

Review Article

Sustainability of autonomous cars: Environmental, social, and economic insights from a systematic review

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ABSTRACT

Autonomous cars are increasingly promoted as transformative technologies for urban mobility, yet their sustainability implications remain contested. Existing studies often focus on isolated aspects like environmental, social, or economic implications without providing an integrated perspective. This study addresses this gap by systematically reviewing existing review papers on this topic through the Triple Bottom Line (TBL) framework. Using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol, 49 review articles published between 2009 and 2024 were identified, screened, and analysed. The results highlight that environmental benefits mainly stem from improved traffic efficiency, optimized driving behaviour, and reduced emissions, especially when combined with electrification. However, rebound effects, resource-intensive production, and unregulated usage may limit net gains. Socially, autonomous cars promise improved safety and greater mobility access for elderly and disabled populations, yet concerns about affordability, trust, labour displacement, and ethical dilemmas persist. Economically, they offer potential cost reductions, productivity gains, and new service models, but high capital costs, regulatory uncertainty, and limited evidence on long-term viability constrain widespread adoption. Overall, the TBL framework reveals strong synergies - such as shared autonomous cars enhancing both environmental and social outcomes - alongside trade-offs where benefits in one domain may create risks in another. The study concludes that the sustainability of these vehicles depends less on technological performance than on governance, deployment strategies, and societal acceptance. Future research should prioritize longitudinal analyses of pilot projects, cross-pillar trade-off assessments, and regionally grounded perspectives beyond high-income contexts.

1. Introduction

As early as the mid-20th century, science fiction began imagining futures shaped by self-driving cars. In one of his science-fiction tales, Keller envisioned a world where autonomous vehicles not only reduced accidents and fatalities, but also revolutionized access to mobility empowering older adults, blind people, and others traditionally excluded from car-centric systems. In his story, driverless cars offered not just safety and inclusion, but also comfort, intimacy, and the transformation of travel time into leisure or utility (Braun, 2019). What was once speculative fiction has gradually entered reality: pilot programs such as Waymo's driverless taxi service (launched in 2018 in Arizona) demonstrate that autonomous driving technology is no longer confined to imagination, even as high-profile incidents involving self-driving prototypes underscore that significant safety challenges remain (Hansson et al., 2021). These advancements are being trialled in

urban and interurban contexts, raising both excitement and concern.

Despite this growing momentum, a key question persists: Will self-driving cars genuinely advance sustainability goals, or could they reinforce existing environmental, social, and economic inequities?

Optimists argue that Autonomous Driving Vehicles (ADVs) could dramatically improve road safety and traffic efficiency, cut greenhouse gas emissions through smoother driving and reduced congestion, and expand mobility access to underserved populations (Guériau and Duparc, 2020; Liu et al., 2019a; Nahmias-Biran et al., 2021). In fact, studies project that self-driving cars can mitigate human errors and increase fuel efficiency via strategies like platooning and eco-driving (Zhao et al., 2018). On the other hand, sceptics caution that without careful implementation, autonomous cars might induce new problems, for example greater travel demand and longer trip distances (the so-called "rebound effect") as people take advantage of convenient, hands-free travel, potentially offsetting efficiency gains and even

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encouraging urban sprawl (Cordera et al., 2025; Onat et al., 2023). Furthermore, autonomous mobility could introduce social challenges such as job displacement for professional drivers, threats to privacy and cybersecurity, and unequal access if deployment is left solely to market forces (Nikitas et al., 2021; Taeihagh and Lim, 2019). Ensuring that self-driving cars deliver a net positive contribution to sustainability is therefore not guaranteed. This paper addresses these questions through a structured examination of autonomous cars within the sustainability paradigm, offering a systematic synthesis of their benefits and risks across different domains.

Although autonomous driving has attracted significant scholarly attention, much of the existing literature remains fragmented, often concentrating on narrowly defined aspects such as traffic safety, technological feasibility, or environmental performance. For instance, numerous engineering studies focus on sensor reliability, control algorithms, and traffic flow improvements, while separate research streams examine public acceptance or ethical dilemmas of ADVs, and others model energy use or emissions impacts (Guo et al., 2019; Lim et al., 2019; Othman, 2021). While these studies contribute valuable insights, they rarely capture the broader picture of how autonomous cars influence sustainability in a systemic and multidimensional way. In particular, comprehensive evaluations that integrate environmental, social, and economic considerations are still scarce, and the lack of interdisciplinary synthesis makes it difficult to assess the net sustainability outcomes of ADVs or to identify trade-offs across different impact areas.

As further discussed, in recent years several reviews have explored individual and specific facets of ADVs deployment, such as ecological externalities, equity concerns, or economic disruptions, but few have attempted to consolidate these insights into a unified framework that considers their interdependencies. To address this gap, the present study adopts the Triple Bottom Line (TBL) framework, a well-established model in sustainability research that evaluates impacts across three interconnected domains: People (social), Planet (environmental), and Profit (economic) (Elkington, 1998). By applying this holistic lens, the study seeks to synthesize existing evidence and provide a more integrated understanding of how ADVs align with, or contradict, broader sustainability objectives. Alternative frameworks such as the United Nations (UN) Sustainable Development Goals (SDGs) or Environmental-Social-Governance (ESG) criteria were also considered, but these were deemed either too expansive for the targeted assessment of transport technologies or primarily tailored for organizational reporting. In contrast, the TBL provides a focused and operational structure that is particularly suitable for evaluating emerging mobility technologies like ADVs (Gahlaut et al., 2024; Nikitas, 2024). Classifying impacts along these three pillars clarifies not only where autonomous cars may advance sustainability, but also reveals areas of potential risk, contradiction, or missed opportunity.

Against this background, the primary objective of this study is to conduct a systematic literature review of existing reviews on autonomous cars, to identify and synthesize their advantages and disadvantages through the lens of the TBL framework.

This piece of research seeks to answer the following research questions:

- Main Research Question (RQ): How could ADVs support sustainability through the TBL lens?
- Sub-questions:
 - RQ1.1: When are ADVs environmentally sustainable?
 - RQ1.2: When are ADVs socially sustainable?
 - RQ1.3: When are ADVs economically sustainable?

By addressing these questions, the study aims to provide a clearer understanding of the conditions under which ADVs can contribute to environmental protection, social equity, and economic efficiency, while also drawing attention to potential trade-offs and limitations. Indeed, progress in one sustainability dimension may inadvertently create new

challenges or opportunities in another, underscoring the importance of a balanced approach.

After this introductory chapter, the paper is structured as follows. In 2. Literature Review it is presented part of the previous literature on the theme, outlining prior studies on autonomous vehicles and sustainability and introducing the TBL framework as the theoretical foundation. In the third section, 3. Methods, it is detailed the systematic approach employed to identify and analyse relevant literature reviews. This includes a detailed explanation of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method, which ensures the rigor and transparency of the review process. The section 4. Results further explores how this framework is applied to categorize and assess the environmental, social, and economic impacts of ADVs, setting the stage for the analysis. Moreover, the advantages and disadvantages of ADVs are synthesized within the three dimensions of the TBL framework. This section highlights key findings regarding the potential benefits and challenges of ADVs, focusing on their implications for sustainability. In 5. Discussion, findings are interpreted comparatively, and limitations and future research directions are integrated. Finally, 6. Conclusions concludes the manuscript by summarizing the main contributions of the review and reflecting on how autonomous cars can support, or hinder, sustainable mobility, depending on the choices made by policymakers, planners, and industry stakeholders.

2. Literature review

The global push for sustainable urban mobility has intensified in response to growing urbanization, environmental degradation, and societal demands for equitable transportation systems (Attard et al., 2023; Boschmann and Kwan, 2008; Grieco, 2015). Cities worldwide are dealing with critical challenges, including traffic congestion, air pollution, greenhouse gas (GHG) emissions, and urban sprawl (Arsenio et al., 2016; Gao et al., 2025). This situation underscores an urgent need to decarbonize and modernize urban transport, prompting many cities to integrate technological innovations with policies that discourage car dependency and encourage cleaner modes of travel (Mouratidis, 2025). While these issues highlight the urgent need for innovative solutions to transform urban mobility and address the inefficiencies of conventional transportation systems, ADVs have emerged as a promising technological advancement with the potential to reshape urban transportation systems and contribute to broader sustainability goals.

In this study, the focus is specifically on autonomous cars, which represent a subset of ADVs, characterized by levels of automation ranging from Level 3 (conditional automation) to Level 5 (full automation), as defined by the Society of Automotive Engineers (SAE) International standard (Shi et al., 2020). For clarity, the terms “autonomous cars”, “self-driving cars” and “ADVs” are used interchangeably to refer to this category of vehicles. These vehicles can perform driving tasks under certain conditions with minimal or no human intervention, distinguishing them from lower levels of automation where the driver remains primarily responsible for vehicle operation. This focus on higher automation levels is critical, as vehicles at SAE Level 3 and above are the ones poised to fundamentally alter mobility patterns, traveller behaviour, and infrastructure needs (Alessandrini et al., 2015).

Autonomous cars are expected to improve traffic flow, reduce road fatalities, and enhance energy efficiency while simultaneously promoting shared mobility services and optimizing land use (Matin and Dia, 2023; Montanaro et al., 2019; Taiebat et al., 2018). Simulation studies suggest that as autonomous cars penetration increases, smoother traffic patterns and higher road capacity can alleviate congestion, yielding significant improvements in network efficiency (Lu et al., 2020). By eliminating human errors, responsible for the vast majority of crashes, higher-level ADVs also have the potential to dramatically improve road safety (Mueller et al., 2020). Moreover, early evidence indicates that autonomous driving systems can maintain more uniform speeds and

closer headways, contributing to better fuel economy and lower emissions per mile (Chandra and Camal, 2016; Mersky and Samaras, 2016). In addition, their potential to enhance accessibility for underserved populations, such as the elderly and disabled, positions them as a possible tool for addressing social equity concerns in urban mobility (Emory et al., 2022; Martínez-Buelvas et al., 2022; Wu et al., 2021), especially if affordable on-demand autonomous cars services can be provided to those who cannot drive. If deployed as shared autonomous cars (e.g. self-driving taxis or shuttles), these vehicles could substantially reduce private car ownership and parking needs, freeing urban space and potentially reducing total vehicle fleet size and emissions (Kondor et al., 2019a; Zhang and Wang, 2020).

