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Review

Environmental impacts of autonomous vehicles: A review of the scientific literature

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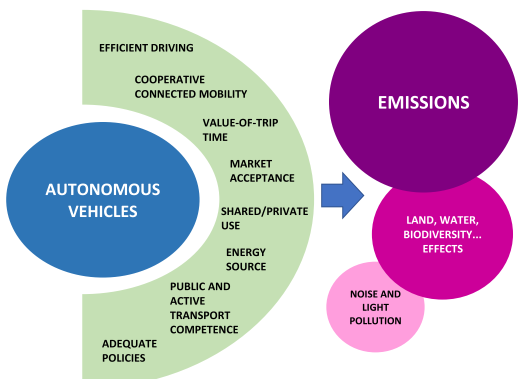
HIGHLIGHTS

- Comprehensive review of AVs impacts on air, land, water, noise & light pollution
- There are few studies focusing on the effects of AVs on the environment
- Most studies have focused on emissions, while other dimensions have been ignored
- Benefits depend on penetration rates, sharing & the interaction with other modes

GRAPHICAL ABSTRACT



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ABSTRACT

Autonomous vehicles (AVs) may have significant environmental impacts although there are still few studies focusing solely on these effects. A vast majority of articles address environmental issues as a secondary outcome and, above all, emissions are the main topic. As the notion of environmental impacts concerns many aspects than just air pollution, this paper aims to explore and show the findings and flaws of current research with a wider vision. For that purpose, a systematic review of the scientific literature was carried out broadening the scope to land, water, noise, and light pollution in addition to air. The results reveal potential benefits of AVs due to technical improvements, new possibilities in design and traffic flow enhancement, but the benefits depend on penetration levels, shared mobility acceptance and the interaction with other modes of transport. On the other hand, negative effects are also identified related to the decrease in the value of trip time and user tendencies. Among other potential impacts, changes in land use are increasingly being studied. These changes can lead to significative impacts on emissions as well as on soil and water although the latter have not yet been considered. Lastly, the likely improvements in noise and light pollution are scarcely explored. Given the lack of study of some of the environmental outcomes of AVs, it is not possible to draw a precise conclusion on their overall impact, calling for more comprehensive studies that enable to identify all the measures to be taken to achieve a sustainable future.

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1. Introduction

In 2015 there were almost 1.3 billion vehicles in use worldwide, of which almost 1 billion were passenger vehicles (OICA, 2021), a figure that may double by the end of the 2020s or early 2030s based on current trends (Sperling and Gordon, 2009). This makes the private car (including all types: passenger cars, SUVs, small vans, etc.) account for approximately 60% of greenhouse gas (GHG) emissions within the transport sector, which is itself the most polluting of all economic sectors. In the USA alone, emissions from this sector amount to almost 2 billion tons of CO_2 equivalent into the atmosphere per year, i.e., almost 30% of all emissions (US EPA, 2020).

The importance of sustainable mobility and development has been reinforced by the growing recognition of the problems caused by climate change (Banister, 2011). For example, the EU's goal of at least −55% greenhouse gas reduction target by 2030 and of climate neutrality by 2050 (European Commission, 2020). In this context, the autonomous vehicle (AV) shows great potential through more efficient driving with lighter and safer vehicles, as well as by favoring shared and on-demand mobility. Although these potential benefits can be substantial, their use can also generate undesirable effects and their introduction must be managed to obtain effective results (Legacy et al., 2018).

The technology to achieve the degree of autonomy to positively influence the environment is still under development. In general, it is considered that the maximum benefit will be achieved, among other factors, at level 5 of automation according to the commonly accepted standard (SAE, 2018). This standard considers 6 levels, from no automation (level 0) to full automation (level 5) with which the vehicle can operate in any environmental condition or infrastructure state. Estimates made by different authors on the availability of this technology are highly variable, although they generally point to a horizon around 2030, considering that 10 to 20 more years will be needed to achieve a scenario with a majority of AVs (Hörl et al., 2016; Milakis et al., 2017a). Regardless of the acceptance of a new technology by consumers, considering the EU-28 passenger car fleet replacement ratio of 5.6% (ICCT, 2018), a high degree of AVs on the roads would not be feasible before 25 years.

