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The Environmental and Resource Dimensions of Automated Transport: A Nexus for Enabling Vehicle Automation to Support Sustainable Urban Mobility

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Abstract

Automation carries paradigm-shifting potential for urban transport and has critical sustainability dimensions for the future of our cities. This article examines the diverse environmental and energy-related dimensions of automated mobility at the city level by reviewing an emerging and increasingly diversified volume of literature for road, rail, water, and air passenger transport. The multimodal nature of this investigation provides the opportunity for a novel contribution that adds value to the literature in four distinctive ways. It reviews from a sustainability angle the state of the art underpinning the transition to a paradigm of automated mobility, identifies current knowledge gaps highlighting the scarcity of non-technical

research outside the autonomous car's realm, articulates future directions for research and policy development, and proposes a conceptual model that contextualizes the automation-connectivity-electrification-sharing-multimodality nexus as the only way forward for vehicle automation to reach its pro-environmental and resource-saving potential.

Contents

1. INTRODUCTION

Automation is a powerful yet disruptive technology. It is still in its infancy, with the potential, if used responsibly, to transform road, rail, air, and water transport in an unprecedented way (1–5). Automation will empower machines to take over the role of the "driver" and provide solutions to mobility problems that, if solved, could reform urban landscapes, as known for decades now, and help establish a new era—the era of the smart city (6). This paradigm transition will expand eventually, when this is financially viable from an infrastructure investment perspective, to less urban contexts.

Smart city: a city that embraces an integrated brand of autonomous, connected, shared, digital, and cloud-based technologies to enable more sustainable, creative, informed, cost-efficient, and people-focused operations

Adopting automated mobility is a transition often linked with key environmental, economic, and social benefits (e.g., 1, 7–16). Automated mobility, in theory at least, could improve accident prevention rates, accessibility, in-vehicle riding experience, and vehicle-sharing business models as well as help reduce road traffic congestion and social exclusion for those currently unable to drive (6–9). But more importantly for the specific context of this review, automated mobility has also the potential, under certain conditions, to lessen air pollution, environmental degradation, and energy consumption (1, 6). Despite its immense potential for positive change, automated mobility if not thoughtfully planned and provided could instead generate serious challenges (17) that include, according to the relevant bibliography (e.g., 6, 12, 16), increased vulnerability to hacking; software and hardware flaws; privacy loss and travel data exploitation; liability allocation challenges; elevated traffic accident and congestion rates, especially during the transition period when automated vehicles could coexist with less sophisticated autonomous, semi-autonomous, and conventional vehicles; behavioral adaptation, situational awareness, and user resistance problems; and labor market disruption and skills reform. But more importantly for the context of this review,

vehicle automation could lead to a rise in emissions and resource overconsumption, as elaborated in Section 7, that could be generated from a potential increased usage of car-based transport in terms of frequency and longer distance for more populations (e.g., people currently unable to drive or have access to an automobile) and empty-running vehicles.

Thus, the transition to a primarily automated urban mobility paradigm that will substitute a transport system, currently contributing ~15% globally to climate-changing gases (18), is clearly tied to a plethora of new unprecedented environmental opportunities and challenges. The scope of the work is to examine these sustainability-centric dimensions of automation for all modes of passenger transport that are projected to be available within cities, including road, rail, air, and water mobility alternatives. The study refers specifically to high and full automation levels. Because autonomous vehicle (AV) systems can improve transport system operations substantially only when they are packaged together with connected vehicle systems (2, 19), this review considers connectivity as a key function underpinning vehicle automation, although these two do not necessarily presuppose each other from a pure technological viewpoint (6). Logistics and long-distance travel are out of our scope, given that they embed extra layers of diversity and problematization requiring a different focus.

The literature review research objectives of this work are set to develop a theoretical and empirical understanding of the following:

1. the environmental and energy-related opportunities and challenges that underpin the full-scale launch of automated urban passenger transport;
2. the factors affecting environmental and resource consumption performance of automated mobility;
3. the nexus of vehicle automation, connectivity, electrification, and sharing and its consequences in the process of transitioning to a more sustainable and holistic transport regime.

The remainder of the review is as follows. Section 2 provides a systematic description of our literature review's research design framework. Section 3 introduces research on automated road transport. Section 4 covers autonomous rail transport, Section 5 autonomous air transport, and Section 6 autonomous water transport, reflecting an emerging but still limited body of literature discussing these agendas. Section 7 is a theorization and contextualization section that offers a conceptual framework showing how multimodal automated transport at the city level underpins environmental sustainability and energy consumption highlighting its technology, market, policy, educational, and legislative dimensions. It also provides relevant policy recommendations. Finally, Section 8 highlights the contribution of this study in the contextualization of problems and opportunities linked with decarbonizing urban vehicle automation and generates new timely research questions.

Levels of automation for autonomous vehicles: the Society of Automotive Engineers' six levels of autonomy: 0, no autonomy; 1, driver assistance; 2, partial automation; 3, conditional automation; 4, high automation; and 5, full automation; the study refers to levels 4 and 5

Autonomous vehicle (AV): a vehicle able to understand its surroundings, move, navigate, and behave responsibly without human input

2. METHODOLOGY

This is a thematically organized narrative review. For consistency and quality control reasons, it follows the article selection and search strategy principles of a systematic literature review (20) examining the peer-reviewed literature published on the environmental repercussions of automated urban mobility for all modes of people travel. However, it goes above and beyond this methodological paradigm to ensure that a holistic coverage is provided.

Our review focuses primarily on Scopus-listed academic journal articles written in English to ensure a minimum level of quality, while limiting the number of articles to be reviewed in the case of prolific research fields such as automated transport. We also cite publications including gray literature outside this strict search spectrum, especially in cases where no or a limited number of

Table 1 Scopus searches underpinning the review[a]

Keyword combinations in academic literature searches	Number of journal articles		
	Initial search	Passing screening	Articles included in the review
Autonomous[b] vehicles AND Environment AND City	117	45	38
Autonomous vehicles AND Environment AND Urban	387	193	68
Automated mobility[c] AND Environment AND City	24	10	8
Automated mobility AND Environment AND Urban	37	18	23
Autonomous cars AND Environment AND City	38	15	10
Autonomous cars AND Environment AND Urban	105	34	19
Autonomous buses AND Environment AND City	4	4	4
Autonomous buses AND Environment AND Urban	6	6	6
Autonomous rail AND Environment AND City	1	1	1
Autonomous rail AND Environment AND Urban	3	2	2
Autonomous tram AND Environment AND City	2	1	1
Autonomous tram AND Environment AND Urban	3	1	1
Autonomous metro AND Environment AND City	1	1	1
Autonomous metro AND Environment AND City	2	1	1
Personal aerial vehicles AND Environment AND City	4	3	3
Personal aerial vehicles AND Environment AND Urban	11	8	8
Autonomous boat AND Environment AND City	0	0	0
Autonomous boat AND Environment AND Urban	2	2	2
Autonomous vessel AND Environment AND City	1	1	1
Autonomous vessel AND Environment AND Urban	3	2	2

[a]The table was last updated on May 5, 2021.
[b]The searches yielded similar results whether using the keyword Autonomous or Automated.
[c]When a term defining more closely mobility was used, such as Personal, Human, People, or Passenger, each of the new searches returned significantly fewer articles, and for a few combinations the return was actually zero.

peer-reviewed articles were available; this broader perspective alone makes this work a narrative literature review and not a strict systematic one.

Numerous searches were undertaken using the Scopus database. Although, we did not confine our literature search in terms of publication year, most of the papers identified (>98%) were published during the past decade. Some searches overlapped (e.g., the results of those using the term City were also coming up when using the term Urban). **Table 1** provides a synopsis of these searches that defined the narrative of the review. The academic material was selected on the basis of the subject-specific relevancy and recency of the research output, the host journal impact factor, and each article's impact as measured by the number of its citations (as a proxy for some older articles); this is a stratified selection process with a clear rationale proposed by best-practices literature (21). Although we acknowledge an element of subjective criteria in the choice of material (selections bias is human nature), this was a methodical process designed to reduce bias and enhance the richness, diversity, and depth of the content. The present approach is comparable with the literature review framework that was used for some of our previous work (6, 22).