However, the literature also emphasizes that these benefits are not guaranteed. While their technical capabilities promise substantial benefits, their impacts are highly context-dependent and influenced by factors such as penetration rates, usage patterns, and urban policies (Bagloee et al., 2016; Faisal et al., 2019; Hopkins and Schwanen, 2023). For example, a high prevalence of privately owned ADVs could induce additional travel demand, longer trips, more frequent journeys, and unoccupied “empty vehicle” relocations, which in turn may offset efficiency gains and worsen congestion or emissions (Zhang et al., 2018). Potential rebound effects, including increased urban sprawl and higher energy consumption, raise concerns about whether ADVs can truly deliver on their sustainability promises (May et al., 2020; Stead and Vaddadi, 2019). As commuting becomes more comfortable or productive in self-driving cars, individuals might choose to live farther from city centres, exacerbating sprawl and vehicle miles travelled (Guerra, 2015). Moreover, researchers highlight that maximizing environmental benefits likely requires coupling vehicle automation with electrification and shared mobility; automation alone, especially if paired with gasoline powertrains, could result in minimal GHG reductions or even increases (Wang and Yang, 2023). Equity issues, particularly regarding affordability and accessibility, further complicate the narrative, as there is a risk that advanced autonomous mobility services may exclude lower-income groups or areas if not deliberately managed through inclusive policies (Fleming, 2018).

Given the complexity of these outcomes, a critical and comprehensive evaluation of the advantages and disadvantages of ADVs is essential. Such an assessment must be grounded within a sustainability framework to ensure that their deployment aligns with the principles of sustainable urban development and effectively addresses the multifaceted challenges facing modern cities. In other words, understanding whether autonomous cars will advance or hinder sustainability goals requires an integrated appraisal that simultaneously considers environmental, social, and economic effects.

For this purpose, the present study employs the TBL framework, first introduced by Elkington in 1998, which expands the scope of traditional financial assessments to include environmental and social dimensions, reflecting a more complete approach to sustainability. By emphasizing the importance of the “Three P’s” (people, planet, and profit) of sustainability, the TBL framework promotes a holistic understanding of value creation, encouraging organizations and policymakers to pursue outcomes that benefit not only shareholders but also wider society and the natural environment. This multidimensional approach is especially pertinent in assessing the sustainability of emerging technologies whose implications span across diverse domains, such as ADVs, which possess the potential to reshape urban mobility, presenting both opportunities and uncertainties. Sustainability in this context necessitates a balanced approach to environmental protection, social equity, and economic viability (Elkington, 1998).

Evaluating these impacts requires an integrated framework capable of capturing the interdependencies among environmental protection, social equity, and economic viability, and the TBL offers such a structure, enabling researchers to move beyond isolated assessments and toward a systemic appraisal of ADVs sustainability potential. Applying the TBL framework in this context helps to build an analysis of how

ADV may align with or diverge from sustainability goals. It allows for the identification of synergies, for instance between environmental benefits like reduced emissions and social improvements such as enhanced mobility access, as well as trade-offs, such as increased economic efficiency at the cost of job displacement. As cities face growing pressure from climate change, urbanization, and social inequality (Buhaug and Urdal, 2013; Das et al., 2024; Reckien et al., 2017), the need for such integrative evaluation tools becomes increasingly urgent.

While other frameworks, such as the UN SDGs or ESG criteria, offer valuable lenses, the TBL is particularly suited to this study for its concise yet comprehensive structure and its frequent application in sustainability assessments within mobility and transport literature (AL-Dosari et al., 2023; Stefaniec et al., 2020). Indeed, recent transport studies have utilized TBL-based analyses to evaluate projects ranging from public transit developments to intelligent transport systems, illustrating its practical applicability in capturing complex sustainability trade-offs (Pan, 2024; Razakova et al., 2023). In the case of autonomous cars, it enables a structured synthesis of fragmented insights across disciplines and provides a grounded approach to understanding where and how autonomous technologies might generate net-positive outcomes or exacerbate existing challenges for people, planet, and profit.

3. Methods

A multi-stage systematic literature review (SLR) (Munn et al., 2018) was conducted to identify and analyse prior review articles on autonomous cars and their sustainability implications (Hiebl, 2023). This study adhered to the PRISMA methodology, which provides a standardized and transparent framework for identifying, selecting, and synthesizing relevant studies (Moher et al., 2010). By employing this methodology, the review ensures both rigor and reproducibility, while systematically categorizing the advantages and disadvantages of ADVs encompassing environmental, social, and economic dimensions.

The primary focus of the review was on secondary studies, particularly literature reviews published in peer-reviewed journals, rather than empirical studies. This decision was made to ensure methodological consistency and to allow for a higher-level synthesis of existing syntheses, consolidating fragmented findings across the literature. By relying on review articles that already apply structured processes to aggregate primary evidence, the study avoids the risk of introducing selection bias through ad hoc inclusion of individual studies.

To maintain relevance, studies published before 2009 were excluded to reflect the technological advancements and evolving policy contexts of the past decade.

The literature search was performed using Scopus, a comprehensive and multidisciplinary academic database. A carefully custom-made query was developed to ensure inclusivity while maintaining focus on the research objectives.

The query comprised three core components:

1. Keywords for autonomous cars:

The search included terms such as “autonomous driving vehicle*”, “self-driving car*”, “autonomous vehicle*”, “autonomous car*” and “driverless car*”, as well as acronyms like “ADV*” and “AVs.” Wildcards (*) were employed to capture variations in terminology (i. e., singular vs. plural forms).

These terms were selected to encompass the diverse ways in which ADVs are referred to across the literature.

2. Sustainability and TBL dimensions:

Keywords such as “sustainab*”, “environmental impact*”, “social impact*”, and “economic impact*” were combined with the phrase “triple bottom line” to ensure alignment with the TBL framework.

This enabled the inclusion of studies that examine the

environmental, social, or economic implications of ADVs.

3. Focus on Literature Reviews:

To target secondary studies, terms like “literature review*”, “systematic review*”, “narrative review*”, and their abbreviations (i.e., “SLR” and “NR”) were included.

This ensured the retrieval of articles that consolidate and synthesize findings from prior research, rather than presenting original empirical data.

The query was further refined by applying filters to restrict the results to articles written in English, published between 2009 and 2024, and classified as peer-reviewed journal articles. In fact, autonomous driving and sustainability are rapidly evolving fields, and publications older than 2009 may not reflect current advancements or challenges. Moreover, it was decided to focus on peer-reviewed journal articles only to ensure academic rigor and quality. This filtering process yielded an initial dataset of 464 documents.

To ensure the relevance and quality of the final sample, a multi-stage screening process was implemented. First, the titles and abstracts of the 464 articles were reviewed to exclude studies that did not address sustainability aspects of ADVs or were unrelated to the topic. Specifically, we removed papers that did not deal with autonomous vehicles (false positives from the search) or did not consider any sustainability aspects (i.e. purely technical papers on sensors or control algorithms). We also excluded articles that turned out to be on unrelated topics (such as “autonomous” systems in other domains) or that were not review/synthesis papers,

This step reduced the dataset to 30 articles, which appeared to meet our criteria.

An additional sample of 19 articles was identified through a backward reference search, which involved examining the reference lists of the initially selected studies. These articles were deemed relevant based on their explicit focus on sustainability and ADVs, bringing the total sample to 49 studies. This selection process has been summarised in Fig. 1.

In auditing the final sample, we also noted that the geographical distribution of reviewed studies is skewed toward the Global North. The majority of included reviews originate from North America and Europe, with a smaller share from East Asia, while only limited representation was found for emerging economies and the Global South. This imbalance indicates that our findings largely reflect developed-country contexts, and we explicitly address in 5. Discussion how sustainability outcomes of ADVs may differ in less-studied regions.

The inclusion criteria focused on:

- Reviews, overviews, or meta-analysis explicitly addressing the environmental, social, or economic dimensions of autonomous cars.
- Studies published in peer-reviewed journals in English after 2009.
- Articles that synthesize findings from prior research rather than presenting original empirical data.

The exclusion criteria included:

- Articles unrelated to autonomous cars or not considering sustainability aspects.
- Primary studies, case studies, or reports lacking peer-review.
- Publications pre-dating 2009 to maintain the relevance of findings.

Throughout the screening process, any ambiguities regarding inclusion were resolved through discussion among the authors, ensuring consensus on the final selection.

For each of the 49 selected studies, we performed a thorough content analysis. Key information extracted included: the sustainability dimensions addressed, the specific indicators or topics covered, the main findings or conclusions regarding ADVs impacts, and any quantified results (such as percentage changes, adoption rate scenarios, etc.). We organized the findings using the TBL structure grouping evidence under environmental, social, and economic impact categories. Within each category, we further noted whether the reported impact was generally positive, so an advantage/opportunity, or negative, so a disadvantage/risk for sustainability.