As an incentive for its development, economic projections estimate that AVs and mobility services will generate a turnover of USD 7 trillion (EUR 5.9 billion) by 2050 (Lanctot, 2017). In addition to economic effects, Greenwald and Kornhauser (2019) identify several problems that AVs could solve, such as 1.3 million annual global accident fatalities, 600 billion driving hours per year with very low seat occupancy, vehicles stopped 96% of the time, driving stress; as well as new opportunities for society related to commercial possibilities, synergies with public transport services, etc.

Due to their potential to change transport in the future, a large amount of scientific literature is being developed on AVs. In fact, it is one of the topics given the greatest attention in the scientific literature today, with publication rate growing at over 30% per year, well above the average of around 8–9% (Gandia et al., 2019). Among all the literature that is generated in this regard, studies on environmental impacts, although still relatively scarce, are receiving increasing attention.

One of the most comprehensive studies on AVs implications, developed by Milakis et al. (2017b), foresees various impacts in relation to time of occurrence according to the ripple effect model, and it is in the third order impacts where only two environmental effects considered are classified, related to energy consumption and air pollution, ranking behind impacts on the transport system itself or on land use.

In one of the few literature reviews focused on environmental impacts, Kopelias et al. (2020) also highlights energy consumption and emissions as the main impacts considered among researchers. The article identifies the factors that can generate them: type of propulsion, vehicle design, platooning, eco-driving, route choice, congestion reduction, vehicle kilometers travelled, on-demand or shared mobility, penetration levels, use by the non-driving population and user preferences. Wadud et al. (2016) also analyzing consumption and emissions, agree on several of these factors and include others such as increased speed, increased weight due to new comfort and entertainment features, and adjusted speeding capacity. Taiebat et al. (2018) also include the need for infrastructure, energy recharging systems and new land uses. The latter is a field of study that is recently receiving attention among researchers, as it can lead to the evolution of new mobility towards a more sustainable scenario or towards an opposite and more polluting one (Nogués et al., 2020).

As with the rest of the literature on AVs, the articles that advance environmental consequences of land use changes only consider the effects on consumption and emissions, related to urban sprawl. However, authors such as Wilson and Chakraborty (2013) and Bicer and Dincer (2018), point out that urban sprawl leads to serious effects on land and water including loss of agricultural land, loss of natural terrain and habitats, flooding, excess water consumption, disruption of the hydrological balance, loss of rainwater, depletion of abiotic resources, acidification, eutrophication, and soil toxicity, among others.

As many possible environmental impacts of automated driving seem to have been disregarded although they can be equally transcendent (European Commission, 2020), this article has a twofold objective: to examine the environmental effects of AVs considered among researchers, and to point out areas scarcely mentioned or unexplored as possibilities for future research.

To this end, this article reviews the content of the different studies on this subject using the Scopus and WoS databases. Search categories were established according to the physical environment that could be affected, broadening the spectrum to other natural environments not normally considered, such as land and water, and other effects such as noise and artificial lighting.

The rest of this article is structured as follows. Section 2 describes the methodology used to select the scientific literature of interest. Section 3 presents the results found in the reviewed literature. This section is structured in 6 subsections. The first one deals with the effects on the air, which is further divided into 4 parts: effects due to the design of AVs, its integrated systems and traffic; effects with mixed traffic of conventional and

AVs according to market penetration; effects of shared mobility; and effects within the transport system as a whole. The second and the third subsections discusses whether and how the current literature addresses the environmental effects of AVs on land and on water. The fourth and fifth subsections review the literature on AVs and noise and light pollution. Finally, Section 4 draws the main conclusions and summarizes the directions in which future research could be focused.

2. Methodology

The review of the existing literature on the environmental impacts of AVs was carried out using the search engines Scopus and Web of Science during August 2020. A first search included the most commonly used keywords to refer to AVs, i.e., "Automated" or "Autonomous" or "Self-driving" or "Driverless" and "Vehicle(s)" or "Car(s)", yielding thousands of references. The search was subsequently extended to terms related to environmental impacts on different physical environments, including noise and light pollution (Table 1).

