates for policies promoting active transportation modes, enhancing public transit, restricting private vehicles in city centers, and designing more compact urban layouts. Acheampong et al. (2021) argue that according to poll data from Dublin, the current views that prioritize car-centric transportation systems are likely to continue in a future where AVs are present. However, the study also proposes that other models emphasizing car-sharing and public transit could emerge with the implementation of appropriate transport policies and educational strategies.

3.2 Impacts of Autonomous Vehicles on Urban Sustainability

Autonomous Vehicles (AVs) are a major technological advancement with the capacity to transform urban transportation networks and contribute to sustainability goals. This study explores the multifaceted impacts of AVs on urban sustainability, covering transportation and mobility effects, environmental considerations, urban development and land use changes, parking demand dynamics, and policy implications.

3.2.1 Transportation and Urban Mobility

A systematic assessment on the immediate, intermediate, and long-term impacts of) AVs on urban mobility was carried out by Rahman and Thill (2023). The research looked at how AVs affect energy use, pollution, traffic patterns, and urban planning techniques. The study revealed that AVs are set to reshape urban transportation and mobility patterns significantly. Additionally, by decreasing vehicle ownership, Vehicle Miles Traveled (VMT), traffic delay, and congestion, AVs promise to enhance urban mobility and accessibility. Moreover, commercial operators stand to benefit from the increased revenue generation, while passengers may experience heightened convenience and productivity through multitasking capabilities. However, there are still concerns regarding personal safety, security, and privacy persist as barriers to widespread AV adoption.

The study conducted by González-González et al. (2019), which utilized a back casting approach to envision the city of tomorrow with the integration of automated vehicles showed that in conjunction with triggering the emergence of new peripheral centers (edge cities), AVs would increase the density of the existing urban fabric by reallocating space for residential, economic, and leisure activities. This likely involved forecasting future urban scenarios and planning strategies backward from a desired future state. In a similar study, Milakis et al. (2017) reviewed literature on the policy and societal implications of automated driving, providing insights into regulatory challenges, social acceptance, and potential equity issues associated with autonomous vehicle deployment. The study revealed that autonomous vehicles could have a clear positive impact on road capacity in the near future. The extent of this influence is correlated to the automation level, collaboration amongst vehicles and the corresponding rates of adoption. A adoption rate of 40% for CACC may be the turning point at which substantial capacity improvements (>10%) may be achieved. On the other hand, a penetration rate of 100% for CACC has the potential to significantly increase capacity.

On the other hand, Wadud (2017) investigated the possibility of the early adoption of fully automated vehicles by conducting a cost-of-ownership analysis. This involved assessing the affordability and economic viability of autonomous vehicles compared to conventional vehicles. The study found that the environmental implications of AVs are noteworthy, with potential reductions in energy consumption and greenhouse gas emissions expected. Additionally, AVs are anticipated to decrease traffic crashes caused by human errors, contributing to safer roads and improved environmental sustainability.

In support of the benefits of adoption of AVs, Moorthy et al. (2017) presented a case study on sustainably mitigating the Last-Mile Problem using shared AVs in the Ann Arbor-Detroit area. The study evaluated the feasibility and effectiveness of shared autonomous mobility services in addressing transportation gaps. The case study found that utilizing public transit choices with AV last mile service resulted in energy savings of up to 37% compared to driving a personal vehicle. The energy and greenhouse gas impacts were highly responsive to the vehicle's powertrain and the number of riders. The findings indicate that implementing an autonomous vehicle (AV) taxi service for last-mile transportation might improve the sustainability of public transportation by encouraging people to switch from using private means to using public means of transportation. Delays in public transportation and the expensive nature of AV technology may pose challenges for a last mile service. Rafael et al. (2020), alternatively, explored the opportunities for improving urban air quality through the adoption of autonomous vehicles. The study assessed how autonomous vehicle technology can mitigate emissions and enhance environmental sustainability in cities. The study demonstrated that the presence of AVs in an urban environment, with a 30% adoption rate, resulted in a marginal 0.7% rise in carbon dioxide (CO_2) and nitrogen dioxide (NO_2) emissions. This increase was attributed to heightened demand and acceleration following stops.