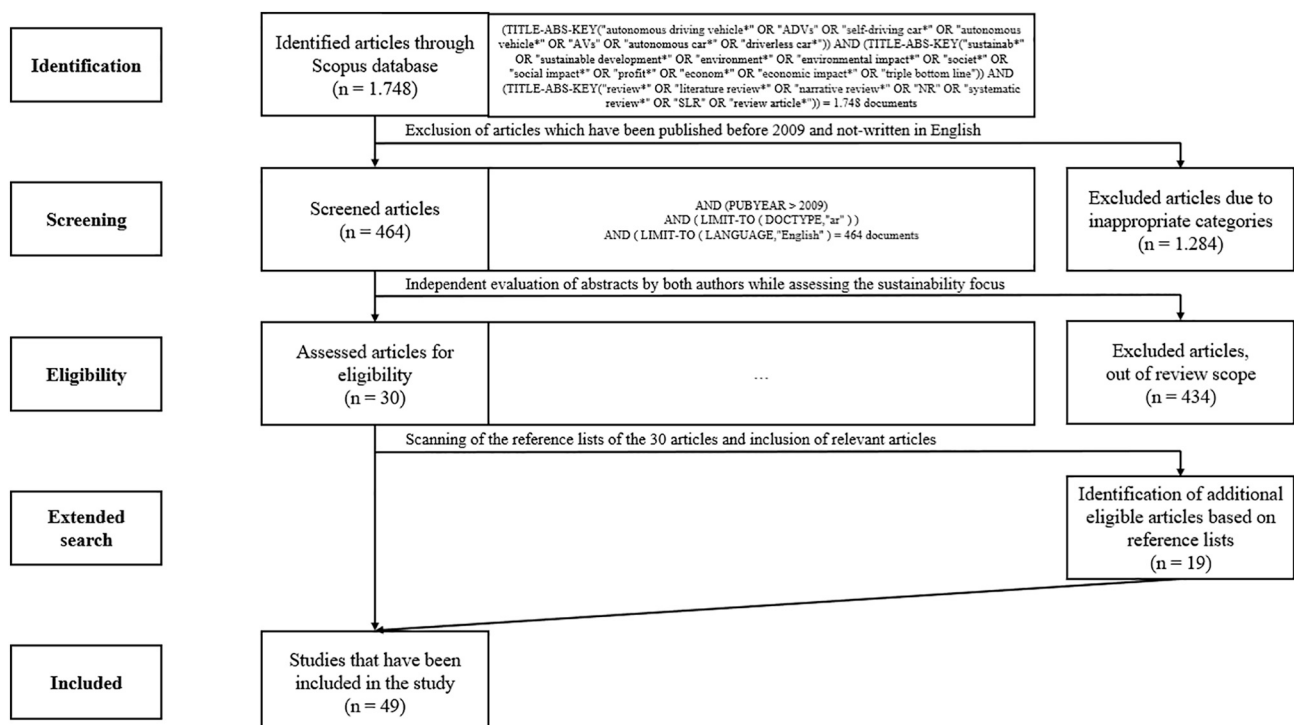


Fig. 1. Flow diagram for the selection of literature reviewed in accordance with PRISMA protocol (Moher et al., 2010).

To integrate quantitative findings, we paid special attention to studies that provided estimates or ranges of impact. We recorded concrete statistics like potential emission reductions, crash reduction percentages, or economic values when available. These quantitative insights are incorporated in the results to add concreteness.

Finally, we synthesized the extracted data into a coherent narrative for each sustainability dimension. We used a pro vs. con approach to ensure balanced coverage of benefits and drawbacks. Preliminary results

were tabulated (as in Tables 3–5) to systematically list the advantages and disadvantages of autonomous vehicles under each TBL pillar, along with supporting sources. These tables served as a tool to verify that we captured all major points and to visualize the distribution of evidence across studies.

By following this rigorous methodology, our review ensures that the conclusions drawn are grounded in a comprehensive survey of the literature. The PRISMA flow and inclusion criteria enhance the

Table 1
Categorization of the review papers based on the Triple Bottom Line framework.

Author(s)	Year	Title of the Paper	Environmental focus	Social focus	Economic focus
Wadud et al.	2016	<i>Help or hindrance? The travel, energy and carbon impacts of highly automated vehicles</i>	X		
Yun et al.	2016	<i>The relationship between technology, business model, and market in autonomous car and intelligent robot industries</i>			X
Vleugel & Bal	2017	<i>More space and improved living conditions in cities with autonomous vehicles</i>	X	X	X
Steck et al.	2018	<i>How Autonomous Driving May Affect the Value of Travel Time Savings for Commuting</i>			X
Wang et al.	2018	<i>Automated, electric, or both? Investigating the effects of transportation and technology scenarios on metropolitan greenhouse gas emissions</i>	X		
Liu et al.	2019	<i>Can autonomous vehicles reduce greenhouse gas emissions? A country-level evaluation</i>	X		
Fraedrich et al.	2019	<i>Autonomous driving, the built environment and policy implications</i>		X	
Cohen & Cavoli	2019	<i>Automated vehicles: exploring possible consequences of government (non)intervention for congestion and accessibility</i>		X	
Dean et al.	2019	<i>Holding the keys to health? A scoping study of the population health impacts of automated vehicles</i>	X	X	
Gandia et al.	2019	<i>Autonomous vehicles: scientometric and bibliometric review</i>	X	X	X
Gavanas	2019	<i>Autonomous Road Vehicles: Challenges for Urban Planning</i>	X	X	X
Marletto	2019	<i>Who will drive the transition to self-driving? A socio-technical analysis of the future impact of automated vehicles</i>	X	X	
Stogios et al.	2019	<i>Simulating impacts of automated driving behaviour and traffic conditions on vehicle emissions</i>	X		
Stern et al.	2019	<i>Quantifying air quality benefits resulting from few autonomous vehicles stabilizing traffic</i>	X		
Cavazza et al.	2019	<i>Management and business of autonomous vehicles: a systematic integrative bibliographic review</i>			X
Milakis	2019	<i>Long-term implications of automated vehicles: an introduction</i>	X	X	X
Kassens-Noor et al.	2020	<i>Sociomobility of the 21st century: Autonomous vehicles, planning, and the future city</i>		X	
Keszezy, T.	2020	<i>Behavioural intention to use autonomous vehicles: Systematic review and empirical extension</i>		X	X
Sohrabi et al.	2020	<i>Impacts of Autonomous Vehicles on Public Health: A Conceptual Model and Policy Recommendations</i>	X	X	
Pourrahmani et al.	2020	<i>Health Impact Assessment of Connected and Autonomous Vehicles in San Francisco Bay Area</i>	X	X	
Alawadhi et al.	2020	<i>Importance of autonomous vehicles liability</i>		X	
Kovacs et al.	2020	<i>Aged mobility in the era of transportation disruption: Will autonomous vehicles address impediments to the mobility of ageing populations?</i>		X	
Kopelias et al.	2020	<i>Connected & autonomous vehicles – Environmental impacts – A review</i>	X		
Rafael et al.	2020	<i>Autonomous vehicles opportunities for cities air quality</i>	X		
Bin-Nun & Binamira	2020	<i>A framework for the impact of highly automated vehicles with limited operational design domains</i>	X	X	
Cugurullo et al.	2020	<i>The transition to autonomous cars, the redesign of cities and the future of urban sustainability</i>	X	X	
Ryan	2020	<i>The Future of Transportation: Ethical, Legal, Social and Economic Impacts of Self-driving Vehicles in the Year 2025</i>	X	X	X
Milakis & Müller	2021	<i>The societal dimension of the automated vehicles transition: Toward a research agenda</i>	X	X	X
Bandeira et al.	2021	<i>Potential Pollutant Emission Effects of Connected and Automated Vehicles in a Mixed Traffic Flow Context for Different Road Types</i>	X		
Martinho et al.	2021	<i>Ethical issues in focus by the autonomous vehicles industry</i>		X	
Papadimitriou et al.	2022	<i>Toward common ethical and safe 'behaviour' standards for automated vehicles</i>		X	
Emory et al.	2022	<i>Autonomous vehicle policies with equity implications: Patterns and gaps</i>	X	X	X
Gasne et al.	2022	<i>Takeover performance of older drivers in automated driving: A review</i>		X	
Almlöf et al.	2022	<i>Frameworks for assessing societal impacts of automated driving technology</i>	X	X	
Jeong et al.	2022	<i>Predicting Changes in the Built Environment in the era of Vehicular Automation</i>	X	X	
Jászberényi et al.	2022	<i>What drives tourists to adopt self-driving cars?</i>		X	
Silva et al.	2022	<i>Environmental impacts of autonomous vehicles: A review of the scientific literature</i>	X		
Othman	2022	<i>Exploring the implications of autonomous vehicles: a comprehensive review</i>	X	X	X
Tengilimoglu et al.	2023	<i>Implications of automated vehicles for physical road environment: A comprehensive review</i>	X		
Shahedi et al.	2023	<i>Barriers to the sustainable adoption of autonomous vehicles in developing countries: A multi-criteria decision-making approach</i>	X	X	X
Pimenta et al.	2023	<i>Long-term effects of autonomous vehicles on the built environment</i>	X		
Chen et al.	2023	<i>Milestones in Autonomous Driving and Intelligent Vehicles: Survey of Surveys</i>	X	X	X
Huda et al.	2023	<i>Understanding the value of autonomous vehicles</i>			X
Hopkins & Schwane	2023	<i>The expected speed and impacts of vehicle automation in passenger and freight transport: A Dissensus Delphi study among UK professionals</i>	X	X	
Dong et al.	2024	<i>Drinking and driving: A systematic review of the impacts of alcohol consumption on manual and automated driving performance</i>		X	
Pan et al.	2024	<i>The impacts of connected autonomous vehicles on mixed traffic flow: A comprehensive review</i>	X	X	X
Busch	2024	<i>Non-user acceptance of autonomous technology: A survey of bicyclist receptivity to fully autonomous vehicles</i>		X	
Rowe et al.	2024	<i>Understanding responsibility under uncertainty</i>		X	
Naiseh et al.	2024	<i>Trust, risk perception, and intention to use AVs</i>		X	

transparency of our process, and the structured TBL categorization provides a valuable foundation for understanding the complex interplay of factors that influence the sustainability potential of ADVs, offering insights for researchers, policymakers, and industry stakeholders alike.

4. Results

The following sections delve into the specific sustainability dimensions to provide a comprehensive understanding of their impacts.

4.1. Classification of the current state of the literature according to the triple bottom line framework

To provide a structured interpretation of the current literature on autonomous driving vehicles, a categorization based on the TBL framework was adopted, as reported in Table 1. This classification facilitates a comprehensive understanding of how ADVs are being evaluated in the academic discourse, revealing both the breadth and limitations of existing knowledge. In Table 2, the temporal evolution of the literature's focus areas across these three pillars from 2016 to 2024 has been synthesized. Notably, the year 2019 witnessed the most prolific academic activity across all three domains, reflecting a peak in scholarly interest in ADVs during this period. The rise may correlate with a broader societal and policy-driven momentum around smart mobility and automation during that time (Noussan et al., 2020).