In the end, we read approximately 1,050 titles of articles, reports, and other sources identified by our search process. Many of the results were not relevant, as they were very technical or did not cover environmental and resource implications to any reasonable degree. In our initial screening we reviewed more than 400 abstracts that were relatively relevant to the scope of the present

work. Our narrative literature review is based on those sources that were genuinely in line with the environmental focus of the analysis. Our article cites altogether 132 studies.

3. ENVIRONMENTAL AND RESOURCE IMPLICATIONS OF AUTOMATED ROAD TRANSPORT

3.1. Connected and Autonomous Vehicles

Connected and autonomous vehicle (CAV): a vehicle able to understand its surroundings, move, navigate, and behave responsibly without human input and at the same time have connectivity functions enabling it to be proactive, cooperative, well-informed, and coordinated

The predominant manifestation of automated mobility reflects road transportation advancements and, in particular, the driverless decedent of the human-driven, uncoordinated, privately owned and used, conventionally fueled vehicle. Connected and autonomous vehicles (CAVs) are vehicles able to understand their surroundings, move, navigate, and behave responsibly without human input (thus being autonomous or automated; see the sidebar titled Automated Versus Autonomous Vehicles) and at the same time have connectivity functions enabling them to be proactive, cooperative, well-informed, and coordinated (6). Most of the literature reviewed tends to narrow down CAVs and AVs to car-equivalents; however, different automated travel modes (that are typically described in the literature with different terms) can be also classified as such. CAVs have evolved to a focal point of current transport studies since autonomous driving has gone from "may be possible" to "inevitable," opening a window of opportunity not only for safer and more relaxed travel but also for travel that may promote and be in sync with sustainable development and environmental preservation principles (23).

Specifically, the launch of CAVs could have major implications for car ownership, road traffic congestion, vehicle miles traveled (VMT), pollutant emissions, and energy consumption, but its repercussions for climate change mitigation are highly uncertain due to competing mechanisms whose magnitudes are difficult to estimate (24). CAVs have the potential in theory to facilitate unprecedented levels of eco-efficiency and function optimization (e.g., eco-driving and platoon-based cooperation), radically reducing the transport sector's adverse energy and environmental impacts (9, 12, 13), especially when programmed to operate aggressively (i.e., drive closer together) on expressways; this could lead to emission reductions by up to 26% (25). However, depending on consumer choices (26), the shared or private provision of CAV services (27), the adoption (or non-adoption) of electric and hybrid power sources to operate CAVs (28), and how these vehicles are programmed (25) could instead result in a net increase in energy consumption and environmental pollution.

This section is the longest, given that 90% of the literature on automated mobility and environmental impacts as of now concentrates on CAVs as a car-equivalent replacement. The subsections

AUTOMATED VERSUS AUTONOMOUS VEHICLES

On the one hand, an automated system typically operates within a well-defined set of rules in a reasonably stable environment, and its decisions made or actions taken are based on predefined heuristics. On the other hand, an autonomous system learns and adapts to dynamic environments and evolves as the environment around it changes; it is a system that in principle has potential for self-governance and self-directed behavior. A vehicle with autonomous technology is automated, but unless it is driverless, it is not really autonomous. An autonomous vehicle with full driverless capacity that does not make the decisions itself (e.g., pick the trip destination autonomously) and follows rule-based norms and traveler preferences actually operates as an automated vehicle. This article views automated and autonomous vehicles as a continuum and appreciates that although the terms could be considered different, they have, for the time being and for the purpose of urban passenger mobility, very similar meanings.

detail the power provision, fleet ownership, and usage dimensions of CAVs that are pivotal for their future environmental impact.

Shared autonomous vehicle (SAV): an autonomous vehicle providing shared on-demand services that replaces self-owned personal-vehicle travel

3.1.1. No consensus yet about the environmental impact of autonomous vehicles. CAVs are projected to impact the total greenhouse gas (GHG) emissions through their potential to reduce vehicle ownership, to increase vehicle use intensity, to change the vehicle fuel consumption rate, to popularize ride-sharing, and to eco-drive (i.e., to optimize braking, acceleration and deceleration, keep steady speed in low revolutions, shift gears early). Pourrahmani et al. (29), using as their case study a full-scale penetration of CAVs in the San Francisco Bay Area, estimated a 10% increase in car travel mileage (i.e., more people using a car more often for longer distances) and an 11% decrease in walk/bicycle trip mode share as well as significant emission reduction by several CAV-enabled mechanisms such as eco-driving [more than 30% carbon dioxide (CO_2) emission reduction], engine performance adjustment (over 20% CO_2 emission reduction), and platooning (i.e., road space use optimization). Moore et al. (30) predict a substantial extent of urban sprawl due to CAVs, potentially up to a 68% increase in the horizontal spread of cities, unless proactive planning and policies are implemented to avert such consequences. These impacts are mostly internally offset such that the overall impact of AV deployment on GHG emissions is not significant in the near- to mid-term. With a higher AV penetration rate achieved, a net reduction in GHG emissions may be possible, but this suggestion should be treated with caution given that the fuel economy levels of AVs are highly uncertain and cause major uncertainties in any simulation results used to project the future (31).

Using elasticities to simulate VMT and energy use impacts of full, private CAV adoption under a range of possible changes to the fuel and time costs of travel, Taiebat et al. (27) forecast a 2–47% increase in travel demand for an average US household. Light-duty VMT in the United States could increase by as much as 14% with nondrivers being responsible for approximately 9% of this increase (32). These results, however, indicate that backfire (i.e., a net rise in energy use) is a possibility, especially in higher income groups, presenting a challenge to policy goals for reductions in not only energy use but also traffic congestion and local and global air pollution, as CAV use increases (27).

A study examining the interactions between CAV technology and the environment at four levels of increasing complexity—vehicle, transportation system, urban system, and society—found that environmental impacts derive from CAV-facilitated transformations at all four levels, rather than from CAV technology per se (33). The study projects net-positive environmental impacts at the vehicle, transportation system, and urban system levels, but expects greater vehicle utilization and shifts in travel patterns at the society level to offset some of these benefits unless future vehicle technology becomes a game-changer (33). Nonetheless, a new ethos of sharing-oriented services and alternatively fuel use can be the key pro-environmental directions that will yield sustainability benefits.

3.1.2. Shared autonomous vehicles. Vehicle automation will enable the emergence of novel business models such as shared autonomous vehicles (SAVs), which could provide, in theory at least, inexpensive on-demand mobility services that could reduce traffic, if used responsibly and not as a modal shift generator that will steer people away from public and active transport (34). In that sense, the on-demand function of SAVs may be as definitive for their overall role when it comes to their environmental and resource consumption footprint as automation itself, given that, according to Fagnant & Kockelman (35), by making people share rides SAVs may save 10 times the number of cars needed for self-owned personal-vehicle travel. In other words, combining on-demand mobility and AVs may amplify adoption of both and further lower energy use and GHG emissions through the use of small, efficient shared AVs (36).

Based on booking time frame, SAV services can be divided into on-demand (the customers can book vehicles in real time), reservation-based (booked in advance), and mixed systems and based on the type of sharing could be classified into car-sharing, ride-sharing, and mixed systems (37). The philosophy behind SAVs is that users must accept sharing rides even with unfamiliar others (38). Business models, travel behavior, public policy, and their expected penetration rates may determine how SAV impacts unfold (39) and how these affect the environment.