3.2.2 Urban Development and Land Use

Numerous studies (Gelauff et al., 2019; Narayanan et al., 2020; González - González et al., 2019) have suggested that the introduction of AVs might change how metropolitan areas are laid up. The study by Rahman and Thill (2023) showed that AVs are likely to exert profound influences on urban development patterns and land use. The advent of AVs may lead to dispersed urban development and intensified sprawl, while also triggering the emergence of new peripheral centers and densifying existing urban fabric. Moreover, space reclaimed from parking areas could be repurposed for various urban amenities and activities, altering the urban landscape.

More importantly, integration of AVs is expected to have substantial impacts on household and workplace settings, particularly in terms of lowering travel expenses. In particular, Narayanan et al. (2020) conducted a comprehensive review of shared autonomous vehicle services, examining various operational models, technological advancements, and regulatory frameworks shaping the emerging market for autonomous mobility. The study demonstrated that the introduction of autonomous vehicles could enhance citizen's welfare benefits and increase revenue for commercial transportation operators.

Moreover, Gelauff et al. (2019) investigated the spatial and welfare effects of automated driving, particularly focusing on whether cities will experience growth, decline, or both due to the adoption of autonomous vehicles. The study findings show that AVs could result in savings of up to 5 billion Euros per year in the Netherlands alone through reductions in generalized transport costs and changes in modal split. In support of this, Fagnant and Kockelman (2018) also conducted a case study examining AVs as a sustainable solution to the Last Mile Problem, specifically in the Ann Arbor-Detroit Area.. The study found substantial economic benefits amounting to $196 billion in the US with a 90% market share of AVs. These benefits stem from the cost reductions associated with congestion, crashes, travel time, fuel use, and parking fees. Additionally, the study by Fagnant & Kockelman (2015) on the barriers and opportunities resulting from the autonomous vehicles, on the social AV impacts, the shows that impacts of crash savings, travel time reduction, fuel efficiency as well as the parking benefits are estimated to approach $2000 per year per for each autonomous vehicle, potentially rising to nearly $4000 when comprehensive crash costs are accounted for. However, it's important to note that while these benefits are significant, they may disproportionately favor households in the wealthiest percentiles, particularly in personal car usage under full automation as elucidated by Wadud (2017). This suggests that while AVs offer economic advantages, there may be equity considerations to address to ensure benefits are distributed more evenly across society.

3.2.3 Parking Demand and Urban Form

The study by Rahman and Thill (2023) revealed that AVs may encourage scattered urban development, decrease parking demand, and improve network capacity which may exert long-term effects. This reduction in parking demand may enhance land productivity by repurposing parking areas for economic activities. AVs could also decrease parking demand in residential areas and business districts through ride-sharing and self-parking capabilities, reshaping urban form and infrastructure. Wellik and Kockelman (2020) study, which utilized the SILO land-use model in Austin, Texas, over a period of 27 years showed that autonomous vehicles influence urban development patterns, transportation infrastructure requirements, and land-use planning decisions. The study revealed significant changes in residential patterns within the metropolitan region of Austin, Texas, under different scenarios of autonomous vehicle (AV) adoption. They found that in a scenario with 100% autonomous vehicles (AVs) compared to a scenario with 0% AVs over a 27-year period (2013-2040), there was a notable reduction of 5.3 to 5.5% in the number of residencies within the metropolitan area of Austin. Conversely, there was a corresponding increase of 5.8 to 6.2% in the number of residencies in the non-metropolitan areas of Austin. These findings suggest that AVs can influence household locations choices by enhancing accessibility, mobility, and convenience while also reducing the opportunity cost associated with travel time. The increased flexibility and efficiency provided by AVs likely contribute to changes in where people choose to live, with more individuals opting for non-metropolitan areas due to improved transportation options and reduced commuting times.

