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Alternatively fuelled connected and autonomous vehicles: Contextualising the state of the art

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ABSTRACT

Connected and Autonomous Vehicles (CAVs) embody an AI-based transformation of paradigm-shifting gravitas that may disrupt, if not planned responsibly, efforts to make sustainable transport planning a priority for mobility provision. Packaging CAVs with alternative fuels can likely stop that. Our study, a thematically organised narrative review, aims to identify and evaluate *awareness, opportunities, challenges* and *policies* that could promote or impede the shift to vehicles that combine the qualities of both connected autonomy and alternative fuelling – i.e., the Alternatively Fuelled Connected and Autonomous Vehicles (AFCAVs). Whilst pro-environmental beliefs and ease of use are important awareness-setting parameters, more and better focused training and campaigns can advance understanding about AFCAVs and their overall societal value. AFCAVs could facilitate cost-saving and encourage shared transport but could generate issues, such as battery pollution and excessive travel. At the same time, supporting policy for them is still scarce and underdeveloped. To date, alternatively fuelled vehicle technologies lack incentivisation, operate on insufficient charging infrastructure with limited geo-spatial coverage and face range anxiety issues. We propose that for AFCAVs to be successful, their travel costs must be low, their environmental value over other vehicles should be demonstrated in a trusted way, an enabling policy framework should be established pro-actively and finally they should be offered on a shared basis with public transport being at the epicentre of any service provision.

1. Introduction

In an era where a robust climate change response is vital for the future of our planet, the liveability of our cities and the prosperity of our societies (Nikitas, Cotet, Vitel, Nikitas, & Prato, 2024; Wey & Huang, 2018), utilising the powerful gifts of the emerging Artificial Intelligence (AI) technologies in a responsible way could be a key for eliminating some of the destructive and polluting side-effects of transport (Nikitas et al., 2021a; Yigitcanlar & Cugurullo, 2020). Vehicle automation, especially when combined with connectivity (Nikitas, Michalakopoulou, Njoya, & Karampatzakis, 2020), can be such a technology since it can offer services with pro-environmental functions like eco-driving and platooning that may also provide enhanced safety, affordability, and efficiency gains (Fan, 2024; Liu, Nikitas, & Parkinson, 2020). Connected and Autonomous Vehicles (CAVs) in particular have the potential to make a positive contribution to sustainable and accessible futures if they are well implemented into the urban landscape and governed by a philosophy that disengages them from the 20th century's harmful car-first culture (Karolemeas et al., 2026; Tsigdinos, Karolemeas, Bakogiannis, & Nikitas, 2021).

CAVs are vehicle technologies that can understand their surroundings, navigate, move, and act responsibly without any human input, while using connectivity functions that enable them to be proactive, coordinated, intelligent, and cooperative (Nikitas et al., 2020). These intelligent fleets could be, in principle at least, a transition-enabling toolkit that will revolutionise transport networks and redefine our cities (Nikitas et al., 2021b). Alternative fuels are understood as those generated from energy sources alternative to fossil-fuels, such as electricity, biofuels, and hydrogen. These non-traditional fuels are typically generated from Renewable Energy Sources (RESs) and can help with fuel efficiency advancement (Fontaras, Pistikopoulos, & Samaras, 2008; Zhao et al., 2025). Whilst the utilisation of alternative fuels in transport can allow for a possibly significant drop in GHG emissions generated from fossil-fuel-powered fleets (Romm, 2006), there are barriers

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associated with maximising the use of these non-conventional energy sources into transport (Achtnicht, Bühler, & Hermeling, 2012).

Shifting to an automated transport system requires not only technology upgrades, but also policy, education, market, and cultural makeovers that make CAVs solely relying on alternative fuels the 'best choice' for the mainstream energy provision of vehicle automation (Nikitas et al., 2026). Alternatively Fuelled Connected and Autonomous Vehicles (AFCAVs) are driverless and cooperative vehicles powered by alternative energy sources (i.e. electricity, hydrogen, and biofuels) different to oil and its traditional byproducts. AFCAVs represent a broader vehicle classification that refers to the technology convergence of driverless autonomy, connectivity, and alternative fuelling even in cases that this is not generated by conventional electric batteries. For instance, whilst AFCAVs can integrate V2X sensors and non-fossil-fuel-based electricity fuels, these vehicles can also be hydrogen-based or primarily biofueled.

Until now there is a limited understanding of the opportunities, challenges, and awareness issues that might lie behind the powerful combination of connected autonomy and alternative fuelling. So far there is a gap in the literature even in terms of actively packaging up all CAVs that use different non-petrol fuelling technologies as a specific unified vehicle category like we try to do in this paper under the umbrella term of AFCAVs. It is likely that only when AFCAVs are studied thoroughly, policymakers can use them as a mechanism for enabling a paradigm-shifting transition to more sustainable transport futures.