Many favorable future scenarios suggest that SAVs could lessen to a significant degree GHG emissions by improving fuel efficiency, alleviating congestion, facilitating the diffusion of alternative fuel vehicles, matching vehicle sizes to trip requirements, and reducing parking needs, among others (23, 40, 41). For instance, Martinez & Viegas's (42) simulation for Lisbon, Portugal, showed that a system based on SAVs and self-driving taxi-buses could reduce carbon emissions by 40% and vehicle mileage by 30%. More pessimistic projections, however, predict that SAVs have also the potential to be counterproductive and instead increase GHG emissions by reducing the cost of travel (i.e., cheaper car travel automatically becomes more accessible and attractive), allowing nondrivers and "zombie cars" traveling autonomously—and empty—around urban roads as they return to depot or perform other tasks to expand the number of VMT (23, 43). A recent work (44) studying SAVs, based on a four-stage Delphi study with 40 international experts in future mobility, reports that sustainability is of secondary importance for key stakeholders when compared with technological aspects, consumer acceptance considerations, and legislative concerns.

Fagnant & Kockelman's (35) preliminary forecasting results predict that each SAV could replace up to eleven conventional vehicles but may add up to 10% more travel distance than comparable non-SAV trips due to relocation issues and by allowing more people to travel more often for longer distances. The study concluded that a SAV-centered transition will probably deliver beneficial emissions impacts, once fleet-efficiency changes and embodied versus in-use emissions are assessed. Assuming that the travel patterns do not change significantly in the future, Gurumurthy & Kockelman (45) suggest significant opportunities for dynamic ride sharing–enabled SAVs; nearly 60% of the single-person trips could be shared with other individuals traveling solo and with less than 5 minutes of added travel time (to arrive at their destinations), and this value climbs to 80% for 15 to 30 minutes of added wait or travel time.

One of the clearest pathways to expand on the possible environmental benefits of a SAV fleet is through electric vehicles (EVs), which tend to be more energy efficient, more reliable, quicker, and may reduce system-wide emissions when coupled with renewable power (46).

Electric vehicle (EV): a vehicle powered by electric rechargeable batteries; demand for EVs is still very low

Autonomous electric vehicle (AEV): a vehicle that is autonomous and electrified at the same time

3.1.3. Electric autonomous vehicles. Although the vocabulary of automation includes terms such as CAVs and AVs that refer to the way a vehicle's course is controlled, other terms like plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), or hybrid electric vehicles (HEVs) refer to the way the vehicle is powered (47). EVs is the generic umbrella term that describes all the vehicles that are powered by electric rechargeable batteries. EVs do not cause any direct CO_2 emissions during operation and reduce fuel costs and radiated noise, but their high purchase costs, despite carbon-related tax exemptions, and range anxiety issues (i.e., concerns about the EV's battery independence without regular charging), hinder for now at least their wider uptake (9). EVs are the closest like-for-like future substitute for current mainstream consumption practices based on car use (48) and by reducing oil dependence have the potential to generate significant road traffic emission reduction benefits (49).

Their integration with AVs, i.e., the autonomous electric vehicles (AEVs), is projected to sustain future transport while their pro-environmental profile may be a key stimulus that could influence their adoption (50). Weiss et al. (51) make the case that automation can be seen as an accelerator of electrification, and the introduction of CAVs may establish the transition to electrified transport.

Life cycle assessment (LCA): a methodology for evaluating environmental impacts associated with all the stages of the life cycle of a product, process, or service

Internal combustion engine vehicle (ICEV): a vehicle with a heat engine that burns fossil fuels (i.e., petrol, gasoline), makes up more than 90% of the world's total vehicle fleet, and produces air pollution emissions

Shared autonomous electric vehicle (SAEV): an autonomous electric vehicle that provides shared on-demand travel services

Annema (52) also suggests that the potential accelerating role of AVs in relation to the uptake of EVs might have the largest positive impacts on the CO_2 emissions per kilometer driven. However, this accelerating role of AV technology in relation to the uptake of EVs is still uncertain.

The results of a life cycle assessment (LCA) of level-4 CAV sensing and computing subsystems integrated into internal combustion engine vehicle (ICEV) and BEV platforms indicate that CAV subsystems could increase vehicle primary energy use and GHG emissions by 3–20% due to increases in power consumption, weight, drag, and data transmission (53). However, when potential operational effects of AEVs are included (e.g., eco-driving, platooning, and intersection connectivity), the net result is up to a 9% reduction in energy and GHG emissions in the base case (54).

Patella et al. (28) developed an integrated approach to evaluate life cycle GHG emissions of AVs in urban areas by simulating the impact of a full AV penetration scenario on a real road network (that of Rome). AEVs show a higher life cycle impact due to battery replacement—on average, 35% compared to conventional ICEVs, 22% compared to HEVs, and 5% compared to BEVs. The lithium-ion battery life cycle (production, intervention of replacement, and end-of-life treatment) was highlighted as an issue, with a contribution of 0.033 kg CO_2eq/km (approximately 30% of the whole impact at the vehicle level). The study nevertheless indicates that the 100% AV penetration scenario generates a reduction of the environmental impact at the mobility system level of approximately 60% (28).

Wang et al. (54) presented a fuel-cycle GHG emissions model for the Greater Toronto and Hamilton Area to evaluate different shares of AVs and the environmental effects of their electrification. Daily operating GHG emissions were estimated at 29,000 t in CO_2eq, with 96% attributed to private vehicles. When accounting for fuel-cycle emissions, the daily total was estimated to be more than 36,000 t for private vehicles. With the introduction of AVs, higher VMT (3.6%–5.4%) and GHG emissions (2.5%) were reported but with their electrification regional GHG emissions were reduced by 5%, and emission intensities of all vehicles by 11% (54).

Finally, Rafael et al. (55) considered the air pollutants nitrogen oxides (NO_x) and CO_2 in three scenarios: (*a*) a baseline scenario; (*b*) an autonomous scenario, assuming an AV market penetration rate of 30%; and (*c*) an electric autonomous scenario, taking into account that those 30% of AVs are pure battery electric cars. The autonomous scenario promoted an increase of both NO_x (+1.8%) and CO_2 (+0.7%) emissions, whereas the electric autonomous scenario resulted in emission reductions of approximately 30% for both air pollutants (55).

3.1.4. Shared autonomous electric vehicles. There are natural synergies between SAV fleets and EV technology, given that fleets of CAVs resolve the practical limitations of today's nonautonomous EVs, including traveler range anxiety, access to charging infrastructure, and charging time management. Fleet-managed AVs relieve such concerns, managing range and charging activities based on real-time trip demand and established charging-station locations (56). According to simulation experiments, shared autonomous electric vehicles (SAEVs) could provide comparable (if not improved) service to travelers with cost savings and overall reduced VMT compared to private vehicle ownership (57).

Using taxi-trip data from New York City, Bauer et al. (58) developed an agent-based model to predict the battery range and charging infrastructure requirements of a fleet of SAEVs operating on Manhattan Island and a model to estimate the cost and environmental impact of providing this service. A SAEV fleet drawing power from the current NYC power grid would reduce GHG emissions by 73% and energy consumption by 58% compared to an automated fleet of ICEVs and provide more inexpensive dollars-per-mile services (58). Loeb et al. (59) reported that reducing charging times and increasing the SAEV fleet size lowers service response times (to trip requests); each SAEV in this study could service approximately 27 trips per day with 489 miles of daily

average travel. Unoccupied travel accounted for 19.6% of SAEV mileage on average, with driving to charging stations accounting for 31.5% of this empty-vehicle mileage (59).

With a SAEV fleet's rollout to the market, the electricity consumed by the fleet will have significant impacts on energy demand and, in turn, drive variation in energy cost and reliability, especially if the charging is unmanaged, hence the need for research, development, and investments on smart charging infrastructure and resource management (60). SAEVs have the potential, however, to serve a key role in optimized energy management strategies, given that they represent an important opportunity for adding significant storage to the grid in a time when intermittent renewable energy penetration is rising. If correctly managed, SAEVs can offer grid-scale load shifting, peak saving, and ancillary services enabling a higher renewable energy penetration and a more resilient electric grid (61).