Researchers have recommended implementing policy measures to encourage the use of Shared Autonomous Vehicles (SAVs), aiming to decrease overall vehicle parking demand. Prior studies have consistently suggested that the increased adoption of Autonomous Vehicles (AVs) and SAVs could lead to reduced parking demand in both residential and business districts. For instance, Fagnant and Kockelman (2018) studied dynamic ride-sharing and fleet sizing for a system of shared autonomous vehicles in Austin, Texas. The study explored optimization strategies for vehicle allocation and sizing to enhance the efficiency and effectiveness of shared autonomous mobility services. The study showed that reduction in parking demand is primarily attributed to factors such as decreased car ownership and increased ride-sharing facilitated by AV technology. Additionally, AVs' ability to drive to inexpensive areas outside of city centers and self-park could further alleviate parking pressure in urban centers. For individuals residing on the outskirts of cities who choose to own AVs, parking at the periphery of city centers may become an attractive option, potentially reducing vehicular traffic within the city. To accommodate commuting traffic, multi-storied parking decks could be utilized to optimize space utilization in urban cores. Establishing convenient drop-off and pick-up locations near homes and workplaces would also enhance the overall experience of travel for commuters. These strategies collectively aim to manage parking demand more efficiently while improving urban mobility and reducing congestion.

Kockelman et al. (2017) on the other hand, conducted an assessment of autonomous vehicles, focusing on their traffic impacts and infrastructure requirements. This could include evaluating how autonomous vehicles affect congestion, travel behavior, road capacity, and urban development patterns. The study revealed that while Avs were not yet widely used in the area, it is anticipated that the introduction of CAVs in Texas would result in a rise in vehicle miles traveled (VMT) due to the reduction in time burdens experienced by drivers. The cost of utilizing a car is increased by the values associated with journey time. However, this cost tends to be reduced due to the increased comfort of traveling to more distant areas. Additionally, individuals who are unable to drive themselves, such as the disabled, may now safely commute.. Therefore, effective policymaking is essential to harnessing the potential benefits of AVs while mitigating potential drawbacks. Policymakers need to understand the complex interactions between AVs and urban sustainability to guide informed decision-making. Moreover, addressing research gaps regarding the social, economic, and environmental implications of AV adoption is crucial for shaping future policies and maximizing benefits.

In summary, the impacts of autonomous vehicles on urban sustainability are multifaceted, encompassing transportation and mobility effects, environmental considerations, urban development and land use changes, parking demand dynamics, and policy implications. While AVs hold great promise for enhancing urban mobility and reducing environmental impacts, careful planning and policy interventions are necessary to realize their full potential while addressing potential challenges.

Table 3.1 Key Studies on Status of Autonomous Vehicles

S/No	Study	Main Topic	Considered AV Services	Key Findings
1	C. Zhang et al. (2019)	Design, Integrated Systems, and Movement of AVs	Electric Autonomous Vehicles	Accelerating and overcoming frictional resistance account for 53.4% of the electric autonomous vehicle's overall energy usage.
2	Liu et al.	Design,	Autonomous	Focusing solely on driving profiles to

	(2019)	Integrated Systems, and Movement of AVs	Vehicles	substitute human-driven vehicles with AVs, indicate potential emission reductions of up to 14%.
3	Conlon et al. (2018)	Design, Integrated Systems, and Movement of AVs	Autonomous Vehicles	Observed emission reductions ranging from 4.7% to 14.5% within a realistic urban setting.
4	Z. Wang et al., 2020a	Design, Integrated Systems, and Movement of AVs	Cooperative Driving Systems	Platooning and Cooperative Eco-driving at Signalized Intersections and Cooperative Adaptive Cruise Control (CACC) are highlighted for their substantial environmental benefits.
5	Bento et al., 2019; Chen and Liu, 2019; Bichiou and Rakha, 2019; Wang et al., 2020; Feng et al., 2018;; C. Z. Wang et al., 2020b; Filocamo et al., 2020	Design, Integrated Systems, and Movement of AVs	Connected Autonomous vehicles	13.8% to 59% emission reduction due to the enhancing of traffic flow at intersections with the integration of autonomous vehicles (AVs), facilitated by vehicle-to-vehicle and vehicle-to-infrastructure connections.
6	F. Ma et al., (2019) Guo et al., (2020)	Design, Integrated Systems, and Movement of AVs	Cooperative Models and Variable Speed Strategies	Advocate for improvements through various cooperative models and variable speed strategies which have the potential to achieve emission reductions of up to 44.62%.