The temporal analysis of the literature in Fig. 2 reveals distinct trends in the evolution of sustainability concerns within ADVs research. A significant spike in publications addressing environmental and social aspects is observed in 2019 and 2020, likely driven by the growing global momentum around climate action, urban sustainability, and the promise of connected, shared, and electric mobility systems (Jones and Leibowicz, 2019; Manders et al., 2020; Taiebat and Xu, 2019). In particular, the peak in social-focused publications in 2020 may reflect the broader societal attention on ethics, equity, and accessibility, themes amplified by the disruptions of the COVID-19 pandemic, which exposed vulnerabilities in mobility systems and underscored the importance of inclusive technological transitions (Griffiths et al., 2021; Kanda and Kivimaa, 2020; Yao et al., 2024). Conversely, a noticeable decline across all three pillars in 2021 suggests a temporary redirection of research priorities, possibly due to the global health crisis and the corresponding emphasis on emergency response and logistical resilience. From 2022 onwards, the literature appears to stabilize, with environmental and social focuses recovering moderately, while the economic focus - though present - remains consistently lower across the years. This pattern may be attributed to the speculative nature of ADVs profitability and the persistent lack of empirical data from real-world deployments, which continue to limit thorough economic assessments (Carreyre et al., 2024; Gu et al., 2025; Nordhoff, 2024). These dynamics not only highlight the evolving maturity and diversification of autonomous cars sustainability research but also point to enduring gaps, particularly in economic viability and governance strategies, that warrant further scholarly attention. The classification according to the TBL framework, therefore,

Table 2

Temporal synthesis of the review papers according to the 3 Triple Bottom Line pillars.

Year	Environmental focus	Social focus	Economic focus
2016	1	0	1
2017	1	1	1
2018	1	0	1
2019	8	7	4
2020	7	9	2
2021	2	2	1
2022	5	7	2
2023	5	3	3
2024	1	5	1

serves as a valuable lens to identify research imbalances, trace shifting academic interests over time, and suggest targeted directions for future inquiry.

This temporal analysis thus highlights how scholarly priorities have evolved and suggests that future research could benefit from greater integration across TBL domains, particularly by expanding the economic and long-term systemic evaluations of ADV deployment scenarios. It also points to opportunities for cross-disciplinary investigations that bridge environmental efficiencies, societal impacts, and economic viability.

4.2. Environmental sustainability

The analysis of the literature under the lens of environmental sustainability reveals a complex picture, characterized by both transformative opportunities and critical challenges. Among the most recurrent and emphasized environmental benefits is the potential for traffic efficiency and optimized driving. Several studies underscore how autonomous cars can reduce congestion, promote smoother acceleration and braking patterns, and optimize routing via real-time data processing, resulting in lower fuel consumption and emissions (Milakis, 2019; Naiseh et al., 2025; Wadud et al., 2016). Traffic efficiency and vehicle energy optimization are among the most frequently cited environmental benefits in the literature (Pan et al., 2024; Ribeiro Pimenta et al., 2023; Stogios et al., 2019). Closely related is the emerging opportunity for shared mobility and fleet size reduction, with authors suggesting that the shift from private car ownership to shared autonomous fleets may reduce the total number of vehicles in circulation, curb parking demand, and lower emissions on a per capita basis (Cugurullo et al., 2021; Gavanias, 2019; Vleugel and Bal, 2018). The prospect becomes even more environmentally promising when autonomous cars are coupled with electric propulsion and clean energy systems, as noted by several experts (Rafael et al., 2020; Sohrabi et al., 2020; Wang et al., 2018), enabling near-zero tailpipe emissions if renewable energy sources are used for charging. Some studies further point to long-term potential under high ADVs adoption scenarios, in which large-scale deployment of shared ADVs could contribute significantly to climate mitigation targets (Milakis and Müller, 2021; Wadud et al., 2016). However, this potential is often framed as conditional, dependent on whether effective policies and regulations guide autonomous cars integration, such as promoting public transport integration and restricting privately owned ADVs (Marletto, 2019). Notably, some scholars also highlight less-discussed benefits such as reduction in traffic noise through smoother driving (Silva et al., 2022), contributing to improved urban soundscapes.

Conversely, the literature warns of several environmental downsides. Foremost among these is the rebound effect and increased travel demand, whereby the convenience and lower perceived cost of ADV travel may stimulate longer commutes, higher travel frequency, and empty vehicle repositioning trips, all of which risk outweighing any efficiency gains (Bin-Nun and Binamira, 2020; Kopelias et al., 2020; Wadud et al., 2016). A particularly concerning scenario is the dominance of private autonomous cars use, which could reinforce car-centric development and urban sprawl, increasing land consumption and environmental degradation (Cugurullo et al., 2021; Jeong et al., 2023; Milakis, 2019).

Other papers caution against new energy demands and manufacturing footprints, stemming from the high-tech components in ADVs such as LiDARs, processors, and sensors, which increase production emissions and resource use (Gandia et al., 2019; Liu et al., 2019b; Stogios et al., 2019). Even during operation, the onboard computational loads may increase energy consumption per kilometre. These issues are particularly critical in low ADVs penetration phases, where the benefits of automation are too marginal to offset the emissions of conventional vehicles (Kopelias et al., 2020; Liu et al., 2019). Moreover, the lack of regulatory oversight may exacerbate autonomous cars' negative impacts, leading to unchecked travel demand and system inefficiencies (Marletto, 2019; Othman, 2022; Silva et al., 2022). Finally,

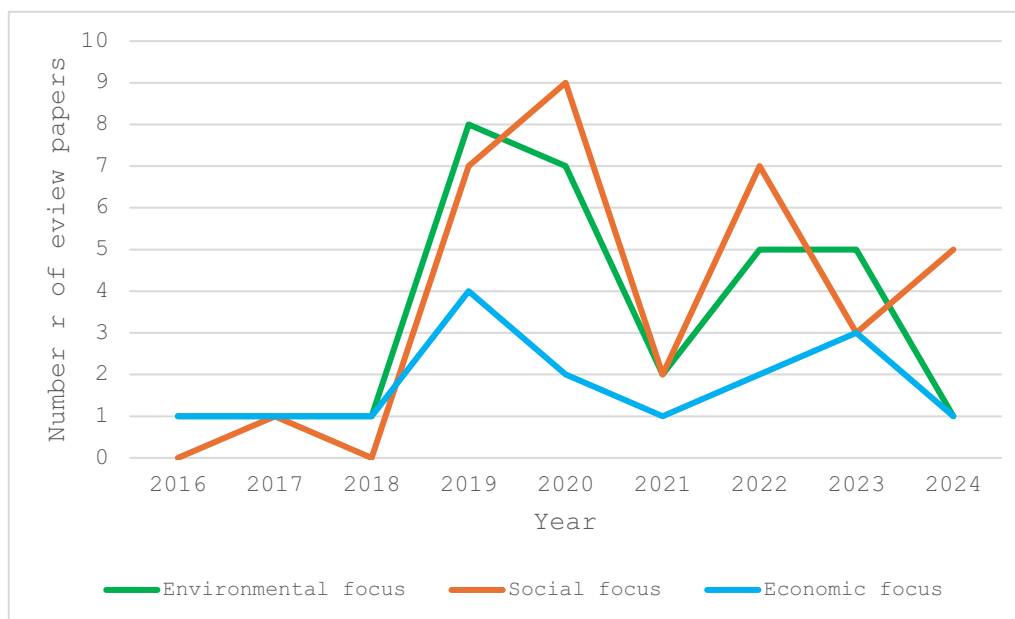


Fig. 2. Temporal representation of the reviews according to the 3 Triple Bottom Line pillars.

cybersecurity vulnerabilities and digital system failures are increasingly noted as indirect environmental risks, particularly in the case of hazardous cargo or systemic infrastructure failures (Pan et al., 2024). These themes are clearly mapped in Table 3, which visualizes the temporal evolution and relative weight of environmental PROs and CONs across the reviewed literature.

Collectively, these insights illustrate that the environmental sustainability of ADVs hinges not only on the technical promise of the vehicles themselves but also on how they are adopted, integrated, and governed within urban systems. While environmental PROs dominate the literature in quantity, the severity and systemic nature of the associated CONs emphasize the need for strategic policy intervention. Therefore, a truly sustainable transition to autonomous cars requires a proactive, systems-oriented approach that mitigates risks and maximizes environmental gains across the life cycle of autonomous mobility.

4.3. Social sustainability

The literature reveals that ADVs carry a broad spectrum of socially sustainable opportunities and threats. As depicted in Table 4, thematic clustering highlights six major social advantages and six principal concerns that frequently recur across studies.

A frequently cited benefit is the potential for improved road safety. By eliminating human error, responsible for the vast majority of traffic accidents, ADVs are expected to reduce crash rates, injuries, and fatalities. Within the TBL framework, road safety is treated as a cornerstone of the social dimension, since it directly impacts public health, equity of access, and overall well-being. At the same time, the literature remains inconclusive on the extent of safety improvements, with most reviews reporting indicative ranges rather than precise estimates due to the limited scale of real-world deployments. This suggests that while safety is the most salient social benefit of ADVs, further empirical research is required to quantify its magnitude under different adoption scenarios. Automation removes impaired driving behaviours such as fatigue, distraction, or intoxication, promising substantial improvements in public health outcomes (Dean et al., 2019; Dong et al., 2024; Pourrahmani et al., 2020). Equally relevant is the expected enhancement in socioeconomic equity and inclusion. Autonomous mobility holds the potential to improve access to transportation for traditionally underserved populations, such as the elderly, people with disabilities, or

individuals in remote or underfunded areas. If implemented within inclusive policy frameworks, ADVs-based mobility services could reduce transport-related exclusion and contribute to broader goals of social justice and accessibility (Emory et al., 2022; Kovacs et al., 2020; Sohrabi et al., 2020).

Another commonly emphasized social benefit is increased travel comfort. By removing the burden of active driving, passengers can enjoy more relaxing or productive travel experiences, potentially improving mental well-being and daily satisfaction (Jászberényi et al., 2022; Pan et al., 2024; Ryan, 2020). This positive perception extends to public outlook as well. Many studies document favourable attitudes toward ADVs, particularly among younger and tech-oriented cohorts. Such receptivity may accelerate public acceptance and support smoother rollout of these technologies (Cugurullo et al., 2021; Kassens-Noor et al., 2020). Urban transformation also features prominently among the projected benefits. ADVs could enhance urban liveability by reducing congestion and the need for parking spaces, especially in city centres, enabling space reclamation for green infrastructure, cycling, or pedestrian zones (Fraedrich et al., 2019; Milakis, 2019; Vleugel and Bal, 2018). Scholars further underline the strategic role of proactive policies, emphasizing how social benefits are maximized when autonomous cars integration is regulated early and inclusively. Measures such as ADV-only lanes, integration with public transport, and equitable pricing models can mitigate exclusionary effects and ensure that technology adoption aligns with sustainable urban planning (Cohen and Cavoli, 2019; Jeong et al., 2023; Marletto, 2019).