Thus, the aim of our study is to identify and evaluate the awareness, opportunities, challenges, and policies around the transition to AFCAVs. The main structure of our work is as follows: Section 2 presents the methodology employed. Section 3 reports our evidence-based results on CAV-focused sustainability-associated benefits and adoption barriers. Section 4 identifies and evaluates the merits, risks, and policies embedded into alternative fuelling. Section 5 analyses the environment and cost advantages of electric autonomous vehicles (EAVs) and their adoption issues. Section 6 synthesises our evidence-based results and depicts the elements underpinning AFCAVs. And finally, Section 7 summarises the contributions of our study, proposes policy recommendations, recognises the limitations of our work, and discusses future research pathways for expanding this study.

2. Methodology

This work is the result of a thematically organised narrative review. Our article selection design adopted the Systematic Literature Review (SLR) criteria, for consistency and quality reasons (Wee & Banister, 2016). While incorporating the principles, eligibility standards, and search methods of SLR, we put emphasis on reporting the emerging literature trends and agendas in a thematically structured foundation as per Nikitas et al., (2021a). Prior to our search, we read CAV-related literature and identified keywords that help to assess AFCAVs. We only used English-written, peer-reviewed academic journal papers from Scopus published in the past ten years, to enhance our search quality standards. Some papers were repeated due to the usage of similar keywords (e.g. some results generated from the application of 'Electrification' were also found when using the term 'Electric Vehicles'). Duplication was addressed appropriately (i.e. eliminating twin articles from the literature count). By having all five authors agreed about the literature coverage presented, we avoided single analyst biases acting as checks and balances to each other (Nikitas et al., 2020). Fig. 1 reports step-by-step our article selection design through a PRISMA diagram.

The identified search keywords reflect our AFCAV scope (i.e. CAVs, alternative fuelling, and their implications to sustainable transport) and were utilised to standardise our SLR keyword-based search manifested in Table 1.

Our initial search resulted in 563 articles. We then only considered accessible papers with relevant titles, keywords, and abstracts. This advanced search retained 98 items. For the final inclusion in our corpus, we considered subject relevance (i.e. papers dealing with AVs, Electrification, and Sustainability) as well as citations attracted (i.e. a relatively reliable proxy for research impact measurement) as our selection criteria. This allowed us to reach a reliable consensus about genuinely important papers that need to be cited. This approach left us with 55 unique papers. We also included some other papers of relevance that

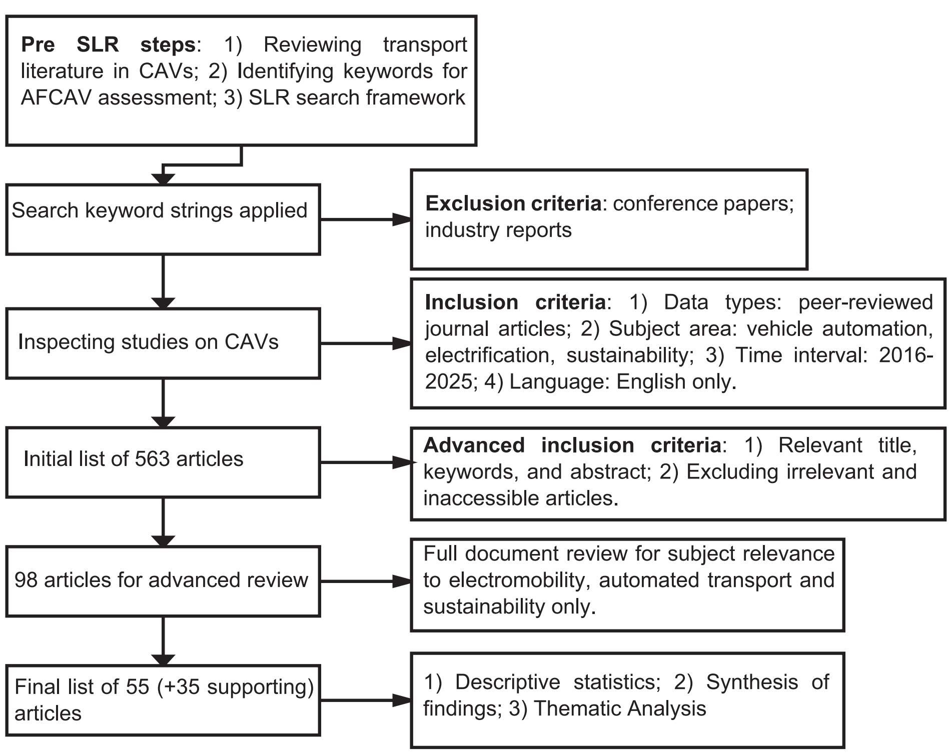

Fig. 1. Literature selection approach: A PRISMA visualisation.