7	Patella et al. (2019a)	Mixed Traffic and Market Penetration Rates	Electric Autonomous Vehicles	Underscores that electric autonomous vehicles (e-AVs) produce 35% more emissions at the vehicle level (including construction, maintenance, and end-of-life phases) compared to a conventional internal combustion vehicle, despite the potential for AVs to achieve operational savings of up to 60% in a scenario where 100% of vehicles are autonomous.
8	Stern et al., (2019)	Mixed Traffic and Market Penetration Rates	Autonomous Vehicles	In field experiments conducted in closed-loop environments, even with low percentages of AVs (as low as 5%), there is evidence that they contribute to stabilizing traffic and reducing abrupt stop-acceleration intervals, resulting in significant emission reductions.
9	Talebpour and Mahmassani (2018)	Mixed Traffic and Market Penetration Rates	Connected and Autonomous Vehicles	Enhanced traffic flow stability due the presence of connected services.
10	Mattas et al., 2018).	Mixed Traffic and Market Penetration Rates	Connected Autonomous Vehicles	If AVs were connected, carbon dioxide (CO_2) emissions could be reduced by up to 5%.
11	Bandeira et al. (2021)	Mixed Traffic and Market Penetration Rates	Connected Autonomous Vehicles	Having autonomous vehicles (AVs) in mixed traffic situations can result in a 4% rise or an 18% reduction in CO_2 emissions. The outcome depends on various factors, including the type of road, driving conditions, and the rate at which AVs are

				adopted.
12	Rafael et al. (2020)	Mixed Traffic and Market Penetration Rates	Autonomous vehicles and Electric vehicles	0.7% increase in CO2 and NOx; 29% reduction with EVs
13	C.R. Lu et al., 2019a	Mixed Traffic and Market Penetration Rates	Electric Autonomous vehicles	A 20% market penetration of electric AVs operating in a mixed platoon with electric human-driven vehicles, utilizing specific cooperative strategies would maximize energy efficiency.
14	S. Wang and Lin, 2020	Mixed Traffic and Market Penetration Rates	Hybrid Autonomous Vehicles	Eco-driving strategies employing hybrid propulsion under mixed driving scenarios demonstrate satisfactory results, with reductions in exhaust emissions exceeding 25%.
15	Anderson et al., 2018	Shared Mobility and AV Fleets	Shared Mobility Services	Shared mobility services could result in savings of up to USD 6000 per household in Europe compared to car ownership.
16	Iacobucci et al., 2018	Shared Mobility and AV Fleets	Shared Autonomous Vehicles	Single AV has the potential to replace from 7 to 11 conventional vehicles depending on factors such as waiting time and cost considerations.
17	Greenblatt and Saxena, 2019	Shared Mobility and AV Fleets	Autonomous Electric Taxis	Autonomous electric taxis could potentially achieve emission reductions of 87–94% compared to conventional vehicles with human drivers
18	Lokhandwala and Cai (2018)	Shared Mobility and AV Fleets	Shared Autonomous Taxis	A group of self-driving taxis that are shared among users may provide the same level of service as the regular taxi system while using 59% fewer vehicles. This would lead to a daily decrease of 725 tons

				of CO2 emissions
19	Bauer et al. (2018)	Shared Mobility and AV Fleets	Autonomous Electric Vehicles	Potential emission reductions of up to 73%, taking into account the existing energy supply mix and the implementation of an efficient infrastructure for charging batteries.
20	H. Zhang et al., 2020	Shared Mobility and AV Fleets	Autonomous Taxis	Factors such as fleet size and recharging protocols can influence the extent of emission reductions.
21	Miao et al. (2019)	Shared Mobility and AV Fleets	Autonomous Taxis	Emissions from an autonomous taxi fleet can be reduced by 42% by accurately forecasting service coverage in different geographic areas and maintaining an optimal ratio of vehicles to charging points.
22	Jones and Leibowicz (2019)	Shared Mobility and AV Fleets	Shared Autonomous Vehicles	Emissions could nearly be eliminated with the application of pollutant fees. However, when focusing exclusively on commuting trips, some models yield less promising environmental outcomes.
23	M. Lu et al. (2018)	Shared Mobility and AV Fleets	Autonomous Taxis	20% of autonomous taxis had the potential to replace all privately owned automobiles used for commuting. However, they also discovered that greenhouse gas emissions increased by 25% as a result of these autonomous taxis making additional trips to find their next passenger.
24	F. Yao et al. (2020)	Shared Mobility and AV Fleets	Autonomous Vehicles	The gradual replacement of traditional vehicles with autonomous vehicles may result in gains of as much as 12.3% in