However, these advantages are counterbalanced by pressing social concerns. Despite automation, persistent safety risks like system malfunctions, unpredictable traffic interactions, or cybersecurity vulnerabilities could undermine actual safety. These risks are particularly relevant for populations such as the elderly, who may find it difficult to retake control in emergencies (Almlöf et al., 2022; Gasne et al., 2022; Pan et al., 2024).

A second risk is inequitable access. Without policy intervention, ADVs-related services might concentrate in profitable urban markets, creating a divide between affluent, tech-savvy users and low-income, rural, or digitally excluded groups. Furthermore, mobility automation may lead to significant job displacement, especially among drivers in logistics or public transport sectors, potentially exacerbating socioeconomic inequality (Kassens-Noor et al., 2020; Milakis and Müller, 2021;

Table 3

Riepilogative list of advantages and disadvantages of Autonomous Driving Vehicles under the environmental sustainability lens.

PROs	Description	Reference (Author(s), Year)	CONs	Description	Reference (Author(s), Year)
Traffic efficiency & optimized driving	Autonomous cars can improve driving efficiency and traffic flow through smoother driving, reduced congestion, optimal routing, and platooning, leading to lower fuel use and reduced greenhouse gas emissions. Studies indicate these optimizations could significantly cut vehicle energy consumption and emissions across the transportation network.	(Wadud et al., 2016); (Gandia et al., 2019); (Milakis, 2019); (Stern et al., 2019); (Stogios et al., 2019); (Kopelias et al., 2020); (Pourrahmani et al., 2020); (Bandeira et al., 2021); (Almlöf et al., 2022); (Chen et al., 2023); (Hopkins and Schwanen, 2023); (Ribeiro Pimenta et al., 2023); (Shahedi et al., 2023); (Tengilimoglu et al., 2023); (Pan et al., 2024).	Rebound effects & increased travel demand	The convenience and lower perceived cost of ADVs travel could induce people to travel more (longer distances, more frequent trips), including unoccupied “empty vehicle” trips. This rebound effect, translated in an increase in total vehicle miles travelled, may offset or even outweigh the efficiency gains, potentially leading to higher overall energy use and emissions.	(Wadud et al., 2016); (Gavanas, 2019); (Bin-Nun and Binamira, 2020); (Kopelias et al., 2020); (Ryan, 2020); (Sohrabi et al., 2020); (Almlöf et al., 2022); (Silva et al., 2022); (Hopkins and Schwanen, 2023); (Shahedi et al., 2023); (Tengilimoglu et al., 2023).
Shared mobility & reduced fleet size	Autonomous driving enables shared mobility models that could reduce the total number of vehicles needed. A smaller overall fleet, combined with less need for parking, means lower manufacturing demands and less idle time, cutting energy use and emissions per capita.	(Vleugel and Bal, 2018); (Gavanas, 2019); (Kopelias et al., 2020); (Cugurullo et al., 2021); (Emory et al., 2022); (Ribeiro Pimenta et al., 2023).	Private ADVs use & urban sprawl	If autonomous cars are predominantly privately owned and used, they could reinforce car-dependent travel patterns. ADVs convenience might encourage longer trips and suburban sprawl (people living farther out), increasing total travel and energy consumption. This may also spur new road infrastructure, expanding the environmental footprint through construction and land use change.	(Dean et al., 2019); (Milakis, 2019); (Pourrahmani et al., 2020); (Cugurullo et al., 2021); (Emory et al., 2022); (Jeong et al., 2023).
Coupling with vehicle electrification & clean energy	Pairing autonomous driving with electric vehicles can greatly improve environmental outcomes. Electric ADVs produce little to no tailpipe pollution, and when charged with renewable energy they significantly cut greenhouse gas emissions and urban air pollutants compared to gasoline vehicles.	(Wang et al., 2018); (Dean et al., 2019); (Rafael et al., 2020); (Sohrabi et al., 2020); (Milakis and Müller, 2021).	Energy demand & manufacturing footprint	Advanced autonomous driving technology can introduce new energy and environmental costs. Running sensors, processors, and other onboard systems contribute to a vehicle's energy consumption, and extra hardware adds weight that can reduce fuel efficiency. In addition, producing and disposing of high-tech components and vehicles entails manufacturing emissions.	(Gandia et al., 2019); (Liu et al., 2019b); (Stogios et al., 2019).
High ADVs adoption (Long-term potential)	Widespread adoption of autonomous cars could yield a major reduction in transport emissions. In optimistic scenarios where ADVs are ubiquitous and optimized, studies project that transportation-related greenhouse emissions could be cut nearly in half, significantly aiding climate goals.	(Wadud et al., 2016); (Milakis and Müller, 2021).	Low ADVs penetration (Short-term impact)	In the near term, with low market penetration of ADVs, environmental benefits are likely minimal. During early adoption stages, most vehicles on the road remain conventional, meaning overall fuel use and emissions see little change. Significant reductions in emissions are unlikely until autonomous vehicles make up a large share of the fleet.	(Liu et al., 2019b); (Kopelias et al., 2020).
Policy-guided sustainable ADVs use	Environmental benefits of ADVs are maximized when guided by strong policies and planning. For example, regulations that promote shared autonomous cars' fleets, discourage excessive private car use and integrate autonomous cars with public transit. This can enhance this technology contribution to sustainability rather than undermining it.	(Marletto, 2019).	Unregulated deployment & outcome uncertainty	Without appropriate policy intervention, autonomous cars could lead to unsustainable outcomes. An unregulated ADVs rollout may exacerbate traffic and pollution through unchecked increases in car travel and urban sprawl. Moreover, there is substantial uncertainty in how ADVs adoption will ultimately impact the environment (studies range from major emission reductions to potential increases) highlighting the risk if deployment is left solely to market forces.	(Liu et al., 2019b); (Marletto, 2019); (Milakis, 2019); (Othman, 2022); (Silva et al., 2022).
Reduced traffic noise	Autonomous cars could help lower traffic noise levels. Smoother driving patterns mean ADVs traffic may generate less	(Silva et al., 2022).	Cybersecurity & hazard risks	Heavy reliance on digital systems and connectivity in ADVs introduces new risks. For instance, a cyber-attack or system failure could cause accidents or	(Pan et al., 2024).

(continued on next page)

Table 3 (continued)

PROs	Description	Reference (Author(s), Year)	CONs	Description	Reference (Author(s), Year)
	noise pollution, improving urban soundscapes.			hazardous material spills, posing indirect environmental dangers and safety concerns.	

Ryan, 2020). Third, ADVs could contribute to reduced physical activity by making door-to-door motorized travel more attractive than walking or cycling, raising public health concerns about sedentary lifestyles. Additionally, over-reliance on automation could lead to erosion of driving skills, with individuals becoming less capable of manual driving when necessary (Gasne et al., 2022; Hopkins and Schwanen, 2023; Pourrahmani et al., 2020). Another major concern is related to trust and ethics. Issues such as decision-making in moral dilemmas (i.e., crash scenarios), concerns about data privacy, and vulnerability to cyber-attacks erode public confidence. The spread of misinformation about ADVs capabilities may further aggravate these anxieties, slowing public acceptance (Cugurullo et al., 2021; Naiseh et al., 2025; Shahedi et al., 2023). Moreover, urban sprawl is a widely discussed unintended consequence. As autonomous cars reduce the disutility of commuting, they could incentivize longer travel distances, prompting residential dispersion and undermining compact city development (Fraedrich et al., 2019; Marletto, 2019; Milakis, 2019). Without appropriate regulation, this could increase vehicle miles travelled and weaken public transit systems. Lastly, regulatory and legal gaps represent a structural barrier to socially sustainable deployment. The absence of clear legal frameworks on liability, safety protocols, and equity mandates creates uncertainty for both developers and users. Without regulatory clarity, urban planners may overlook key inclusion criteria or safety thresholds, allowing market dynamics to drive outcomes misaligned with social priorities (Emory et al., 2022; Gavanas, 2019; Rowe et al., 2024).

Overall, the social dimension of ADVs presents both transformational promises and substantial challenges. As the literature suggests, maximizing positive impacts will depend not only on technological performance, but also on robust governance, inclusive policy design, and continuous monitoring of social outcomes. The future of autonomous cars as a socially sustainable innovation will ultimately depend on how societies address these interwoven issues across safety, equity, trust, and urban dynamics.

4.4. Economic sustainability

ADVs offer substantial economic potential, promising to reshape transportation systems. However, the realization of these benefits is contingent upon navigating a complex landscape of structural, financial, and labour-related risks.

On the positive side, ADVs are frequently positioned as drivers of industry innovation and investment. Major automotive and technology firms are allocating considerable resources toward autonomous driving development, fostering economic growth, high-tech job creation, and competitive advantage (Pan et al., 2024; Shahedi et al., 2023). This industrial momentum is coupled with the expectation of increased operational efficiency, particularly in freight and public transport. By automating vehicle operation, ADVs can reduce congestion, optimize fleet management, and enable passengers to reclaim travel time for work or leisure, thus enhancing productivity across the economy (Emory et al., 2022; Huda et al., 2023; Steck et al., 2018). A key advantage emphasized in the literature is the reduction in travel and operating costs. Through lower fuel consumption, labour savings, and improved routing, autonomous cars could decrease per-mile costs for both users and service providers (Chen et al., 2023; Huda et al., 2023; Milakis, 2019). These efficiencies are amplified in shared-use scenarios, where vehicle utilization is maximized, and infrastructure demands can be reduced. In this context, urban optimization, such as repurposing

parking infrastructure and avoiding costly road expansions, emerges as a significant economic gain, especially for dense metropolitan areas (Gavanas, 2019; Vleugel and Bal, 2018). Moreover, ADVs enable the development of new business models and revenue streams, like for instance automated ride-hailing services. These innovations have the potential to transform how transportation is monetized and offer fertile ground for start-ups and incumbent firms alike (Cavazza et al., n.d.; Chen et al., 2023; Yun et al., 2016). Additionally, monetizing benefits such as accident cost avoidance and reduced congestion can further justify public and private investment in infrastructure and services (Milakis and Müller, 2021).