A case study of SAEVs in Austin, Texas (62), looking at a timeline from 2020 to 2050 with constant travel demand, indicates that the strategic deployment of a SAEV fleet can reduce cumulative energy and GHG emissions by 60% in the base case, with a majority of this benefit resulting from electrification. Further reductions up to 87% can be achieved with accelerated electrical grid decarbonization, dynamic ride-share, longer vehicle lifetime, more energy-efficient computer systems, and faster fuel efficiency improvements for new vehicles (62).

3.1.5. Internal combustion engine connected and autonomous vehicles. Although battery-powered electric and hybrid-electric AVs may eventually enjoy more widespread use than conventional AVs (63), energy management is harder and more significant for conventional AVs (64). Practically, an ICEV fully utilizes less than a third of the energy produced by its engine (i.e., approximately 75% of energy being wasted in each car) something that cumulatively results in a significant amount of energy loss in total across the global fleet of passenger vehicles (64). These losses are significant enough to impact global energy demands, hence the need for resetting fuel economy benchmarks and the need for vehicle manufacturers and researchers to investigate new technologies to enhance fuel economy and minimize emissions (65). Results show that the intelligent energy management system in AV fleets could reduce the vehicle energy consumption up to 7% (64).

Chen et al. (66) evaluated fuel consumption impacts of AVs in the United States. The proposed data-rich analytical framework considers dynamics in fleet turnover and fuel efficiency and utilized a network activity database containing detailed information of national road links. Impacts of automation on fuel consumption are quite wide-ranging according to the authors with the potential to reduce fuel consumption by 45% in the optimistic case or increase it by 30% in the pessimistic case. The study also concludes that automation on urban roads has larger potential on fuel savings than highway automation (66).

Mersky & Samaras (67) developed a method to incorporate the impacts of AV technology within the bounds of current fuel economy testing and simulated a range of automated following drive cycles to estimate changes in fuel economy. The study shows that AV algorithms designed without considering efficiency can degrade fuel economy by up to 3%, whereas efficiency-focused control strategies may equal or slightly exceed the existing US Environmental Protection Agency's fuel economy test results, by up to 10% (67). This suggests the need for a new near-term approach in fuel economy testing to account for CAVs.

With regard to the impacts of the internal combustion engine autonomous vehicle (ICEAV), two key parameters that need to be discussed are air quality and pollutant emissions. Today approximately 91% of the world's population lives in areas exceeding the World Health Organization guidelines for healthy air of 10 μg/m3 PM2.5 per year (68, 69). This means that air pollution, for which ICEVs are already a major source and which has evolved to a global leading risk factor

for public health (70), may become even worse if ICEAVs become the mainstream option for AV services (71).

Papantoniou et al. (72) developed five simulation scenarios, including different percentages of automated and human-driven vehicles (0%, 25%, 50%, 75%, and 100% of AVs), investigating NO_x and CO emissions in each scenario. Results indicate that conventionally fueled AVs both in mixed traffic and as the sole vehicle option (i.e., 100% penetration) produce more NO_x emissions in comparison with the scenario of 100% human drivers (72); AVs have the poorest performance in terms of average speed and flow and generate the highest emission values per kilometer. Similarly, the production of CO indicates that mixed traffic of AVs and human drivers leads to higher emissions than the unique existence of one driving behavior. This is probably because with mixed traffic, the "perfect" behavior of AVs is not familiar to human drivers and as a result leads to more conflicts and consequently more vehicle emissions due to the aggressiveness of the conflict events (73).

Stern et al. (74) examined the potential reduction of vehicular emissions caused by the whole traffic stream, when a small number of AVs (5% of the vehicle fleet) are designed to stabilize the traffic flow and dampen stop-and-go waves. The researchers used vehicle velocity and acceleration data from a series of field experiments that use a single autonomous-capable vehicle to dampen traffic waves on a circular ring road with 20 human-piloted vehicles. Vehicle emissions (hydrocarbons, CO, CO_2, and NO_x) of the entire fleet may be reduced by between 15% (for CO_2) and 73% (for NO_x) when stop-and-go waves are reduced or eliminated by the dampening action of the AV in the flow of human drivers (74). Therefore, in theory, it is possible by using a small fraction (5%) of AVs to actively dampen traffic waves and as a consequence reduce air pollution. However, lower reductions in emissions may be realized from a deployment of AVs in a broader range of traffic conditions (74).

Another study (75) implemented three different AV penetration rates for through traffic along a freeway corridor in the city of Porto (Portugal) by considering long-term market predictions (10%, 20%, and 30%). These scenarios were compared to the current situation in terms of CO_2, CO, NO_x, and hydrocarbon emissions; travel time; and stop-and-go situations. The emissions and traffic performance of each scenario were evaluated on three levels: (*a*) overall study domain, (*b*) corridor, and (*c*) impact of AVs on conventional vehicles. AVs yielded small savings in emissions in the overall study domain for automation levels below 30%. Corridor-level analysis showed that AV technology leads to 5% decreases in emissions and travel time penalties of up to 13% for AVs and conventional vehicles, when compared to the existing situation (75).

3.2. Autonomous Buses

Literature during the past decade has focused almost exclusively on personal or shared cars. Yet, lately the autonomy of other road transport modes and particularly of buses started to emerge as an important topic for the future of mobility services (76). The research on autonomous buses (ABs) thus far has been focusing mainly on five themes: (*a*) technology development, (*b*) user acceptance, (*c*) safety, (*d*) socioeconomic aspects, and (*e*) legislation and policy issues. There is limited research to date focusing on the environmental implications of ABs per se, with the most recent being Zhang et al.'s (77). This paper suggests that CAV technology in buses can reduce exhaust emissions and save energy, especially when incorporated in a transport system that employs a managed and priority lane strategy.

One relevant development direction for ABs that has been reported frequently describes the need for a universal shift toward buses that are supported by both electrification and automation, as a means of increasing the energy efficiency of mobility services (78). The Autonomous Electric Bus (AEB) combines both autonomous driving efficiency and an eco-friendly powertrain. AEBs

offer potential for reduced environmental pollution, heat generation, and noise pollution due to the use of electricity, while providing several seats that allow travelers to share their rides with others, thus reducing the total number of vehicles needed (79).

The size and use of the buses could influence their environmental performance. Automated shuttles (or pods) that are now in a prototyping phase in various projects around the world (80) may be a more car-like substitute moving 8–10 people at a time. These minibuses could facilitate first-/last-mile neighborhood feeder AB services that can contribute more environmental gains than any type of AVs (81). The final trend with critical environmental implications is the gradual shift toward higher AB service frequency and the need for extra infrastructure to support this transition (82).

Mobility-as-a-Service (MaaS): a system that offers multimodal packages of personalized mobility replacing privately owned vehicles through the use of an all-in-one digital platform that integrates journey planning, booking, smart ticketing, and real-time information services on a subscription or "pay-as-you-go" basis

4. ENVIRONMENTAL AND RESOURCE IMPLICATIONS OF AUTOMATED RAIL TRANSPORT

Rail industry has been the first one to test and implement automated transport in city-level applications (83). Such automated options have existed for decades for both urban and interurban rail services. They include light rail and underground services, following the Automatic Train Operation feature introduction in the London Underground Victoria Line in 1967. There are five Grades of Automation (GOA) for rail services: GOA 0: manual operation with no automatic train protection; GOA 1: manual operation with automatic train protection; GOA 2: semi-automatic train operation; GOA 3: driverless train operation; GOA 4: unattended train operation. Yet, automation has not been fully realized due to the inherent difficulties and risks to handle unexpected situations or incidents (84). Due to rail network complexities and legal requirements, it is not anticipated that full automation with no train driver or attendant is envisaged universally in the near future.

Automated rail transport has not led to significant environmental benefits other than eco-driving, which has certainly made a positive contribution. This impact is an outcome of both the increased demand for rail services worldwide over the past century and the intertwined need for rail infrastructure. Given the low emissions of this mode (85), automation of rail services contributes to reducing the negative environmental externalities of urban transport, particularly from a network perspective (86). Electrification and automated charging of carriages has the potential to further lower the environmental footprint of rail transport, especially where electricity provision is based on renewable energy (87).