				emission reduction.
25	Rahman and Thill (2023)	Urban Sustainability and AVs	Autonomous Vehicles	AVs are poised to reshape urban transportation and mobility patterns. By reducing vehicle ownership, VMT, traffic delay, and congestion, AVs promise to enhance urban mobility and accessibility.
26	González-González et al. (2019)	Urban Sustainability and AVs	Autonomous Vehicles	In conjunction with triggering the emergence of new peripheral centers (edge cities), Autonomous vehicles will also contribute to the increased density of urban areas by reallocating space for domestic, economic, and recreational activities.
27	Milakis et al. (2017)	Urban Sustainability and AVs	Autonomous Vehicles	Avs are anticipated to significantly enhance road capacity in the near future. The extent of this influence is correlated to the level of automation, level of cooperation among vehicles and the corresponding rates of adoption.
28	Moorthy et al. (2017)	Urban Sustainability and AVs	Shared Autonomous Mobility Services	The study evaluated the feasibility and effectiveness of shared autonomous mobility services in addressing transportation gaps. Utilizing public transit choices with AV last mile service resulted in energy savings of up to 37% compared to driving a personal vehicle.
29	Wadud (2017)	Urban Sustainability and AVs	Fully Automated Vehicles	Conducted a cost-of-ownership analysis for the early adoption of fully automated vehicles. Found that AVs have noteworthy environmental implications, with potential reductions in energy consumption and greenhouse gas emissions.
30	Rafael et al.	Urban	Autonomous	The study assessed how autonomous

	(2020)	Sustainability and AVs	Vehicles	vehicle technology can mitigate emissions and enhance environmental sustainability in cities. The study revealed a modest increase of 0.7% in CO2 and nitrogen oxides (NOx) emissions due to heightened demand and acceleration after stops in an urban area with a 30% penetration rate.
31	Gelauff et al. (2019)	Urban Sustainability and AVs	Autonomous Vehicles	Investigated spatial and welfare effects of automated driving. AVs could result in savings of up to 5 billion Euros per year in the Netherlands alone through reductions in generalized transport costs and changes in modal split.
32	Fagnant and Kockelman (2015)	Urban Sustainability and AVs	Autonomous Vehicles	The study is based on a case study examining AVs as a sustainable solution to the Last Mile Problem, specifically in the Ann Arbor-Detroit Area. The study found substantial economic benefits amounting to $196 billion in the US with a 90% market share of AVs
33	Narayanan et al. (2020)	Urban Sustainability and AVs	Shared Autonomous Vehicle Services	The study presents a comprehensive review of shared autonomous vehicle services, examining various operational models, technological advancements, and regulatory frameworks shaping the emerging market for autonomous mobility.
34	Wellik and Kockelman (2020)	Urban Sustainability and AVs	Autonomous Vehicles	Autonomous vehicles influence urban development patterns,, transportation infrastructure requirements, and land-use planning decisions. The study revealed significant changes in residential patterns within the metropolitan region of Austin,

				Texas, under different scenarios of autonomous vehicle (AV) adoption
35	Kockelman et al. (2017)	Urban Sustainability and AVs	Connected Autonomous Vehicles	The study revealed that while Avs were not yet widely used in the area, it is anticipated that the introduction of CAVs in Texas would result in a rise in vehicle miles traveled (VMT) due to the reduction in time burdens experienced by drivers.
36	Fagnant and Kockelman (2015)	Urban Sustainability and AVs	Autonomous Vehicles	The study, which focused on the barriers and opportunities resulting from the autonomous vehicles, on the social AV impacts, the shows that impacts of crash savings, the reduction in travel time, improved fuel efficiency, and parking benefits are projected to be around $2000 annually per autonomous vehicle. This figure could rise to nearly $4000 when factoring in comprehensive crash cost savings.
37	Greenblatt and Saxena, 2018; Gawron et al., 2019; Liu et al., 2018a	Urban Sustainability and AVs	Electric Motors, Shared and On-Demand Mobility	The study presents a comprehensive review of shared autonomous vehicle services, examining various operational models, technological advancements, and regulatory frameworks shaping the emerging market for autonomous mobility. The study demonstrated that the introduction of autonomous vehicles could enhance citizen's welfare benefits and increase revenue for commercial transportation operators.
38	May et al., 2020	Urban Sustainability	Autonomous Vehicles	A study in Austin Texas which utilized the SILO land-use model conducted for 27