Table 1
SLR search design.

Scope	Keywords
AFCAVs	*Connected and Autonomous Vehicles, Connected and Automated Vehicles, Autonomous Vehicles, Electric Vehicles, Electrification, Sustainability, Alternative Fuels, Transport Policies, Travel Costs, Electric Autonomous Vehicles, and Fuel Cell Vehicles.*
Search Platform	**Search String**
Scopus	TITLE-ABS-KEY ((“Connected and Autonomous Vehicles” OR “Connected and Automated Vehicles” OR “Autonomous Vehicles” OR “Electric Vehicles” OR “Electrification” OR “Alternative Fuels” OR “Sustainability” OR “Transport Policies” OR “Travel Costs” OR “Electric Autonomous Vehicles” OR “Fuel Cell Vehicles”) AND (LIMIT-TO (DOCTYPE, “jp”)) AND (“vehicle automation” OR electrification OR sustainability) AND (LIMIT-TO (TIME, “2016–2025”)) AND (LIMIT-TO (LANGUAGE, “English”)))

supported our discussion on automated transport, energy, and environment and the work's overall framing. Ultimately, 90 papers are referenced in our review paper.

3. Connected and autonomous vehicle background

3.1. CAVs and their travel benefits

CAVs can generate benefits, such as traffic congestion relief, collision rate reduction, and fuel economy wins (Bagloee, Tavana, Asadi, & Oliver, 2016; Liu et al., 2019). Whilst vehicle connectivity can help to improve traffic safety and travel optimisation (Liu et al., 2020; Yusuf, Khan, & Souissi, 2024), the automation enables eco-driving (Kopelias, Demiridi, Vogiatzis, Skabardonis, & Zafiropoulou, 2020). CAVs have a significant potential in lowering GHG emissions (Igliński & Babiak, 2017; Neufville, Abdalla, & Abbas, 2022; Wadud, MacKenzie, & Leiby, 2016) if these vehicles are powered by battery electricity or hydrogen fuel cells (Prideaux & Yin, 2019). More precisely, the use of electricity in CAVs can help to decrease GHG emissions by 80% compared to an identical oil-based vehicle (Fox-Penner, Gorman, & Hatch, 2018). Also, CAVs can contribute to a fuel consumption drop by 45% (Chen, Gonder, Young, & Wood, 2019). Whilst Fox-Penner et al. (2018) highlighted the capabilities of non-fossil-fuel-based CAVs in reducing emissions, Chen et al. (2019) suggested that the eco-driving functions of CAVs can also advance the efficiency of fuel utilisation. This is to say, CAVs can amplify both fleet electrification and the optimisation of fuel use, to support the target for greener transport (Nikitas et al., 2021a).

Also, CAVs may work primarily as shared fleets something that can allow for a more responsible use of resources. Shared CAVs can significantly reduce the overall Vehicle Miles Travelled (VMT) if they are introduced within a dynamic ride-sharing system (Fagnant & Kockelman, 2016). This indicates that CAVs must be operated ideally on an on-demand shared basis, if the goal is to create a more sustainable transport eco-system (Nikitas et al., 2020). Some studies have indeed concentrated on user preferences to automated travel frameworks (i.e. shared, private, and public). For instance, Acheampong, Cugurullo, Gueriau, and Dusparic (2021) shows that shared CAVs can be the most unpopular travel mode among the three. However, their study did not look specifically into user perceptions towards the costs for shared or privately owned CAVs, which can determine the uptake of CAVs according to Webb, Wilson, and Kularatne (2019).

3.2. Challenges towards the adoption

Despite the abovementioned positive projections, CAVs were reported as unaffordable when it comes to their price tag per se (Bansal & Kockelman, 2017; Fagnant & Kockelman, 2015). For instance, CAVs can be expensive to maintain since their annual maintenance costs could be around 1000 US dollars (Talebian & Mishra, 2018). However, whilst the study of Talebian and Mishra (2018) focused on the Willingness-To-Pay (WTP) for the maintenance expenses of CAVs, it did not explore how the maintenance costs would be different (or similar) between private and shared automated travel. Also, CAVs if not planned responsibly may lead to sustainability-related side-effects and resource-based risks detrimental to transport eco-systems (Nikitas et al., 2021a). This is primarily because fossil-fuel-based CAVs can increase energy consumption and environmental pollution (Phan et al., 2020).