The procedure was carried out in three phases. The first consisted of identifying articles with the keywords indicated. Only scientific journal articles published in English were taken into account, resulting in 1143 articles (Table 2). After identification, a review was carried out to eliminate duplicate articles and those that did not correspond to the field of study (e.g., autonomous marine vehicles) (932 articles), as well as those that were not sufficiently representative of the field they studied (126 articles). As a result of these exclusions, 93 articles were finally selected for this research, of which 15 were located using the "snowball" technique both forwards and backwards. Additionally, 7 references relevant enough to reinforce the vision of the recent literature on the subject were taken into consideration.

3. Results

Most of the results obtained refer to environmental impacts on energy consumption or emissions (75%). As regards impacts on land, a body of literature is beginning to develop with several references, but these hardly refer to environmental effects, but rather to urban planning effects. No references were found that identify effects on water in the initial review although 2 references appeared as a result of the snowball technique. Effects on noise and light pollution are scarce.

For each physical environment, sub-themes were identified, with these divisions being most notable in the most studied aspects (Fig. 1). Analyses have different approaches, from the operational point of view of a particular vehicle and in its interaction with other vehicles to studies at fleet level and on-demand or shared mobility services, at city or even country level.

3.1. Air quality effects: atmospheric pollution and emissions

Variation on emissions is the most studied environmental impact of AVs and its results can be classified into three groups. The first group includes studies about operational concepts in different situations and in a 100% AVs traffic environment; the second group refers to a mixed traffic environment with variations on penetration levels and in different cases as well; and finally, the third group corresponds to the impacts of fleets and shared mobility (Table 3). This section also includes references about the effects of AVs on the transport system as a whole and the compatibility with other modes of transport but they are not compiled into the three mentioned groups (shown in Table 3) because these studies advance for now more qualitative than quantitative conclusions.

3.1.1. Effects due to the design, integrated systems and movement of AVs

Among the variables that affect AVs consumption and emissions, one could first consider those derived from its own design, the driving systems used and the rest of the necessary equipment. According to C. Zhang et al. (2019), accelerating and overcoming frictional resistance consume the 53.4% of the whole energy consumption of an electric autonomous vehicle so any improvement in the driving efficiency will result in lower consumption and therefore lower emissions. In fact, results estimated with MOVES (Motor Vehicle Emission Simulator of the US Environmental Protection Agency) only considering driving profiles to replace human-driving vehicles by AVs, advance emission reductions up to 14% (Liu et al., 2017b). Similarly, Conlon et al. (2018), obtain reductions between 4.7% and 14.5% considering a realistic urban context. Much of the efficiency would be achieve through the improvement of the traffic flow thanks to different cooperative driving systems including from which Cooperative Eco-driving at Signalized Intersections and Cooperative Adaptive Cruise Control (CACC) and Platooning would be the ones with the highest environmental benefits (Z. Wang et al., 2020a).

There is a large body of literature proposing models using the diverse operational concepts under different cases. Many studies analyze the improvement of traffic at intersections with AVs as a result of connections between vehicles and with the infrastructure itself, with reductions in emissions ranging from 13.8% to 59% (Bento et al., 2019; Bichiou and Rakha, 2019; Chen and Liu, 2019; Feng et al., 2018; Filocamo et al., 2020; Z. Li et al., 2015; Lin et al., 2017; Stebbins et al., 2017; C. Wang et al., 2020; Z. Wang et al., 2020b). Also, several authors propose improvements through different cooperative models (F. Ma et al., 2019) and variable speed strategies (Guo et al., 2020) with potential to reduce emissions of up to 44.62%.

Other studies discuss the incorporation of various dynamic routing systems and eco-driving strategies that also result in traffic improvements (Djavadian et al., 2020; C.L. Liu et al., 2019; J.Q. Ma et al., 2019; Tu et al., 2019; Zhai et al., 2019). Results advance significative fuel savings and emission reductions above 40%. Related to driving operations, Stogios et al. (2019) analyze the fluctuation in emissions by simulating various traffic conditions and varying certain driving behavior parameters. Emissions can decrease by 26% or increase by 35% depending on whether the vehicles are aggressively or cautiously programmed. Other advanced possibilities relate to dynamic double-parking that both increases parking capacity and reduces emissions (Estepa et al., 2017).