However, the wider introduction of automated transport options within cities may have a negative impact (6%) on light rail use due to travelers preferring car-centric options such as SAVs. Similarly, the availability of other automated transport services is anticipated to have a negative impact on urban journeys to and from airports due to increased competition (88). Other experts have also alluded to similar outcomes and reduced rail service demand (33).

Essentially, modal shift generated by a reduction in urban rail ridership demand could be damaging in sustainability terms from a network perspective, given that the per-passenger environmental implications of individual (e.g., private car) transport options are considerably higher. Additionally, lower utilization and maintenance levels of rail infrastructure will further increase the negative implications on the environment.

Nonetheless, the overall environmental implications and their respective time frames will not be known unless there is reliable data available about the alternative mode being used instead of rail, as has been illustrated by a study of US urban rail systems (89). Despite its contemporary uncertainties (90), Mobility-as-a-Service (MaaS), a system aimed at replacing private cars with app-based personalized mobility packages integrating public, active, and taxi-like transport, stands out as a contender to introduce rail services in automated transport systems with wider positive implications at the traveler, network, and city levels.

5. ENVIRONMENTAL AND RESOURCE IMPLICATIONS OF AUTOMATED AIR TRANSPORT

Personal aerial vehicle (PAV): an autopiloted flying vehicle that offers unprecedented levels of fast, on-demand urban mobility using the free air space

Vertical take-off and landing (VTOL): a technology enabling personal aerial vehicles to take off from and land almost anywhere, making them far more flexible for the city context—no need for airport runways that use an abundance of space

Personal aerial vehicles (PAVs) or personal aerial transport systems (PATS) will bridge the niche between scheduled airliners and ground transport, offering unprecedented levels of fast urban on-demand mobility by making use of the free air space (6). Lately a critical part of the literature in an effort to popularize and create a sense of familiarity to this new untested mode uses the provocative term "flying cars" for these vehicles.

PAVs are projected to be capable of serving as an alternative to overcongested ground transport and able to reform our cities by creating urban air traffic, as soon as higher automation at affordable prices is achieved. PAVs will carry passengers with no piloting skills and will be more accessible to the general public when compared with helicopters today. Solving issues around the allocation of launching, landing, and parking space, the establishment of no-fly zones and flight corridors, the introduction of search, alarm, and rescue operation systems, the interaction with other modes and synergies with ground AV systems may allow PAVs to contribute to reducing traffic congestion and the adverse effects of pollution in best-case scenarios (91). Nevertheless, for PAVs to be operational, there are some key challenges that need to be addressed relating to traffic safety and accident prevention, public (un)acceptance, expensive infrastructure, risk and disaster management, trespassing and needless surveillance, visual intrusion, and excessive air traffic concerns (92, 93).

At present, we do not fully understand the far-reaching environmental and resource impacts likely to be imposed by PAVs. Although PAVs may be an electric-powered or hybrid mode, a substantial fleet of such vehicles could demand significant energy resources and increase the overall amount of people travelling and VMT (94, 95). The only way PAVs may be able to yield sustainable environmental benefits in terms of overall VMT reduction and GHG emission reduction is if they are deployed exclusively as shared mobility services operating through ride-sharing schemes and replace individual and not shared/public transport surface travel (32). Like any other EV-based technology, PAVs would need to utilize renewable energy–generated power (i.e., wind, solar, hydro, nuclear, geothermal) and not rely on fossil fuels to be clean (96), although any such power increase could still compromise our overall ability to meet the global 2050 climate goals in a timely manner.

Changes in vehicle design may be also a powerful way to save energy and minimize environmental harm. Given that it is not practical, or financially viable, to build traditional airplane runways on every city corner, vertical take-off and landing aircrafts (VTOLs) could be the new norm that, according to Sutherland (97), is quieter and more fuel efficient than propeller-based helicopters. These aerial machines will fly from airport-lite bases called vertiports.

Findings from a recent study (98) demonstrated the potential of VTOLs in reducing GHG emissions in a specific usage scenario, when compared against internal combustion engine–based personal aerial vehicles (ICEPAVs) and battery electric engine–based personal aerial vehicles (BEPAVs). More specifically, according to a highly conservative comparison of one occupant per vehicle on a 100-km point-to-point trip, an electric VTOL has a 35% reduction in GHG emissions compared to ICEPAVs but a 28% increase compared to BEPAVs (97, 98). If the system is based on ride-sharing, however, VTOLs reduce GHG emissions by 52% compared to an ICEPAV and 6% relative to a BEPAV (97, 98). All in all, the capability of these vehicles to reduce reliance on fossil fuels and tailpipe emissions measured as carbon CO_2eq (99) will help to establish the long-term sustainability of PAVs.

Given that PAVs will be based on rotors and will act as big fans creating air disturbance and thus air nuisance (95), maximum sound decibels, at certain times of day and days of week and within an appropriate distance of densely populated areas, will be required to inform a comprehensive noise ordinance to advise sustainable flying car operation (95, 100). Future policy considerations

should account for environmental concerns (101), by informing the commuting population about the possible environmental effect of PAVs, possibly within a comparative context including conventional vehicles, EVs, as well as CAVs (102).

PAVs are still in an embryonic phase of their growth trajectory. Volocopter, a pioneer in urban air mobility that collaborates with Lufthansa, has launched thus far only some public trial flights, and Uber Elevate aims to launch commercial flights in 2023, not within cities but between suburbs and cities in the regions of Dallas, Los Angeles, and Melbourne. Kilometer-based fares, number of PAVs per vertiport, and passenger process times at vertiports will have a significant impact on urban air mobility demand according to simulated scenarios that show PAVs being more popular for shorter distances (103). Unmanned aerial vehicles, drones, and other smart aircrafts that will not focus on passenger services will serve as complementary flying technologies to PAVs, and together they will be barometers of the day-to-day functionality, operability, and environmental performance of smart cities (6).

6. ENVIRONMENTAL AND RESOURCE IMPLICATIONS OF AUTOMATED WATER TRANSPORT

Automation in waterborne transport seems inevitable in the twenty-first century (104), given that autonomous vessels can reduce both cost and environmental impact to successfully complete routine surface and underwater activities (105). Their operations in coastal or river cities can help reduce surface transport significantly. The cruise industry has been a locomotive of the tourism sector until the COVID-19 restrictions were imposed, making its future uncertain. Each cruise ship stop at a city harbor has significant implications on the local economy, transport network, and environmental ecosystem due to peak demand within constrained and often vulnerable areas. Carnival Corporation & PLC, a cruising giant, has been found to emit 10 times more sulfur dioxide compared to the overall 260 million cars in Europe for 2017 (106). Therefore, reducing the environmental implications of water transport would be positive for the local and global environment.

In this context and following stricter environmental regulations (emission control areas) imposed globally by the MARPOL convention since January 1, 2020, the maritime transport industry has turned its attention to automation and electrification of its fleet (107). Norway has established the first autonomous shipping company in the world, which was planning to launch the first ever fully autonomous and electric container vessel in 2020; however, plans have been altered due to COVID-19 and the need to conduct more feasibility studies including infrastructure requirements and environmental implications on both the sea and land side of operations. At an urban level, the Autoferry project in Trondheim by the Norwegian University of Science and Technology envisages carrying at least 12 passengers on a fully autonomous electric vessel. The journey on water will last less than one minute, significantly reducing travel time from the current 10–15 minutes on foot, whereas the vessel can charge during each stop (108). Such developments are of high interest for maritime and coastal-based cities and states, particularly given the reduced energy requirements to transport the electric batteries using power generated by fuel due to water buoyancy.

Consequently, it is no surprise that cities interested in their environmental footprint, from Trondheim to New York and from Amsterdam to Singapore, are closely monitoring developments emphasizing the need to work towards a connected, cooperative and automated inland waterways transport, integrated into the digital transport ecosystem (109). The Roadmap for Smart and Autonomous Sea Transport Systems signed between Norway and Singapore at the end of 2020 confirms this interest and paves the way for further research in this field. Other advancements in the field include the Rolls-Royce-led project AAWA, which envisaged a remotely operated automated vessel to be available by the end of 2020.