On top of that, there are barriers such as unawareness, limited understanding, technological issues, and perceived hazards to the embracement of CAVs as evident in Jing, Huang, Ran, Zhan, and Shi (2019). Issues like behaviour adaptation barriers, situation awareness concerns, and pedestrian interaction limitations can significantly hinder the adoption of these vehicles (Rezwana & Lownes, 2024). Also, travel safety concerns especially in mixed-traffic situations are of critical importance to the adoption of CAVs (Martínez-Díaz & Soriguera, 2018; Yusuf et al., 2024). Whilst transport planners should consider the uptake of shared CAVs as a political agenda (Marletto, 2019), solutions to CAV adoption that are interinstitutional, cross-border, pro-environmental, and dynamic are needed (Nikitas, Njoya, & Dani, 2019). These technological and political barriers indicate the need for a more comprehensive CAV-related policy framework, to inform governments and businesses about the possible pathways towards a genuinely sustainable, user-oriented travel paradigm.

4. Alternative fuelling interventions

4.1. Alternative fuels and their implications to sustainable transport

Alternative fuels such as electricity and hydrogen have environmental implications to transport (Hassan et al., 2023). Fuel cell vehicles (i.e. hydrogen-based fleets) have the potential to bring more emission-free and economically sustainable travel benefits (Franzitta, Curto, Milone, & Trapanese, 2017; Kardooni, Yusoff, & Kari, 2016), provided that these vehicles are designed responsibly and used effectively (Ajanovic & Haas, 2018) focusing on becoming a mainstream option decisively reducing fossil-fuel-dependent consumption (Momete, 2018). For instance, whilst hydrogen-based vehicles produce water vapours as their only fuel generation byproduct (Sánchez-Bastardo, Schlögl, & Ruland, 2021), bio-hydrogen (i.e. the combination of biofuels and hydrogen) as a fuelling option can help to reduce transport emissions (Liang et al., 2021; Manoharan et al., 2019), such as those caused by conventional vehicles powered by the Internal Combustion Engine (ICE) as per Chang, Hwang, and Wu (2017).

However, the abovementioned studies comparing conventional oil-based fuels with alternative fuelling and their sustainability impacts are not entirely conclusive; it is not clear whether the benefits would come primarily from the cleanliness of alternative fuels themselves, or the potential for optimising energy usage in transport. For instance, the generation of fossil-fuel-based electricity and its utilisation in transport have resulted in unnecessary and low-efficient energy use (Achtnicht et al., 2012; Zhao et al., 2025). Unlike these conventionally fuelled fleets, human-driven vehicles powered by renewable electricity (i.e. those generated from hydrogen or solar power) can produce lower GHG emissions (Zhang, Du, Li, Cai, & Qi, 2025) but have higher operational expenses due to the absence of automation (Becker et al., 2020; Loeb & Kockelman, 2019). Connected automation can open pathways for cheaper travel that is at the same time more sustainable.

Electric Vehicles (EVs) can produce CO_2 emissions that are up to 26 times lower compared to ICE-based vehicles (Fiori et al., 2019; Teixeira & Sodré, 2018). However, EVs may still lead to air pollution (Fuinhas et al., 2021). Whilst electromobility has the potential to add eco-friendly and energy-efficient qualities to transport, EVs have issues on their operability and functionality (Egbue and Long, 2012). On the one hand, the battery and charging infrastructure costs of EVs represent a major socio-technical barrier to their uptake (Coffman, Bernstein, &

Wee, 2017a). On the other hand, their refuelling infrastructure is not broadly available (Haustein, Jensen, & Cherchi, 2021; Kougias, Nikitas, Thiel, & Szabó, 2020). Besides, whilst the privately-owned and human-driven EVs might be expensive as their energy expenses are still high (Becker et al., 2020), these vehicles can result in severe energy waste especially in highly congested traffic (König & Neumayr, 2017). This is more likely because most EVs for now are primarily powered by fossil-fuel-based electricity and more importantly, equipped with insufficient driverless autonomy or connectivity that supports fuel-efficient travel (Kopelias et al., 2020). EVs would also likely generate battery waste pollutants when there is a high demand to use them for longer travel. Thus, it should be noted that human-driven EVs on their own might not directly lead to more sustainable transport per se.

4.2. Current policies

Policy interventions for enabling the success of alternatively fuelled vehicles are vital to promote the transition towards sustainable mobility (Banister, 2008; Silvia and Krause, 2016). On the one hand, governments should offer financial incentives based on consumer needs for EV adoption (Coffman, Bernstein, & Wee, 2017b; Wolf, Schröder, Neumann, & de Haan, 2015). On the other hand, the implementation of these decarbonisation-targeted policies should focus on the reduction of battery pollution generated from EVs (Zubi, Dufo-López, Carvalho, & Pasaoglu, 2018). EV-related investments dedicated to incentivisation, user-friendly legislative frameworks, pro-environmental education, marketability and cultural change need to support the transition from the combustion engine era to a new age (Nikitas et al., 2021a). For instance, public charging infrastructure can be a massive restraint disproportionally pushing people away from EVs (Wang, Fan, Sun, & Liu, 2023). These abovementioned studies suggest that an EV-enabling policy framework that can help, among others, to improve the availability and accessibility of charging infrastructure is required.