Furthermore, some studies warn of the need to consider the entire life cycle of a vehicle and not only focus on its operational phase. To this end, Patella et al. (2019a) indicate that, at vehicle level (construction, maintenance and end-of-life phases), electric autonomous vehicles (e-AVs) generate 35% more emissions than a conventional internal combustion vehicle, even though, in the operational phase, the AV could achieve savings of 60% in a 100% AVs scenario.

3.1.2. Effects with mixed autonomous vehicles/conventional vehicles traffic and different AVs market penetration rates

The penetration of AVs will be gradual, so that for a considerable period of time it will be common for conventional and autonomous vehicles to coexist. In closed-loop field experiments, the presence of AVs, even in low percentages (5%), stabilizes traffic and smoothens stop-acceleration intervals, achieving significant emission reductions (Stern et al., 2019). Talebpour and Mahmassani (2016), analyzing a mixed traffic string with conventional human-driven vehicles, connected human-driven vehicles and AVs, conclude that the presence of connected vehicles improves traffic flow stability, as with AVs, although automation is more effective than connectivity alone in preventing shockwaves. Also, AVs show higher throughput than the connected ones at similar market penetration. However, in real traffic modeling with human drivers, the presence of AVs does not always improve traffic conditions. In high density traffic conditions, not interconnected

Table 1
Specific keywords used in the literature review.

Air	"Emissions" OR "Pollution" OR "Global Warming" OR "Greenhouse" OR "Carbon" OR "Air Quality"
Land	"Built Environment" OR "Land Use" OR "Urban Form" OR "Territorial Impact"
Water	"Water Pollution" OR "Water Contamination" OR "Aquatic Toxicity" OR "Water Consumption"
Others	"Noise Pollution", "Light Pollution"

Table 2
Number of selected references.

Keywords	Sources identified	Duplicates/off Topic	Initial review	Not representative	Selection by “Snowball” and relevance	Final Selection
“Emissions” “Pollution” “Global Warming” “Greenhouse” “Carbon” “Air Quality”	968	812	156	98	12	70
“Built Environment” “Land Use” “Urban Form” “Territorial Impact”	139	89	50	39	3	14
“Water Pollution” “Water Contamination” “Aquatic Toxicity” “Water Consumption”	18	18	0	0	2	2
“Noise Pollution”	16	12	4	3	2	3
“Light Pollution”	2	1	1	0	3	4

AVs tend to slow down when considering safety and comfort parameters generating 11% more emissions but if AVs were connected, CO_2 reductions of up to 5% could be achieved (Mattas et al., 2018). Results advanced by Bandeira et al. (2021) suggest that the presence of connected AVs in mixed traffic scenarios could lead to 4% increases in CO_2 emissions but also to 18% decreases depending on the road type, the driving settings and the penetration rate.

Rafael et al. (2020) study the impact of AVs on air quality in an urban area with a penetration rate of 30%, showing a slight 0.7% increase in CO_2 and NO_x emissions as a consequence of increased demand and accelerations after stops. However, an autonomous vehicle scenario with 30% electric vehicles could achieve a 29% reduction in emissions. In the same line, some studies indicate that the highest energy efficiency is achieved with 20% e-AVs market penetration in a mixed platoon with electric human-driven vehicles and certain cooperative strategies (C.R. Lu et al., 2019a) because with higher market rates, the regenerative energy of the vehicles tents to decrease. However, if internal combustion manually driven vehicles are considered in the string, higher percentages of electrification (autonomous or human-driven) are positive. Eco-driving strategies with hybrid propulsion under mixed driving scenarios also show satisfactory results, reducing exhaust emissions above 25% (S. Wang and Lin, 2020).

Different studies show that the ratio of AVs in traffic affects two fundamental parameters: road capacity and speed limit. As the presence of AVs increases, road capacity improves and emissions can be reduced by up to 30%, as long as speed do not increase above an optimum level (Hwang and Song, 2019). Similarly, in a simulation of a real motorway section with relatively congested traffic patterns (between 70% and 90% of the road capacity), the introduction of AVs yields benefits from 2% to 58% in terms of emissions generated. However, if an extreme scenario of heavy congestion (3 times road capacity) is simulated, although vehicle flow is improved, environmental degradation is not avoided (Li and Wagner, 2019). That is, in congested situations, connected AVs, by increasing road capacity, in turn increase traffic density and generate more emissions in absolute terms (Makridis et al., 2020).