		and AVs		years showed that autonomous vehicles influence urban development patterns, transportation infrastructure requirements, and land-use planning decisions. The study revealed significant changes in residential patterns within the metropolitan region of Austin, Texas, under different scenarios of autonomous vehicle (AV) adoption
39	H. Zhang et al., 2020	Urban Sustainability and AVs	Autonomous Vehicles	Emission reduction may be non-significant or could even be negative due to potential increases in traffic density resulting from improvements in road capacity
40	Jones and Leibowicz, 2019; M. Lu et al., 2018	Urban Sustainability and AVs	Shared Autonomous Vehicles	Outcomes may be influenced by variables such as the number of vehicles in the fleet and the availability of charging infrastructure.
41	González - González et al., 2020	Urban Sustainability and AVs	Autonomous Vehicles	Changes in commuting behavior due to reduced travel costs could affect residential locations and the placement of businesses.

4.0 Conclusion

The systematic review underscores the growing attention within the scientific community on the likely environmental impacts of autonomous vehicles (AVs), primarily concentrated on analyzing energy consumption and emission levels. Researchers investigate a range of elements in different settings, such as innovative design and driving options, collaboration with other vehicles and infrastructure, the use of electric engines, and the potential to enhance shared and on-demand transportation. (Greenblatt and Saxena, 2018; Gawron et al., 2019; Liu et al., 2018a).

The implementation of cooperative driving systems, facilitating the efficient management of vehicle movements in traffic environments, is noted to result in reduced emissions. Similarly, in scenarios involving both conventional and autonomous vehicles, pollution levels tend to decrease as the presence of AVs in traffic increases (May et al., 2020). However, some studies indicate that depending on the proportion of autonomous vehicles, the reduction in emissions may be minimal or even adverse. This potential outcome is attributed to possible increases in traffic density stemming from enhanced road capacity. (H. Zhang et al., 2020). Additionally, with low levels of AV presence, there could be a worsening of the inefficient behavior of human drivers.

According to numerous authors, AVs have the potential to drive more efficiently and when combined with shared mobility, they can greatly reduce emissions. Simulations conducted on self-driving taxi fleets in actual metropolitan settings reveal impressive reductions in emissions, especially when combined with renewable energy sources. However, some studies caution that outcomes may be influenced by variables such as the number of vehicles in the fleet and the availability of charging infrastructure (Jones and Leibowicz, 2019; M. Lu et al., 2018). Factors such as pollutant fees may boost the environmental advantages of shared mobility, although the occurrence of empty trips might lead to increased emissions.

The deployment of AVs is anticipated to have an effect on road mobility and extend to the entirety of the transportation system. Researchers have found that certain users are eager to adjust their behaviors and accept this new technology (May et al., 2020). However, AVs may also attract active transport users, potentially negatively impacting overall emission assessments. Few models analyze emissions involving other transport modes on a large scale, such as at the national level, with positive results typically observed in the long term and highly dependent on a wide range of factors.

Current research is centered on exploring the capacity of autonomous vehicles (AVs) to impact land utilization. While numerous models indicate that urban sprawl is a probable outcome, alternative theories advocate a rise in urban density or a hybrid of both. Reduced travel expenses may lead to changes in commuting behavior, which can have an impact on where people choose to live and where businesses are located (González-González et al., 2020). Articles discussing land use changes also emphasize the positive elements, such as the liberation of urban area that is currently allocated for parking or highways. Enhancements in urban traffic management may result in the creation of more habitable cities, hence deterring the migration of people to residential areas. Population redistribution resulting from autonomous vehicles (AVs) is contingent upon various circumstances, and findings from studies cannot be immediately substituted for one another. However, there is a scarcity of comprehensive studies examining the environmental impacts of changes in land use, with a particular emphasis on energy use and emissions.

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