Benefits of such technological evolution are apparent from an economic perspective, particularly for urban transport where wages constitute a major part of operational costs (110). Moreover, benefits extend also to environmental implications, for example when on search and rescue missions, given that response time and risk are minimized, resulting in reduced travel time and respective emissions. Given the regulations introduced by several countries in the European Union to protect ports and their urban environment (Directive 2016/802—the so-called Sulphur Directive), water transport automation may have a positive impact. What remains uncertain is the time frame of introducing such automation, given that Rolls-Royce Marine (111) envisaged that remotely operated local vessels would be tested by 2020, remote controlled unmanned coastal vessels by 2025, remote controlled unmanned ocean-going ships by 2030 and autonomous unmanned ocean-going ships by 2035. These automated operations will need to be facilitated by on-shore information and communications technology, whereas other vessel maintenance activities previously carried out by crew onboard will need to be conducted at ports (107, 112), all of which will require relevant infrastructure and resources to enhance connectivity while increasing the carbon footprint accordingly depending on the type of energy source employed.

No specific studies exist currently about the wider impact of highly automated water transport on marine wildlife and ecosystems (e.g., due to maintenance activities), so this is an area on which further research is pertinent. Overall, researchers such as Ghaderi (107) have argued that key policy recommendations for water transport automation should focus on coordinating regulations and standards regionally and internationally while supporting workforce training and skill development, considering its wider environmental implications.

7. CONTEXTUALIZATION AND THEORIZATION

The results of our narrative literature review provide evidence that there is a rapidly growing interest in vehicle automation and a universal recognition that this is a milestone for the next mobility paradigm at the city level and beyond. At the same time, however, self-driving's range of capabilities remains unclear (113), and despite the acknowledgment that sustainable development principles should govern this mobility paradigm transition (114–117), there is still an alarming scarcity of research focusing specifically on the following:

1. the environmental and energy-related aspects reflecting and affecting the potential introduction of an automated transport paradigm, especially when it comes to non-CAV multimodal applications of vehicle automation—results do not reach a clear consensus on whether automation can yield benefits for the environment;
2. the non-technical aspects of existing low-carbon modes of automated ground transport like ABs (that are trialed in experimental projects) and autonomous light rail and metros that may be operational for decades now in a few cities but have not been widely adopted beyond the context of vibrant metropoles;
3. the non-technical aspects of air and water automated solutions that may have the biggest environmental and energy consumption impact if utilized appropriately (or inappropriately) and express innovative multimodality; and
4. the identity, form, and benefits of the nexus between vehicle automation, connectivity, sharing, and electrification and its consequences in the process of transitioning to a more sustainable and holistic transport regime—no one until now considered multimodality (defined here as a quality that does not only encompass a departure from a road transport–based monoculture by looking equally at rail, air, and water modal choices but also reflects the mass transit side and potential of mobility) as a critical part of this nexus.

Other than reviewing a multidisciplinary body of literature through the lens of sustainability that helped us identify the above knowledge gaps, our article proposes a conceptual model putting into context the different dimensions and relationships of vehicle automation and articulates future directions for research and eco-friendly policy development.

The technical, behavioral, and regulatory uncertainty around vehicle automation means that it would be unwise to claim that we can actually predict the precise impacts of automation on transportation energy consumption or carbon emissions (41). The uptake of vehicle automation, in isolation or with a principal emphasis on automated car services, will possibly result in moderate reductions in CO_2 emissions per mile due to cleaner engine technology and eco-driving, but it may also generate a potentially high growth in VMT compared to business as usual, through effects such as longer distances traveled, increased use of transportation by underserved groups or empty-running vehicles, increased travel speeds, and higher value of time for commuting (118). This means that the net energy and GHG emission balance, at its best, will be neutral, but it may also be negative (52, 119).

The response of stakeholders responsible for the transition to an artificial intelligence (AI)-based mobility paradigm to this negative but likely scenario is to ensure that vehicle automation is not a stand-alone intervention but one that is complemented by not only connectivity, electrification, and sharing but also, as we explicitly suggest, a fifth element—multimodality. Reviewing the literature, we discovered that autonomous cars have enjoyed, in all of their possible future alterations covered in this article, a disproportionally vast focus, and they are the frontrunner in R&D vehicle automation applications. However, not even the shared connected autonomous electric car-equivalent can support alone genuinely pro-environmental and energy-saving urban futures.

This work challenges and "derails" this line of thinking and emphasizes the importance of multimodality and, much like Currie (120), the irreplaceable role of public transport even in a future form that is significantly different from what is typical today (e.g., the use of smaller pod-like ABs, as described in Section 3.2). This may be the key for reversing the single-occupant vehicle trip trend that scholars (e.g., 121) see as the root of the traffic congestion challenges we face today. This is why we introduce in our theorization the element of sharing not only as an expression of on-demand car-based sharing services but also as an attribute that reflects clearly the significance of mass transit use (122). Sharing automated mobility resources should be a two-dimensional process that not only includes but actually emphasizes the merits of public transport and is not an attribute primarily governed by a monolithic pro-car tendency to equate sharing with car-centric rentals or rides. AI and big data techniques embedded in CAV technologies could revolutionize parts of public transport, disengaging it from an inflexible fixed route and timetable normality, enabling real-time, demand-supply matching mobility sharing that could ultimately blur the differences between private and public transit as viewed today. Special care should be given to PAV-related mobility so that this is provided on a ride-sharing and public transport basis only. This approach could reduce the unprecedented phenomenon of air transport traffic that cities will face and will have to manage for the first time ever; any private-based business model of flying, especially if costs of owning a PAV in the future are affordable, should be controlled or abandoned.

Electromobility has been characterized as a particularly complex ecosystem (123), and it could become even more complicated when vehicle automation arrives. For sustainability reasons, low-carbon electricity production that is independent from fossil fuels along with grid integration (124) is crucial for the electrification of vehicle automation and needs to be supported by an extensive and expensive EV-charging infrastructure (96). Nonetheless, promoting alternative vehicle propulsion systems seems to be the cleanest and least energy-consuming scenario going forward for vehicle automation in all city travel modes (2). The potential accelerating role of vehicle automation in relation to the uptake of electrification of mobility services might have the

Artificial intelligence (AI): a machine's ability to simulate the human mind by interpreting data it receives from its environment, learning from the data, and using that learning to successfully complete tasks, even in novel scenarios

Transit-oriented development (TOD): a strategy that integrates land-use and transport planning principles to support sustainable transport services, by concentrating urban development around public transit stations

largest positive impacts on the GHG emissions per mile driven, but this accelerating role of AV technology for EV uptake is uncertain and not easily measurable with what is known to date (52).

In more generic terms, the decarbonization of transport, in general, and automated transport, in particular, have emerged in the environmental-transport discourse, but it has focused almost exclusively on techno-optimism (e.g., aiming the perfect fit of vehicle automation with electrification or the creation of superior clean engine technology), despite the fact that technological optimism has repeatedly proven unrealistic (125). Thus, when embracing the transition to an automated urban transport system, we cannot rely solely on technology advancement, which is of primary importance nonetheless, but must rely also on policy, legislation, market and educational dimensions reflecting and affecting the environmental and resource usage agendas of automation.

For instance, to prevent undesired environmental and energy-related impacts, public administrations must govern the transition to automated mobility, steering it to adapt to urban livability standards (126) through immediate action, relevant legislation, far-sighted planning, and cooperation of various sectors and stakeholders. Much like Gallagher et al. (127) proposed for energy technology innovation systems, transport automation innovations should be based on a combination of both incremental, cumulative changes and radical, discontinuous changes that can only emerge if the various innovation dimensions are nurtured simultaneously.