Both batteries and fast-charging facilities should be designed smartly so that the range and refuelling availability can be amplified for EVs (Haustein et al., 2021). Monetary incentives like rebates and tax alleviation can mitigate the unwillingness to purchase EVs (Broadbent, Allen, Wiedmann, & Metternicht, 2022). An effective measure for the EV uptake is to establish a zone that only opens to electrified fleets (Wolf et al., 2015). Sometimes planners in special geo-spatial conditions should utilise the advantages of their local eco-system to support the uptake of alternative fuelling. For example, for some islands where refuelling stations are covered adequately, range anxiety is a significantly lesser problem which can accelerate the implementation of electromobility as the mainstream (Kougias et al., 2020).

Despite these policy propositions, the use of the present-day EV fleets can lead to extra VMT and additional battery pollution (Nikitas et al., 2021a; Skeete, Wells, Dong, Heidrich, & Harper, 2020). Also, regulations that can help hydrogen refuelling stations to be more accessible are very scarce for now (Zhang et al., 2025). Furthermore, policy initiatives built around the adoption of biofuel-based or hybrid vehicles (i.e. bio-hydrogen-based fleets) are needed (Achtnicht et al., 2012; Chang et al., 2017), especially when the uptake of these non-fossil-fuel-powered fleets can help policymakers to escape from the conventional oil-based transport (Sánchez-Bastardo et al., 2021). The abovementioned studies convey an important message for the future of alternatively fuelled transport: alternative fuels need to play a transformative role, policy measures that motivate the public to change their travel behaviour should be designed and promoted adequately and alternative fuelling side-effect mitigation strategies should be identified and adopted.

5. Electric autonomous vehicles as an example of AFCAVs

5.1. Eco-friendliness and user-oriented advantages

Electric Autonomous Vehicles (EAVs) constitute the most well-studied AFCAV (Nikitas et al., 2021a) and that is why they are singled out in this section. They are perceived as a vehicle technology taking up the advantages of both vehicle automation and electrification in an interdependent way (Monios and Bergqvist, 2020; Zhuge & Wang, 2021). EAVs have the potential to facilitate eco-friendliness, since these vehicles can advance energy utilisation, mitigate range anxiety, and reduce transport pollution (Greenblatt & Saxena, 2015; Greenwald & Kornhauser, 2019; Guo et al., 2021). Some studies have employed the activity-based travel demand simulation to evaluate the dynamics of fuel-cycle GHG emissions. For instance, the vehicle automation and electrification combination can significantly help to reduce the intensities of GHG emissions (Wang et al., 2018). However, the study has focused on metropolitan areas and thus, did not explore the indirect effects of EAVs on the pollution reduction in suburban areas and villages. Also, compared to fossil-fuel-based human-driven vehicles, shared EAVs can lessen air pollutants and advance energy utilisation at the same time (Miao, Jia, Li, & Qiu, 2019; Rafael et al., 2020). This highlights the need of embracing electricity in shared CAVs if fostering greener transport futures is the goal of planning (Grahn, Qian, & Hendrickson, 2023; Nikitas et al., 2020).

Cost, according to the literature, is another crucial factor underpinning the adoption of shared EAVs (Webb et al., 2019). For instance, energy costs for the electric and autonomous taxis can be lower compared to traditional oil-based vehicles (Becker et al., 2020; Dlugosch, Brandt, & Neumann, 2022). Also, EAVs can help to improve travel comfort and would be easier to use compared to conventional fleets (Hardman, 2021; Madigan, Louw, Wilbrink, Schieben, & Merat, 2017). However, the existing research is yet to explore user demand towards EAVs; very few studies have specifically examined the life-cycle cost reduction potential of these vehicles by their use cases (i.e. private, public, and shared).

5.2. Adoption barriers

Many studies have discussed the barriers towards the adoption of EAVs (Wu et al., 2019). For instance, their battery can be damaged when exposed to very low or high temperatures (Jaguemont, Boulon, & Dube, 2016; Zhao, Zhang, Liu, & Gu, 2015). This may lead to extra pollutants that can affect the environmental performance of EAVs, and this could be a serious sustainability issue as there might be a possible VMT increase due to the uptake of vehicle automation (Hardman, 2021). However, this study has only studied partially AVs and not yet explored the abovementioned battery-related issues (i.e. vulnerability and travel pollution) affiliated to fully developed CAVs. There are also range anxiety issues specific to battery-based vehicles, since the availability of refuelling technology (e.g. wireless charging) is still low for now (Wang et al., 2023). This could affect the adoption of EAVs, especially when the demand for automated travel is high (Chen, Kockelman, & Hanna, 2016). Also, people might be unwilling to use EAVs or recommend the vehicle to others (Park, Kim, & Ohm, 2015); untested technologies even when they promise a wealth of benefits could be difficult to trust at least in an early transition phase (Tsigdinos et al., 2026). This possibly means that awareness-raising exercises and educational campaigns designed to inform people about the advantages and disadvantages of EAVs are needed.