Despite these opportunities, several challenges complicate the path to economic sustainability. A foremost concern is the high upfront and ongoing costs of autonomous driving technology, including advanced sensors, real-time connectivity, software updates, and cybersecurity systems. These financial burdens are particularly acute for cities and small-scale operators, potentially limiting widespread adoption and scalability (Gandia et al., 2019; Huda et al., 2023; Othman, 2022). Market uncertainty further clouds the economic case for ADVs. The technology remains in a nascent stage, with unclear timelines for regulatory approval, liability frameworks, and insurance norms. Investors and municipalities face difficulty forecasting return on investment, while manufacturers contend with inconsistent demand projections (Keszey, 2020; Shahedi et al., 2023). This immaturity of the business case, especially in less urbanized contexts, undermines confidence in the profitability and long-term viability of autonomous cars ventures (Cavazza et al., n.d.; Yun et al., 2016). The risk of job displacement is another critical issue. While ADV deployment may create new technical roles, it threatens to eliminate many driving-related jobs across logistics, public transit, and taxi services. Without proactive retraining and labour market policies, these transitions could exacerbate economic inequality and provoke social resistance, thereby delaying adoption (Emory et al., 2022; Milakis and Müller, 2021; Ryan, 2020). Other economic downsides include induced urban sprawl, which may increase infrastructure maintenance costs and reduce the efficiency of land use (Milakis, 2019). If autonomous cars encourage longer commutes and residential decentralization, anticipated savings in urban transport could be offset by increased externalities (Gavanas, 2019; Milakis, 2019). Lastly, cybersecurity investments and liability risks may impose ongoing costs on both public and private actors, especially as autonomous cars become targets of hacking or software vulnerabilities (Pan et al., 2024).

In such a scenario, cities could bear the costs of autonomous cars integration without receiving the projected efficiency dividends. Taken together, the literature underscores that while ADVs offer compelling economic benefits, particularly in terms of productivity, innovation, and operational efficiency, these are not guaranteed. Rather, they depend on well-designed policies, inclusive deployment strategies, and adaptive economic planning. Table 5 highlights how the most cited economic PROs concentrate on system efficiency and market innovation, whereas the most frequently mentioned CONs involve high costs, labour disruptions, and systemic uncertainties. These findings suggest that achieving economic sustainability with ADVs requires not only technological readiness but also institutional foresight and socioeconomic resilience.

5. Discussion

This study provides a systematic synthesis of the literature

Table 4

Riepilogative list of advantages and disadvantages of Autonomous Driving Vehicles under the social sustainability lens.

PROs	Description	Reference (Author(s), Year)	CONs	Description	Reference (Author(s), Year)
Improved road safety	Autonomous cars significantly reduce human error-related crashes, leading to fewer accidents and injuries. By removing impaired or distracted driving (i.e., eliminating drunk-driving incidents) and reacting faster than humans, ADVs can save lives and improve public health.	(Dean et al., 2019); (Gandia et al., 2019); (Bin-Nun and Binamira, 2020); (Pourrahmani et al., 2020); (Ryan, 2020); (Milakis and Müller, 2021); (Papadimitriou et al., 2022); (Hopkins and Schwanen, 2023); (Shahedi et al., 2023); (Busch, 2024); (Dong et al., 2024); (Pan et al., 2024).	Persistent safety risks	Self-driving cars cannot eliminate all dangers. Accidents can still occur due to system failures or unpredictable conditions. Older drivers and others might also struggle to take over control in emergencies. Additionally, connecting vehicles to networks introduces cybersecurity threats, which pose new safety risks.	(Martinho et al., 2021); (Almlöf et al., 2022); (Gasne et al., 2022); (Pan et al., 2024).
Socioeconomic equity & inclusion	ADVs promise greater mobility for those who traditionally lack access. Elderly, disabled, and non-drivers could travel more independently, while underserved communities might benefit from new shared mobility options. With thoughtful policies, autonomous technology can improve transportation accessibility for all.	(Gavanas, 2019); (Milakis, 2019); (Keszey, 2020); (Kovacs et al., 2020); (Sohrabi et al., 2020); (Almlöf et al., 2022); (Emory et al., 2022); (Gasne et al., 2022); (Othman, 2022); (Chen et al., 2023); (Jeong et al., 2023); (Naiseh et al., 2025).	Risk of inequitable access	There is a concern that autonomous driving benefits may not reach everyone equally. High costs and digital requirements could create an “ADVs division”, where wealthy or tech-savvy groups gain mobility advantages while low-income, rural, or older people are left behind. Furthermore, widespread automation may displace professional drivers like taxi and truck drivers, potentially widening socioeconomic gaps without intervention.	(Cohen and Cavoli, 2019); (Kassens-Noor et al., 2020); (Ryan, 2020); (Sohrabi et al., 2020); (Milakis and Müller, 2021); (Emory et al., 2022); (Chen et al., 2023); (Hopkins and Schwanen, 2023); (Rowe et al., 2024).
Increased travel comfort	Without the burden of driving, riders experience more comfort and less stress during trips. Passengers can relax or safely multitask. For instance, working or enjoying entertainment, turning travel time into productive or leisure time instead of a stressful activity.	(Ryan, 2020); (Jászberényi et al., 2022); (Pan et al., 2024).	Reduced physical activity & skills	By making door-to-door car travel effortless, ADVs could encourage a sedentary lifestyle, as people might walk and cycle less, raising public health concerns about physical inactivity. Also, as drivers rely on automation, they may lose driving proficiency over time. This skill erosion means individuals could struggle or respond slowly when manual control is needed.	(Dean et al., 2019); (Kassens-Noor et al., 2020); (Pourrahmani et al., 2020); (Gasne et al., 2022); (Hopkins and Schwanen, 2023).
Positive public outlook	Public attitudes toward ADVs have been optimistic in many studies. A considerable segment of people shows curiosity or enthusiasm for self-driving cars, and high public interest suggests an openness to adopting the technology, which could facilitate its societal rollout.	(Kassens-Noor et al., 2020); (Cugurullo et al., 2021).	Trust and ethical concerns	Public acceptance remains a challenge due to trust and ethical issues. Many are uneasy about how ADVs handle safety and moral decisions (i.e., in crash scenarios) and worry about data privacy or vehicle hacking. Misinformation about autonomous cars' capabilities or incidents can further reduce confidence and slow adoption.	(Vleugel and Bal, 2018); (Keszey, 2020); (Cugurullo et al., 2021); (Almlöf et al., 2022); (Papadimitriou et al., 2022); (Hopkins and Schwanen, 2023); (Shahedi et al., 2023); (Busch, 2024); (Naiseh et al., 2025).
Better urban liveability	Autonomous mobility could make cities more liveable. If autonomous shuttles and shared ADVs reduce private car use, cities could see less traffic congestion and a diminished need for parking space. Freed-up parking space and smoother traffic flows can improve air quality and urban living conditions for residents.	(Vleugel and Bal, 2018); (Fraedrich et al., 2019); (Marletto, 2019); (Milakis, 2019); (Hopkins and Schwanen, 2023).	Potential for urban sprawl	Without proper planning, ADVs might encourage people to live farther from city centres, since commuting becomes easier, thereby increasing urban sprawl. Additionally, convenient autonomous travel could draw riders away from public transit and lead to more vehicles on the road, including empty cars relocating themselves,	(Fraedrich et al., 2019); (Marletto, 2019); (Milakis, 2019).

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Table 4 (continued)

PROs	Description	Reference (Author(s), Year)	CONs	Description	Reference (Author(s), Year)
Need for proactive policy	Autonomous cars represent an opportunity for policymakers to steer outcomes positively. By updating regulations and urban plans, governments can address social concerns early and ensure autonomous cars deployment enhances accessibility, safety, and environmental goals.	(Cohen and Cavoli, 2019); (Marletto, 2019); (Jeong et al., 2023).	Regulatory & legal gaps	potentially undermining transit systems and congesting cities. Governance is currently playing catch-up with autonomous driving technology. Many regions lack clear laws on autonomous driving liability and safety oversight. This regulatory lag, combined with scarce real-world data, leaves urban planners without guidance and can result in policies that overlook social equity, failing to prevent negative outcomes.	(Gavanas, 2019); (Alawadhi et al., 2020); (Emory et al., 2022); (Rowe et al., 2024).

Table 5

Riepiologative list of advantages and disadvantages of Autonomous Driving Vehicles under the economic sustainability lens.

PROs	Description	Reference (Author(s), Year)	CONs	Description	Reference (Author(s), Year)
Industry investment	Automotive and tech industries are actively investing in ADVs development, driving industry growth and innovation.	(Shahedi et al., 2023).	Market uncertainty and financial barriers	High market uncertainty (slow adoption, regulatory hurdles) and economic instability (inflation, investment risk) may slow autonomous cars deployment and deter investment.	(Keszezy, 2020); (Shahedi et al., 2023).
Increased operational efficiency and productivity	Automation in transport (i.e. transit and freight) and autonomous cars use allows travellers to work or rest during trips, reduces congestion, and increases overall productivity.	(Steck et al., 2018); (Ryan, 2020); (Emory et al., 2022); (Huda et al., 2023).	Induced urban sprawl	Cheaper and easier travel may encourage suburban sprawl, offsetting some urban efficiency gains.	(Milakis, 2019).
Reduced travel and operating costs	ADVs adoption can lower operating expenses (i.e. reduced labour and fuel costs) and decrease per-mile travel costs for users and businesses.	(Milakis, 2019); (Chen et al., 2023); (Huda et al., 2023).	High upfront and ongoing costs	Large initial capital investments and ongoing maintenance/upgrade expenses for autonomous driving technology and infrastructure may erode these cost savings.	(Vleugel and Bal, 2018); (Gandia et al., 2019); (Othman, 2022); (Huda et al., 2023).
New business models and market opportunities	ADVs emergence creates new mobility services and business models (i.e. automated ridesharing, autonomous vehicles tourism, etc.) and opens new revenue streams.	(Yun et al., 2016); (Cavazza et al., n.d.); (Gavanas, 2019); (Chen et al., 2023).	Market immaturity and unclear business case	Yet immature markets and unclear business models/business cases pose challenges to profitability and investment.	(Yun et al., 2016); (Cavazza et al., n.d.).
Optimized urban infrastructure	Shared ADVs and reduced parking needs can free up urban space and lower demand for new transport infrastructure.	(Vleugel and Bal, 2018); (Gavanas, 2019).	Integration costs	Upgrading city networks and infrastructure is expensive, and easier travel may spur suburban development, offsetting some benefits.	(Gavanas, 2019); (Milakis, 2019).
Advanced technology and resource efficiency	Smart ADVs technologies improve logistics and can reduce energy use and number of vehicles needed, optimizing resource use.	(Pan et al., 2024).	Cybersecurity and system costs	Significant investment in cybersecurity, software updates, and liability management is required, increasing ongoing costs and risks.	(Pan et al., 2024).
Monetization of safety and congestion benefits	Reductions in crashes, emissions, and congestion represent significant economic benefits, which can be quantified to support ADVs investments.	(Milakis and Müller, 2021).	Liability and insurance uncertainty	Unresolved legal liability and insurance frameworks for ADVs create uncertainty and potential extra costs in the transport sector.	(Ryan, 2020).
Industry growth and new employment	Autonomous vehicles industry growth can create jobs in vehicle manufacturing, tech development, and new mobility services.	(Shahedi et al., 2023).	Job displacement and labour disruption	Widespread driving automation threatens existing driving-related jobs and can cause significant labour market disruption and retraining costs.	(Ryan, 2020); (Milakis and Müller, 2021); (Emory et al., 2022); (Chen et al., 2023).

evaluating the sustainability impacts of ADVs across environmental, social, and economic dimensions, using the TBL framework. The results demonstrate that while these vehicles hold transformative potential, their sustainability is contingent on complex, context-dependent

interactions. In the following, we interpret these findings highlighting cross-cutting trade-offs, acknowledging the study's limitations, and outlining directions for future research.