CAVs should be used predominately as first- and last-mile solutions and neighborhood feeders to complement more mainstream mass transit–oriented systems, thus serving the concept of transit-oriented development (TOD); this in an uneasy union because of their traditionally contradictory roles, so future planning efforts need to assist with balancing tensions and achieving beneficial outcomes (22). The TOD concept would be served even better if CAVs were replaced with low-speed pod-based ABs capable of sharing space with active transport modes for this first- and last-mile role (128). MaaS, a novel brand of app-powered, integrated, and multimodal transport packages including travel planning, booking and ticketing, and real-time information services (129), should promote as its backbone the use of public transport options when it comes to its automated services; private and single-occupancy CAV options should be restricted or dicentivized (e.g., charged significantly higher).

Travel demand measures for automated cars such as energy and air pollution taxes, maximum speed limits, road pricing and parking pricing policies, and car-free developments hindering the growth of VMT could be put in place to ensure further energy- and emissions-related benefits and push people to automated mass transit options (13, 130). Awareness campaigns, information provision exercises, education and training workshops and automated transport scheme trials and living labs that inspire familiarity with these vehicles could help people become more aware of their future travel behavior choices when multimodal automated mobility services are an option.

Figure 1 presents an original conceptual model putting into context the diverse dimensions of vehicle automation in relation to its four complementary and empowering counterparts: (*a*) connectivity that permits through wireless communication services AV functions to utilize their technological potential (e.g., platooning); (*b*) electrification that fuels automated transport and allows it to be oil-free and less polluting provided that electricity is based on renewable energy sources; (*c*) sharing that allows on-demand and public transport services to transport more people simultaneously and control traffic; (*d*) multimodality that disengages transport for the monoculture of automobility. The arrows in **Figure 1** highlight the importance of technology development from a supplier perspective and technology uptake from the general public, policy and legislation, market dynamics (i.e., user demand and behavior versus mobility providers' supply), and education including elements as simple as information provision. The scenario described in the area where the five spheres are coexisting provide the outcomes of an autonomous, connected, electrified,

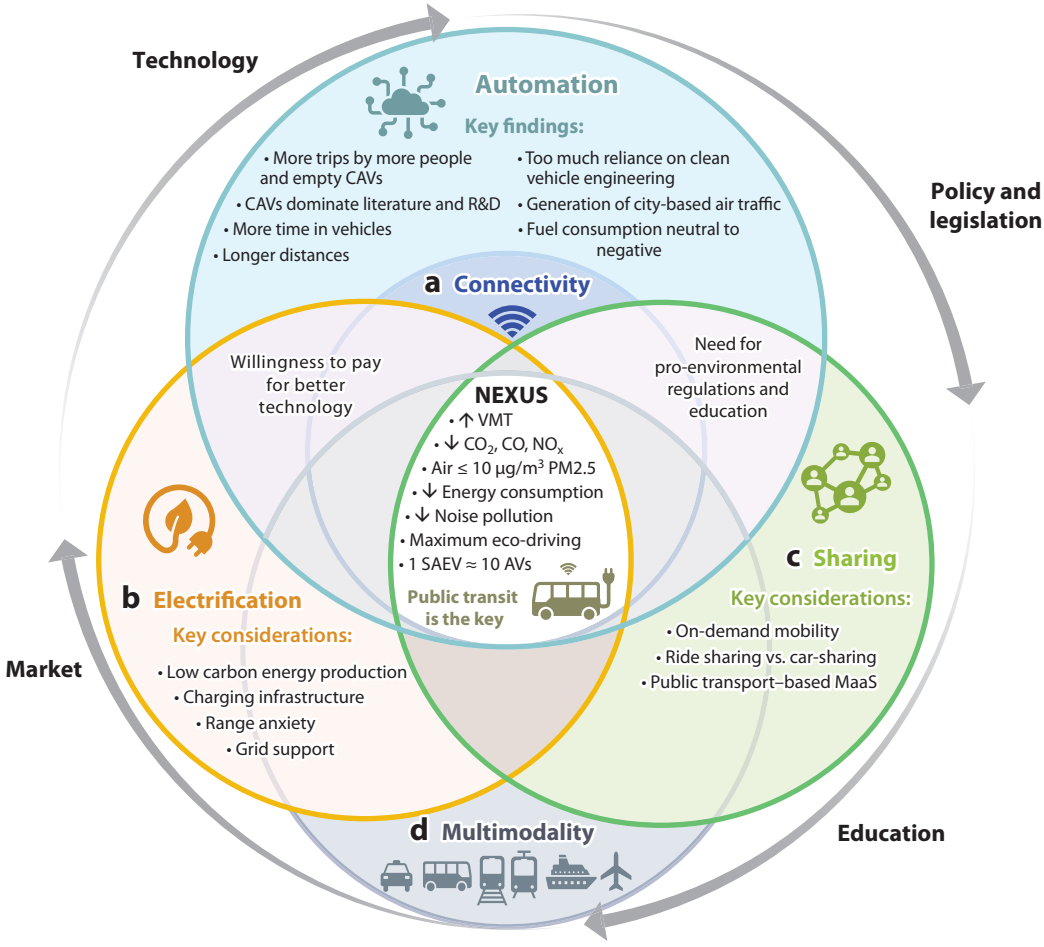

Figure 1

Vehicle automation in relation to its four complementary and empowering counterparts: (*a*) connectivity that allows AVs to communicate and cooperate (e.g., platooning), (*b*) electrification that makes automated transport oil-free and less polluting provided that electricity is based on renewable energy sources, (*c*) sharing that allows on-demand and public transport services to move more people simultaneously, (*d*) multimodality that reflects a departure from a road transport-based monoculture and also emphasizes the mass transit side and potential of mobility. The figure also highlights the importance of technology development, policy and legislation, market dynamics, and education as mechanisms defining the principles and nature of transport automation. If the automation-connectivity-electrification-sharing-multimodality nexus (i.e., represented in the graph by the area where the five circles/counterparts intertwine) is genuinely prioritized with an emphasis on public transport provision, then vehicle automation may help facilitate a transition to more sustainable futures. Abbreviations: AV, autonomous vehicle; CAV, connected and autonomous vehicle; CO_2, carbon dioxide; MaaS, Mobility-as-a-Service; NO_x, nitrogen oxides; R&D, research and development; SAEV, shared autonomous electric vehicle; VMT, vehicle miles traveled.

shared, and multimodal mobility resource provision; this is the sustainable scenario that yields the most environmental and resource conservation–based benefits and can be visualized with a snapshot of an autonomous, connected, and electrified bus (see the center of **Figure 1**).

Table 2 projects the possible environmental and energy-related quantifiable changes of vehicle automation per mode and further contextualizes the ideal nexus scenario. The effect column refers to net system effects and not necessarily to per-vehicle or per-mile effects.

Table 2 Key environmental and energy results/projections for different automated mobility options