Compared to other AFCAVs (i.e. hydrogen-powered CAVs and biofuel-based CAVs), EAVs (i.e. battery-based CAVs) that integrate the wireless refuelling and eco-driving functions would significantly advance travel efficiency (Kopelias et al., 2020; Yusuf et al., 2024). Also, hydrogen-based CAVs could be more unaffordable and bring more ethical issues compared to EAVs. This is because hydrogen fuel technologies are underdeveloped for now (Ajanovic & Haas, 2018; Zhang et al., 2025), and tehir use may result in responsibility distribution problems, i.e., being unclear about responsibility allocation in the aftermath of a safety-related incident caused by hydrogen-powered CAVs. At the same time, hydrogen-based fleets have greater potential to minimise transport emissions (Sánchez-Bastardo et al., 2021), when compared to ICE-based vehicles (Puškár, Živčák, Král, Kopas, & Lavčák, 2021). Furthermore, whilst some studies suggested that trust is a factor that underpins the adoption of EAVs like electric autonomous buses (Herrenkind, Brendel, Nastjuk, Greve, & Kolbe, 2019), there is limited research that has so far assessed the cost-benefit ratio for the potential uptake of hydrogen-powered or biofueled CAVs.

The literature so far conveys a message that although EAVs have pro-environmental, cost-reduction and ease of use benefits, the awareness about them and their potential acceptance are still low; people do not know much about the wealth of benefits that the combination of these two technologies may offer. Studies have explored the two different technologies (i.e. EVs and CAVs) mostly in an isolated fashion and not jointly; EAVs per se have not been studied extensively. So far there are insufficient policy frameworks designed around EAVs that can help to mitigate the barriers of their adoption, i.e., battery vulnerability, range anxiety, charger availability, behaviour shift, and extra VMT generation.

6. Synthesis of evidence: the elements defining a transition to AFCAVs

The study examined papers focusing on three key areas (i.e. CAVs, alternative fuelling, and EAVs) underpinning the corpus of research that is related to the AFCAV agenda. The evidence-based findings in our work imply that the success of AFCAVs requires the pro-active strategic delivery of a dynamic and systematic sustainability-centric regulatory framework. This indicates the need to consider together technology, regulation, education, and market interventions for the purpose of supporting pro-environmental automated transport (Nikitas et al., 2021a). However, the transition to a new radical regime (i.e. replacing fossil-fuel-based vehicles driven by people with alternatively fuelled vehicles that are connected and automated) is not a straightforward nor an uncomplicated process. Time, patience and careful design should underpin every step of the way. One approach to accelerate acceptance by building trust is to demonstrate that AFCAVs have the capability to lower energy and passenger travel costs altogether (Becker et al., 2020). Furthermore, it should be crucial to integrate AFCAVs, from a very early stage, with shared and even more importantly with public transport operations, since shared automated mobility must enable a new travel behaviour ethos and focus on the integration of the overall transport provision (Marletto, 2019).