Environmentally, the most frequently cited advantages are related to

improved traffic efficiency, optimized driving behaviour, and emissions reductions, especially when paired with electrification and renewable energy integration. These findings corroborate earlier projections that link automation with energy savings and lower GHG emissions. However, the potential environmental gains are heavily moderated by behavioural responses and deployment strategies. The rebound effect, where greater travel convenience induces additional demand, emerges as a critical concern that could offset emissions savings. Closely related to this is the issue of behavioural adaptation and modal substitution. The advent of autonomous cars may lead to notable changes in travel behaviour, including shifts away from active and public transportation modes. The convenience and door-to-door service of ADVs could induce modal substitution, potentially drawing riders from walking, cycling, and transit. Several studies warn that an unregulated ADVs rollout might discourage walking and cycling, resulting in a less active population and increased vehicle use (Botello et al., 2019; Pettigrew et al., 2020). For instance, one survey found that 18 % of participants would use ADVs for trips they currently walk and 32 % for trips they currently cycle, predicting that overall physical activity levels could decline with widespread ADVs adoption (Booth et al., 2019). Such behavioural shifts may erode both the environmental and health benefits of sustainable transport. Policymakers should therefore anticipate and counteract potential negative modal shifts, for example by investing in active transport infrastructure and integrating ADVs services with public transit, so that these vehicles do not unintentionally reduce walking, cycling, and transit use. Similarly, increased vehicle manufacturing, energy-intensive sensors, and unregulated usage patterns may result in higher lifecycle emissions. Such findings illustrate both the promise and fragility of the environmental case for ADVs and underscore the importance of governance mechanisms that actively prevent a return to car dependency and urban sprawl. Beyond environmental impacts, autonomous cars adoption is poised to be transformational for urban planning, with potentially divergent implications for city density and infrastructure. On one hand, easier and faster travel in ADVs could spur urban sprawl: by lowering the time and effort cost of commuting, ADVs may enable people to live farther from city centres (Duarte and Ratti, 2018). Indeed, one simulation study in a U.S. metropolitan region projected up to a 68 % increase in horizontal urban spread under widespread ADVs use (Moore et al., 2020). This suggests autonomous cars could intensify suburbanization if not carefully managed. On the other hand, ADVs also present opportunities for urban densification and infrastructure repurposing. As human-driven cars are phased out, cities could reclaim substantial land from parking and roadways. Researchers note that autonomous fleets, especially if shared, might drastically reduce parking demand, for example each shared autonomous vehicle could eliminate the need for more than 20 private parking spaces (Zhang and Guhathakurta, 2017). Fewer parking garages and lots could then allow infill development and new green spaces in downtown areas (Kondor et al., 2019b; Narayanan et al., 2020). Additionally, infrastructure design may shift to accommodate ADVs operations, with curbside drop-off zones, dynamic traffic management, and dedicated autonomous cars lanes or corridors becoming integral to city planning. Taken together, these dynamics make clear that ADVs could either decentralize cities through sprawl or augment urban density by freeing up land. Which trajectory prevails will largely depend on policy choices and whether ADVs are predominantly privately owned or deployed as shared fleets. This highlights the importance of proactive urban planning and zoning policies to steer ADVs adoption toward sustainable outcomes.

Closely related to these dynamics, the role of shared mobility emerges as pivotal for realizing system-level sustainability benefits. Autonomous vehicles' fleets could significantly improve transportation outcomes if utilization rates are high and fleet size is optimized to demand. Prior studies show that car-sharing services increase vehicle usage efficiency - for example, each shared car can replace approximately 10–15 privately owned cars (Turoń, 2023) - thereby reducing the overall vehicle fleet and freeing up parking space. Other research

emphasizes sustainable transport and service optimization as core features of car-sharing systems (Bischoff and Maciejewski, 2019; Zhu et al., 2023). Evidence also shows that car-sharing's impact is heterogeneous: one latent-class analysis found that environmentally motivated car-sharers completely replace private car use (leading to large drops in car ownership and usage), whereas utilitarian sharers, especially those who were previously carless, may actually increase their driving when given access to shared cars (van der Linden et al., 2025). Notably, car-sharing often complements public transport rather than competes with it, underscoring the importance of integrating ADVs-based sharing services with transit (Ceccato and Diana, 2021). Extending the focus to ride-sharing, autonomous vehicles could further enhance efficiency through higher occupancy per vehicle, such as car-pooling and on-demand shuttles, which can improve energy and carbon performance per passenger (Olave-Cruz et al., 2025). However, these benefits are conditional on effective fleet management and algorithms to minimize empty re-positioning trips. Finally, in the broader Mobility-as-a-Service (MaaS) context, shared ADVs have the potential to act as key enablers of integrated, multimodal systems (Yang et al., 2023). Conversely, if adoption remains limited and private autonomous cars ownership dominates, the sustainability potential of these vehicles could be severely undermined (Fielbaum and Pudāne, 2024).

From a social standpoint, the literature reflects a nuanced view. Prominent social benefits include improved safety through reduction of human error, increased mobility for underserved groups, and enhanced comfort and productivity during travel. Among these, road safety stands out as the most critical and widely recognized contribution of ADVs to social sustainability. However, despite broad consensus that automation can substantially reduce crashes, the precise level of reduction remains uncertain. The lack of large-scale longitudinal data means that safety benefits are often projected rather than observed, making this a priority area for future empirical and scenario-based studies. These advantages are especially salient for elderly, disabled, and non-driving populations. Nevertheless, access to these benefits is not guaranteed. Concerns about unequal access, public trust, and job displacement pervade the literature. In particular, the digital divide and affordability barriers risk exacerbating mobility inequities, and widespread job losses in driving occupations could impose serious social costs unless mitigated by forward-looking policies. Furthermore, ethical dilemmas, skill degradation, and the risk of social isolation further highlight that the impacts of ADVs on well-being are multidimensional and contested.

Economically, the review uncovers both robust optimism and structural uncertainty. Proponents emphasize cost reductions, productivity gains, and the creation of new business models and service industries, including fleet-based mobility services and data-driven applications. These developments are associated with wider economic stimuli and new employment opportunities in tech-oriented sectors. However, the literature is equally rich in cautionary perspectives. High initial investments, cybersecurity costs, regulatory ambiguity, and limited consumer willingness to forego private vehicle ownership remain major obstacles. In addition, the relative scarcity of empirical studies focused on economic sustainability, compared with the environmental and social dimensions, suggests that the financial viability of ADVs remains underexplored and requires further systematic investigation.

A core contribution of this paper lies in demonstrating how the TBL framework enables an integrated assessment of these findings. Rather than treating environmental, social, and economic dimensions as silos, the TBL perspective reveals points of synergy, such as shared ADVs enhancing both air quality and accessibility, as well as inherent tensions. For example, maximizing travel convenience and economic returns may increase vehicle miles travelled, undermining climate and public health objectives. Likewise, efforts to lower costs might exacerbate labour market disruption unless paired with inclusive transition policies. This highlights the need for adaptive governance frameworks that balance efficiency, equity, and sustainability objectives, while remaining

responsive to evolving deployment contexts.

Finally, the temporal and thematic analysis conducted in 4. Results highlights important trends in the literature. Environmental and social impacts have received sustained attention since 2019, maybe influenced in part by global discourses on climate resilience and equity. Conversely, the economic dimension appears underrepresented and underdeveloped, a gap likely stemming from the early-stage market maturity of ADVs technology. This trend reinforces the call for future research to explore financial modelling, cost-benefit analyses, and policy incentives that could make autonomous cars deployment both profitable and inclusive.

In sum, the sustainability of self-driving cars depends less on the technology itself and more on how it is embedded in broader systems of regulation, planning, and social norms. A TBL-based lens not only allows for a structured synthesis of fragmented findings but also equips policymakers, planners, and scholars with a roadmap for navigating the complexities of sustainable ADVs integration. Future studies should adopt multidisciplinary and longitudinal approaches to further investigate these trade-offs and inform responsible technological transitions.

To translate these insights into practice, we also propose a set of operational policy measures that can help steer ADVs adoption toward sustainability objectives:

- **Zoning and land use:** Revise zoning regulations and urban design guidelines to prepare for ADVs. For example, cities can reduce or eliminate minimum parking requirements in new developments (anticipating lower private car ownership) and pickup/drop-off zones or autonomous cars lanes to safely integrate autonomous shuttles. Planners should also consider transit-oriented development strategies so that ADVs services complement, rather than compete with, public transport.
- **Public-Private Partnerships (PPPs):** Forge partnerships between government and private ADVs developers/operators. PPPs can facilitate the deployment of autonomous cars infrastructure such as smart traffic signals or dedicated ADVs corridors, and pilot programs in a cost-sharing manner (Liu et al., 2024). Additionally, transit agencies and ADVs companies can collaborate to offer first-mile/last-mile solutions.
- **Data governance and sharing:** Establish frameworks for ADVs data governance to ensure that the wealth of data generated by autonomous cars is used for public good. Policymakers should mandate or incentivize data sharing between ADVs operators and city authorities (for traffic management, urban planning, and safety improvements) while enforcing strict privacy protections for users (Creutzig, 2021; Freemark et al., 2019). Clear guidelines on data ownership, cybersecurity, and interoperability will build public trust and enable smarter urban mobility management.
- **Regulation and standards:** Develop adaptive regulations and standards specific to ADVs, including safety certifications, software reliability standards, and requirements for electric/low-emission ADVs fleets to align with sustainability goals. Governments can also use policy levers like tax incentives or congestion pricing to encourage shared autonomous cars use over private ownership, maximizing positive environmental impacts.