Automated passenger mobility	Effect	Summarizing comments
Autonomous vehicles (AVs)		The expectation is that by serving more populations more frequently and for longer distances and creating empty vehicle trips, AVs, in isolation, could increase motorized traffic. Due to better engine technology and eco-driving energy usage, GHG emissions on a per-vehicle basis will be lower but not in total unless the vehicles are shared and fleets are electrified from renewable energy sources.
Vehicle miles traveled (VMT)	↑	
Energy usage	↑	
Fuel efficiency	↑	
Greenhouse gas (GHG) emissions	↑	
Autonomous buses (ABs)		This work highlights the need to stop automatically synonymizing connected and autonomous vehicles (CAVs) with car-equivalents. ABs, even in their smaller but more flexible and shared-space-friendly pod-like forms, need to be prioritized in transport planning for sustainability reasons and be the cornerstone of new Mobility-as-a-Service (MaaS) systems that replace private mobility by disincentivizing car-centric road transport. Transit-oriented development (TOD) should use ABs as a key ingredient that complements rail-based transit.
VMT	↑	
Energy usage	↓	
Fuel efficiency	↑	
GHG emissions	↓	
Autonomous rail		Autonomous rail in all its variations (e.g., metro, tram, monorail) is the most tested form of automated urban transport hitherto and in an ideal scenario could lead to environmental improvements, as long as it creates significant modal shift from private CAVs. It can be the mass-transit basis for TOD and MaaS systems that could reshape urban landscapes. Literature has severely understudied autonomous rail and its environmental and energy implications.
VMT	↑	
Energy usage	↓	
Fuel efficiency	↑	
GHG emissions	↓	
Personal aerial vehicles (PAVs)		PAVs could revolutionize urban passenger mobility, alleviating surface transport congestion and replacing it with sky traffic. If PAVs adopt a model similar to the conventional private car–based mobility of today, they could be devastating for the environment. However, all the projections suggest that PAVs will be used in shared mobility and public transit schemes most likely powered by electricity. This is the most difficult automated technology to forecast.
VMT	↑	
Energy usage	↑	
Fuel efficiency	Not applicable	
GHG emissions	↑	
Autonomous vessels		Water transport with functions defined by automation like eco-driving and clean engine technology could be a significant complement to city transport systems. Today urban water transport is severely underdeveloped despite a vast ability to provide pro-environmental public transit services, in some part due to labor costs. If autonomous vessels replace CAV trips, local environmental degradation could be reduced.
VMT	↑	
Energy usage	↑	
Fuel efficiency	↑	
GHG emissions	↓	
Nexus		Creating a genuine nexus, where automation, connectivity, electrification, sharing, and multimodality coexist and are manifested predominately via a public transport–centered MaaS, could be the only way to facilitate a genuine pro-environmental and energy-efficient mobility ethos centered on automation. If any of the five elements is missing, then vehicle automation could lead to adverse repercussions for cities globally. If motorized transport is too predominant, however, net VMT might still increase when compared with current values because more people will be (more) mobile and travel longer distances. Still, this rise will be minimal compared with having a car-centric AV paradigm instead of the nexus.
VMT	↑ (or stable)	
Energy usage	↓	
Fuel efficiency	↑	
GHG emissions	↓	

8. CONCLUSIONS

The self-driving functions, advanced vehicle design, enhanced engine fuel performance, and eco-driving technology as a whole cannot guarantee alone the transition to the type of sustainable urban futures that cities have been linking to vehicle automation. The net energy and GHG

emission balance for automated urban passenger mobility, without moving to a transformative paradigm where automation, connectivity, electrification, sharing, and multimodality form a nexus that is at the epicenter of the shift, seems, at its best, to be neutral or most likely negative because CAVs may seriously increase VMT (i.e., unoccupied CAV trips as well as more people traveling more often and for longer distances). Connected, autonomous, electrical, shared, and multimodal mobility will need to be the primary form of travel service provision for achieving environmental benefits including less traffic congestion, decreased atmospheric emissions, cleaner air, fewer contributions to global warming and climate change, optimized energy usage, greener fueling, and reduced resource overconsumption.

Our literature review, which looked into autonomous transport technologies and their environmental footprint, suggests that many questions are yet to be answered in a definitive way. Moreover, most of the existing studies are theoretical forecasts based on entirely simulated scenarios or the use of early AV functions supervised in most cases by humans in segregated (or at a minimum, mixed-traffic) environments. We recommend, in line with Kopelias et al. (47), that more experimental studies should be produced before we can better understand the extent of environmental effects that could be generated by those systems and their significance. Such studies need to be conducted both before and after participation in ongoing AV trials (e.g., 131) and coordinated internationally to provide input for thorough analysis at the global level.

Additionally, although some still inconclusive literature exists on AVs and specifically autonomous cars, other modes of automated transport have been severely under-researched, especially when it comes to their environmental and energy implications. Future research should be focused on the priorities, dimensions, expressions, interdependencies, and efficiencies of the nexus introduced in our conceptual framework (**Figure 1**).

This article identified the ingredients of the winning recipe that could enable automation to facilitate a transition to more sustainable futures by adding the pillar of multimodality (that is underpinned by an increased focus on public transport use) and emphasizing more emphatically the role of connectivity as a key enabler of automation in the already celebrated triptych of automation-electrification-sharing. However, we still feel that the precise formula of success that will enable automated urban mobility to play a genuinely pro-environmental role is yet to be entirely decoded. Developing a holistic and systematic understanding of the potential impacts of CAV transport systems on (*a*) the physical and cultural shape of the smart city; (*b*) the dynamics of the emerging shared mobility economy that challenges those characterizing reduced automobile ownership as utopian imaginary (132); (*c*) the user willingness and market readiness to embrace electrification; and (*d*) the embracement of multimodality, especially in its public transit forms for sustainability reasons, is still a work in progress.

CAV-based technology and solutions, even in the form of the ideal nexus we propose, may not be a panacea on their own. A transition to sustainable urban mobility futures also needs to be centered around active transport prioritization interventions, virtual commute and teleworking initiatives, and travel demand mechanisms.

SUMMARY POINTS

1. The literature tends to narrow down the terms CAVs and AVs to car-equivalents; however, other automated travel modes, especially those with a public transport dimension, offer significantly higher sustainability potential.
2. There is a scarcity of research examining the environmental and energy-related aspects of the automated transport paradigm for city travel, especially when it comes to

non-CAV applications of vehicle automation—there is barely any such research for bus, rail, water, and air transport automation initiatives.

3. Simulations and early AV stage experiments have generated conflicting results that do not reach a clear consensus on whether automation can yield genuine benefits for the environment.
4. In all likelihood, the uptake of vehicle automation in isolation, and with an emphasis on autonomous cars, will result in moderate reductions in GHG emissions per mile that would be critically outweighed by a potentially high growth in VMT.
5. The net energy and GHG emission balance for automated urban passenger mobility, without moving to a transformative paradigm where automation, connectivity, electrification, sharing, and multimodality form a nexus that is at the epicenter of the shift, seems, at best, to be neutral or most likely negative.
6. Autonomous, connected, electrical, shared, and multimodal mobility will need to be the primary form of future travel service provision for achieving environmental benefits such as traffic congestion decline, decreased atmospheric emissions, cleaner air, fewer contributions to global warming and climate change, optimized energy usage, greener fueling, and reduced resource overconsumption.
7. This nexus-based transition is not an easy one and has technological, market-based, behavioral, educational, and regulatory elements that need to be thoroughly studied and understood.
8. Automation carries positive paradigm-shifting potential for mobility as long as it is not a techno-fix and a stand-alone intervention and appreciates its critical sustainability implications for the future of our cities.

FUTURE ISSUES

1. More experimental studies at both the vehicle and the network system levels need to be produced before we understand the extent and significance of environmental and energy effects that could be generated by those systems.
2. The wider impact of automation deployment should be evaluated for both users and non-users explicitly, including the essential infrastructure requirements from curbside amendments to maintenance areas at ports and vertiports, including information communication technologies investment and infrastructure.
3. The bidirectional relationships between CAV transport systems and (*a*) the physical and cultural shape of the smart city, (*b*) the emerging shared mobility economy, (*c*) the user willingness and market readiness to embrace electrification, and (*d*) the embracement of multimodality, especially in its public transit forms, have not yet been entirely defined—some future opportunities and challenges are not yet visible based on contemporary knowledge.
4. Given the multifaceted nature of the autonomous transition, it is important to assess the environmental implications of SAEVs, acknowledging that on the one hand these vehicles may have significant impacts on energy demand and, in turn, drive variation

in energy cost and reliability, and on the other hand can also act as energy storage and distribution units.

5. MaaS can become the elevator of the automated mobility nexus discussed herein with the precondition that its backbone is multimodal public transport and car-centric services are seriously disincentivized; if MaaS establishes as the mainstream but suffers from "uberization," then there will be no environmental or energy wins.
6. Legislation, travel demand measures, meticulous planning, trials and living labs, awareness campaigns, and training schemes with a pro-environmental emphasis as well as robust investment projects comprise a policy toolbox that influences travel behavior; without it the ideal automated transport formula for crafting pathways to sustainable urban futures described herein will remain unrealized.

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