We found that so far there is a research scarcity in the environmental

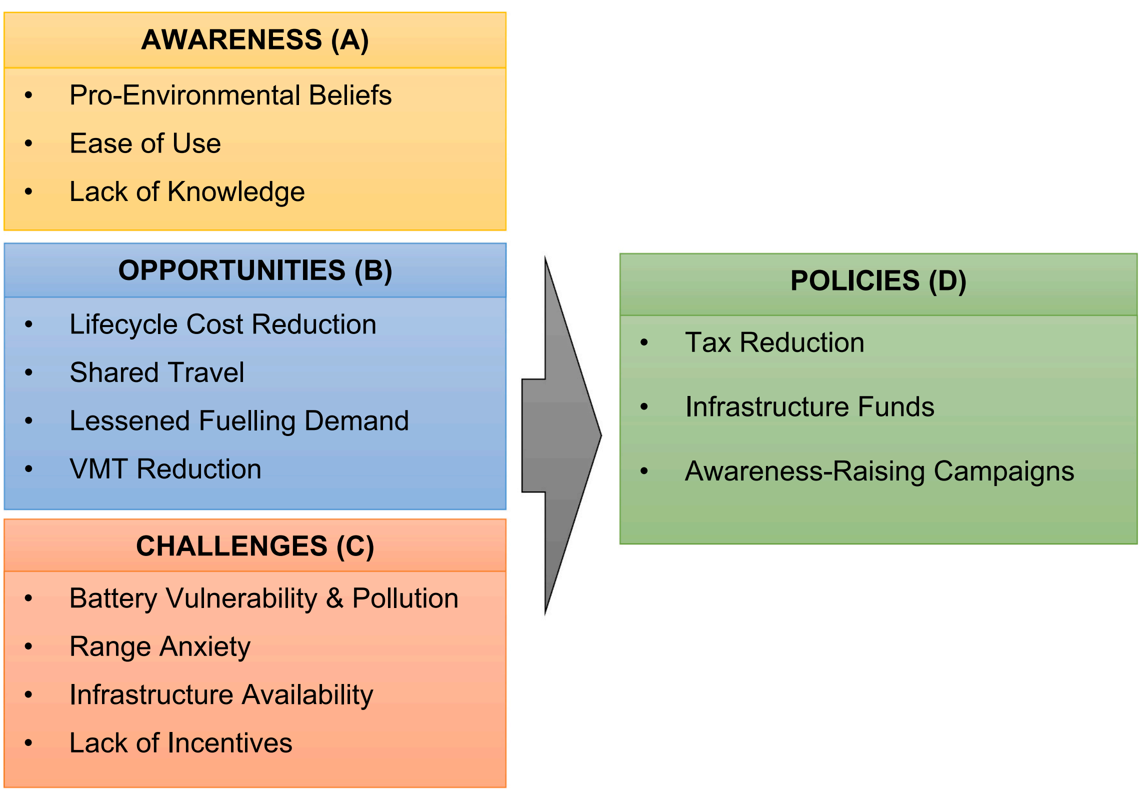

Fig. 2. A Conceptual Framework for the Elements underpinning AFCAVs.
(A) Awareness: Whilst pro-environmental beliefs and ease of use (i.e. the fact that one does not have to drive AFCAVs physically) are key indicators reflecting and affecting concept awareness, the public might have very insufficient knowledge about the benefits and potential risks of these vehicles in environmental, social and economic terms.
(B) Opportunities: A key opportunity refers to the potential reduction of life-cycle costs for AFCAVs. Also, these vehicles can be a key component of Mobility-as-a-Service (MaaS) or equivalent schemes. Shared AFCAVs will help to reduce refuelling demands, lower VMT, and mitigate resource-based barriers.
(C) Challenges: So far EVs, the present-day ancestor of AFCAVs, have insufficient refuelling infrastructure with a limited coverage, and at the same time their battery can be vulnerable to some temperatures (i.e. $<$-15 °C or $>$ 35 °C). These issues can create problems like range anxiety severities and extra pollution. Also, cost and legislative incentives are underdeveloped and not powerful or holistic enough to make a change.
(D) Policies: Whilst current studies have suggested some possible benefits and risks around the adoption and use of battery electricity in CAVs, so far there is almost no market-ready policy framework that could be adapted to the implementation of AFCAVs. Also, there is very limited research that has examined or came up with policies, to facilitate the adoption of other alternative fuels (i.e. hydrogen and biofuels) in CAVs. On top of that, policy initiatives for lessening the generation of extra VMT from AFCAVs and the side-effects that come with this likely increase are needed.

and social benefits of using AFCAVs and its potential risks. Also, almost no policy initiatives are available that can help to mitigate the issues and risks generated from these vehicles (e.g. range limitations, extra VMT generated, and battery use and disposal side-effects). Following the identification of these abovementioned gaps, we propose a conceptual framework in Fig. 2 referring to the awareness, challenges, opportunities, and policies underpinning the transition to AFCAVs.

7. Discussion and conclusions

7.1. Contributions

Vehicle automation and connectivity packaged with alternative fuels could facilitate the transition to more sustainable transport eco-systems. However, there are obstacles either already existing or soon to be generated from the integration of connected autonomy with alternative fuelling. Following a thematically constructed narrative review using a keyword-based search, our work primarily inspected research in automated and alternatively fuelled transport. Firstly, we found that pro-environmental beliefs and ease of use are for now the critical psychological factors that can underpin the intention to use AFCAVs. Secondly, we identified the opportunities (e.g. facilitating cost-saving, compatibility with shared mobility schemes and on-demand service provision) promoting the shift to AFCAVs. Thirdly, we analysed the challenges (i.e. insufficiency of refuelling infrastructure with limited coverage, battery vulnerability and pollution, lack of incentivisation, and range anxiety) restraining the transition towards AFCAVs. Finally, our work suggested that there is limited awareness around the likely merits and concerns underpinning AFCAVs and therefore we demonstrated the importance of awareness-raising initiatives like campaigning, consultation and educational activities. We also showed that the transition to AFCAVs can be possible through a systematic policy framework that helps to address issues like the generation of extra VMT (Nikitas et al., 2021a).