By addressing zoning, partnerships, data, and regulatory standards, these recommendations provide a concrete action plan to accompany the insights of our review and enhance its utility for decision-makers.

At the same time, it is important to clarify the regional scope of our findings. Most of the studies included in our review originate from the Global North (primarily North America and Europe, with some coverage of East Asia). As such, our conclusions predominantly reflect high-income, technology-leading contexts. In the future, it could be interesting to expand this study to discuss how sustainability impacts of ADVs may differ in the Global South and emerging markets. In fact, many cities in developing countries are characterized by organic urban

growth, informal transit systems, and weaker enforcement of traffic rules (Pojani and Stead, 2018). In such environments, ADVs might encounter difficulties in navigating chaotic traffic patterns or could face constraints due to limited digital and charging infrastructure, reducing expected efficiency or electrification benefits. Social and economic effects such as job displacement of drivers or the affordability of ADVs services may also be more severe in emerging economies. On the other hand, ADVs could help address persistent challenges in developing cities such as improving safety in high-crash environments or expanding access in underserved areas if carefully adapted to local conditions (Pink et al., 2021; Thaitatkul et al., 2024). We therefore caution that our review's conclusions are most directly applicable to developed countries, and we call for more regionally focused studies to explore the sustainability trajectory of autonomous cars in diverse global contexts. By explicitly acknowledging this regional scope, we ensure readers understand both the boundaries and transferability of our conclusions.

Nevertheless, several other limitations of this study must be acknowledged. First, the analysis relies exclusively on secondary data from existing literature reviews, which offer a broad overview of the field, but may omit emerging insights from recent primary studies or grey literature that are not yet captured in review publications. This reliance on aggregated insights may limit the ability to capture evolving trends or empirical findings related to local pilot projects, real-world deployments, or context-specific experiences of ADVs integration. Future research should therefore complement review-based syntheses with up-to-date primary data collection, large-scale surveys, and comparative case studies of pilot programs, which can provide more granular evidence on local variations and lived experiences of autonomous mobility. In addition, meta-analyses of empirical studies could be employed to validate or challenge the claims distilled in review literature. While focusing exclusively on review articles allowed us to map overarching patterns, convergences, and contradictions in the sustainability debate, this choice inevitably limited the inclusion of recent empirical findings, particularly from local pilot projects and regionally specific case studies not yet covered in reviews. Incorporating such primary studies through systematic meta-analyses and comparative evaluations would provide more granular evidence and further enrich the insights generated here.

Second, this review does not quantitatively assess the magnitude or likelihood of the reported impacts. The qualitative PRO/CON structure offers a balanced summary but does not differentiate between impacts in terms of their empirical strength, generalizability, or likelihood of occurrence. As such, the conclusions may reflect a certain level of subjectivity based on how often themes appear rather than how decisively they have been verified. A promising avenue for future work is the adoption of mixed-method approaches that integrate systematic reviews with quantitative modelling, such as multi-criteria decision analysis, cost-benefit assessment, or agent-based simulations. Structured expert elicitation techniques (e.g., Delphi panels) and scenario modelling could further provide probabilistic estimates of the most likely sustainability outcomes of ADVs under varying policy, technological, and behavioural conditions.

Third, the temporal limitation of the reviewed literature (2009–2024) and the exclusion of non-English and non-peer-reviewed sources may have constrained the diversity of perspectives captured, particularly from Global South contexts where mobility challenges and policy landscapes differ significantly. More inclusive and regionally focused reviews - especially from Latin America, Africa, and Southeast Asia - are needed to ensure that the global sustainability narrative on ADVs does not remain skewed toward high-income, tech-leading nations. Future research could also adopt comparative cross-country perspectives to examine how contextual differences in governance capacity, infrastructure readiness, and cultural attitudes shape the sustainability trajectory of ADVs. Such analyses would not only broaden the evidence base but also support more globally representative policy recommendations.

Beyond addressing these limitations, there are several broader directions for future research. A deeper exploration of cross-pillar dynamics is essential, and studies could investigate, for example, how technological design choices such as energy-efficient algorithms, vehicle-sharing platforms, or data governance structures, mediate trade-offs between environmental efficiency and social inclusion. Then, longitudinal and real-world studies are crucial to track how the projected sustainability outcomes of ADVs evolve as the technology matures and scales. Evidence from early deployments can reveal whether initial promises hold true or whether unintended consequences emerge over time. Moreover, there is a need for interdisciplinary collaborations that bring together transport engineering, behavioural science, economics, and urban planning to produce integrated insights that single-discipline studies cannot capture. Finally, participatory and co-design approaches that actively involve citizens, workers, and local stakeholders in shaping autonomous mobility strategies may help ensure that the development of ADVs aligns with community priorities and values, thereby strengthening both legitimacy and sustainability.

Despite these limitations, the study provides a valuable foundation for further inquiry. By addressing the identified gaps and pursuing these future research avenues, scholars can generate more robust, inclusive, and actionable knowledge to guide policymakers and industry actors. Ultimately, as the field matures, the integration of interdisciplinary methodologies, regionally grounded analyses, and participatory approaches will be essential to fully understand and steer the sustainability trajectory of autonomous mobility systems.

6. Conclusions

This review contributes to the growing body of literature on sustainable autonomous mobility by providing an integrated evaluation of autonomous cars' impacts through the TBL lens. We systematically examined how ADVs may support or hinder environmental quality, social well-being, and economic vitality, synthesizing findings from dozens of studies. The results show that autonomous cars have the potential to substantially improve urban sustainability lowering emissions and energy use, enhancing traffic safety, and creating new economic efficiencies and services. At the same time, they pose significant challenges that must be addressed, including the risk of increased travel demand and associated emissions, threats to employment and privacy, high implementation costs, and unequal access if market forces alone dictate deployment.

In reflecting on our research questions:

- When are ADVs environmentally sustainable? Autonomous cars are environmentally beneficial under conditions of high clean-energy usage, ride-sharing adoption, and effective countermeasures to rebound effects. For example, fleets of electric ADVs in a city with supportive transit and land-use policies could dramatically cut per-capita transport emissions. Conversely, if autonomous cars are simply added into traffic, their environmental sustainability diminishes. Thus, ADVs support environmental goals when coupled with renewable energy and smart urban planning, and when their efficiency gains are not negated by more driving.
- When are ADVs socially sustainable? Autonomous cars promote social sustainability if they improve safety and accessibility for all, and if the benefits of autonomy are broadly shared. This scenario is more likely if autonomous cars services are made accessible in underserved areas, if policies cushion the workforce transition, and if strong privacy protections are in place. ADVs are socially sustainable when their deployment leads to safer roads and greater mobility without exacerbating inequality or eroding public trust. Our review suggests this requires deliberate efforts to include marginalized groups and maintain public engagement.
- When are ADVs economically sustainable? Economically, autonomous cars make sense when efficiency gains outweigh costs and

when new economic opportunities compensate for disrupted sectors. In concrete terms, ADVs are sustainable if, over time, they reduce transportation costs, increase productivity (i.e., through reclaimed time), and contribute to economic growth, while initial investments are amortized and transitional economic harms (job losses, industry shifts) are managed. The condition “when” is largely a factor of scale and policy: early on, costs are high, but as the technology matures and scales, the cost per mile of ADVs could fall significantly, potentially below that of conventional cars, and delivering net economic benefits. And ensuring those benefits are inclusive, and not just captured by a few firms, is part of the economic sustainability equation.

For policymakers, this means proactively shaping the trajectory of autonomous mobility. Governments should not take a hands-off approach, but instead, they should set clear sustainability-oriented guidelines for ADVs deployment. Examples include mandating that autonomous cars fleets be zero-emission, requiring data sharing from ADVs operators for city planning, enforcing “shared ride” targets or congestion fees to prevent empty vehicle cruising, and updating building codes to anticipate reduced parking needs. Moreover, policy can encourage public-private collaboration on pilot projects that demonstrate how autonomous vehicles can serve societal goals such as an autonomous bus line improving transit coverage in a suburb. International knowledge exchange will also be valuable; cities and countries can learn from each other's autonomous driving experiments to refine best practices and avoid pitfalls.

For industry practitioners and urban planners, the recommendation is to engage with the broader ecosystem. Technology developers should work together with municipalities to ensure that autonomous cars services complement public transportation and fill genuine mobility gaps, rather than simply undercut existing systems for profit. And consumers and city authorities are more likely to embrace ADVs technology if it is seen to further environmental and social objectives. In fact, companies that prioritize safety and transparency, openly reporting on ADVs performance, errors, and improvements, can build trust and achieve social license to operate more quickly. Meanwhile, urban planners should integrate autonomous cars scenarios into their long-term plans, considering how traffic flow might change, how curb side demand for pick-up/drop-off will increase, and how land currently used for extensive parking could be gradually redeveloped. Early integration of autonomous cars considerations into planning can help cities maximize benefits and minimize disruption.

In conclusion, autonomous cars are not inherently “sustainable” or “unsustainable”, it is the choices we make in deploying them that will determine their net impact. This study has provided an overview of the opportunities and challenges from environmental, social, and economic perspectives. If stakeholders take a holistic, proactive approach, autonomous vehicles can be a cornerstone of future sustainable transport systems, helping to reduce carbon footprints, save lives, and enhance mobility for all. If not, we risk repeating past mistakes, where car-centric development solved some problems but created others. The coming decade will be pivotal as theory gives way to practice in the ADVs domain. We urge decision-makers to use the insights from systematic evaluations like ours to steer autonomous mobility in a direction that maximizes shared benefits and minimizes harms.

CRediT authorship contribution statement

Giuseppe de Leo: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Giovanni Miragliotta:** Writing – review & editing, Visualization, Supervision, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to improve the clarity, coherence, and readability of the manuscript by refining sentence structures, correcting grammar, and ensuring consistency in terminology. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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