Our conceptual framework decodes the key elements and their distinctive expressions and dimensions underpinning AFCAVs. It has derived from current studies on both CAVs and alternative fuelling technologies. We tried to combine knowledge from these two worlds that is usually siloed introducing the umbrella term AFCAVs. We made an effort to re-evaluate the impacts of fossil-fuel-based CAVs, human-driven EVs and fuel cell vehicles. Our framework also offered some possible directions to further research underlining the need to identify and contextualise user perceptions on life-cycle costs and fuel range in relation to shared AFCAVs. We argue that for AFCAVs to be successful in environmental and societal terms their travel costs must be lowered, and they should be primarily integrated in shared mobility, public transit, and multimodal transport initiatives.

7.2. Policy implications

Our work identifies some policy initiatives that require the joint efforts from governments, automotive businesses, energy providers, AI business players and consumer group representatives for enabling the responsible implementation and use of AFCAVs. First, governments should offer incentivisation triggers (i.e. tax reduction) to lower travel costs for AFCAVs. For instance, policymakers should subsidise energy providers to develop local transport hubs that prioritise the renewable energy grids as the fuelling pathway to AFCAVs. This can allow for an energy cost reduction that facilitates the uptake of AFCAVs, especially in countries where the market share of fossil-fuel-based electricity is much higher (Logan, Nelson, Lu, & Hastings, 2020; Wang et al., 2023). Second, governments need to restrict the use of privately-owned AFCAVs and more importantly, prioritise the vehicle provision on a shared basis integrated with public transit and multimodal transport anchored by MaaS. To exemplify this, policymakers should legislate funding for transport providers to upgrade fast-refuelling facilities, V2X sensors, and safety protocols for shared travel only. However, legal incentive offerings should not be the only solution; the day-to-day implementation of AFCAVs also requires enterprise innovators (e.g. AI business partners) to analyse their operational requirements. Last, governments and transport providers should advance the understanding of the public towards the long-term merits and potential risks of AFCAVs. For example, policymakers and automotive businesses should offer engagement sessions, awareness campaigns, interactive workshops, trial opportunities and dynamic two-way consultation exercises that will help the public to understand better and also voice their concerns about this new vehicle technology.

7.3. Reflections and limitations

Our research has, similarly with any other social science research, some limitations that we acknowledge. This is not a primary data study that could produce entirely new insights. Our future work will employ a mixed method approach to address some of the knowledge gaps we identified herein. Our literature review study might have missed some research because for our article selection we basically used vehicle-related keywords (e.g. *Connected and Autonomous Vehicles*, *Electric Vehicles*, and *Electric Autonomous Vehicles*) and not more generic ones (e.g. *Automated Transport* or *Autonomous Mobility*). This was a measured choice to minimise the number of articles examined; any other keyword selection approach would lead to a lot more articles to be reviewed many of which would certainly be outside the scope of the work. We also relied greatly on our criteria for article selection (i.e. subject relevance) which some could suggest that may be too broad for a literature review study (Meline, 2006). Also, some analyst bias in the way themes have been interpreted should be unavoidable as in any literature review or qualitative study (Knowles, Ferbrache, & Nikitas, 2020). Furthermore, we believe that neither CAVs nor AFCAVs can alone make a monumental difference to the future transport landscape, since a vehicle-oriented system can never be a panacea in sustainability terms (Thomopoulos & Nikitas, 2019). Human-centric and place-based solutions that revolve around active transport, telecommuting and travel demand measures designed to reduce car usage and ownership are equally pivotal.

7.4. Future research directions

Our work informs the design of future research that could possibly validate, expand, and further contextualise our AFCAV framework. Future research needs to inform stakeholders responsible for the transition to transport futures (i.e. governments, transport providers, and local authorities), on how to practically facilitate a more sustainability-led implementation of AFCAVs. Also, future studies should analyse the factors underpinning AFCAV adoption looking for answers first from experts that have the necessary know-how to project how these factors will unfold and then from the general public that will be the users (or non-users) of these intelligent vehicle fleets through interviews and surveys. Furthermore, there is a need to consider geo-spatial and cultural differences in the uptake of these vehicles (i.e. how would populations with different culture backgrounds and socio-demographics perceive AFCAVs?). Our continuation work consists of an elite interview study with AFCAV-relevant experts and a survey-based study that examines AFCAV attitudes by the general public in the UK and China.

CRediT authorship contribution statement

Zimu Zhang: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Kalliopi Michalakopoulou:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis. **Georgios Nikitas:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis. **Na Liu:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis. **Alexandros Nikitas:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

None.

Data availability

No data was used for the research described in the article.

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