The location of AVs within the queue of circulating vehicles should be considered in the analyses. Although the longer response times of conventional vehicles may destabilize traffic, an increase in the penetration rate of connected AVs improves efficiency and lowers emissions because they can process the information provided by the vehicles ahead (Jin et al., 2020). For instance, if an AV is placed at the front of a row of partly conventional and partly autonomous vehicles, the whole group can achieve up to 2% additional fuel savings and linearly reduce emissions (C. R. Lu et al., 2019b).

Just as movement optimization at intersections with exclusively AV traffic is being developed, mixed traffic cases at intersections are also beginning to be studied, generally leading to improved intersection performance, and thus reduced emissions (Jiang et al., 2017; Kamal et al., 2020; Z. Yao et al., 2020). Nevertheless, low penetration levels of connected AVs could increase emissions due to inefficient behavior of non-connected human driven vehicles (McConky and Rungta, 2019). The implementation of Cooperative Adaptive Cruise Control (CACC) systems and speed strategies also has a positive influence in mixed traffic environments (Huang et al., 2020; Ghiasi et al., 2019). In this regard, Yu and Fan (2019) presents an optimal variable speed limit strategy that can achieve up to 7.8% emissions reduction with a 10% AV market penetration.

3.1.3. Effects of shared mobility, shared autonomous vehicles (SAVs) and other fleets of AVs

Mobility service platforms allow passengers and drivers to optimize supply and demand. In economic terms, savings of up to USD 6000 per household in the USA are estimated by using shared mobility services instead of car ownership (Anderson et al., 2014). Given the potential of such platforms, the effects of AV fleets (SAVs, Autonomous taxis or aTaxis) have begun to be studied as possible alternative transport options to conventional vehicles.

Different results indicate that a single AV can replace up to 11 conventional vehicles (Fagnant and Kockelman, 2014) or between 7 and 10 if the waiting time/cost ratio is considered (Iacobucci et al., 2018). These outcomes could induce significant reductions in emissions, which in the case of autonomous electric taxis could reach 87–94% with respect to conventional vehicles with a human driver (Greenblatt and Saxena, 2015).

Similarly, Gawron et al. (2019) estimates that a fleet of autonomous taxis in Austin, Texas (USA) could achieve up to a 60% reduction in emissions with respect to conventional vehicles and even 87% reductions with a 92% renewable electricity generation and other improvements. Also J. Liu et al. (2017a) conclude that if fares for those services are low enough, emission reductions of between 16.8 and 42.7% can be achieved. Equally positive are the 40% emission reductions obtained in Lisbon (Martínez and Viegas, 2017).

Lokhandwala and Cai (2018) estimate that a fleet of shared autonomous taxis can maintain the same service levels of the traditional taxi system in New York (USA) with 59% fewer vehicles and reducing emissions by 725 tons of CO_2 per day. Similarly, Bauer et al. (2018) obtain possible emission reductions of up to 73% in Manhattan (NY, USA) considering the current composition of electricity supply and establishing an optimal battery charging infrastructure. Factors such as the size of the fleet and the recharging protocols have certain influence in the variation of emissions (H. Zhang et al., 2020). In this line, Miao et al. (2019) propose 42% emissions reduction for an autonomous taxi fleet with an appropriate estimate of service by geographic area and a correct ratio of vehicles per charging point.

Several studies analyze the introduction of pollutant fees to encourage shared mobility. In this regard, Jones and Leibowicz (2019) show that emissions could be almost zero if pollutant fees are applied. However, some models, analyzing exclusively commuting trips, show fewer promising results from an environmental point of view. While 20% of autonomous taxis could provide the same service as the entire fleet of private vehicles dedicated to commuting, greenhouse gas emissions increase by 25%, mainly due to “empty” journeys to find the next passenger (M. Lu et al., 2018).

In general, considering large-scale mobility services with human drivers and autonomous vehicles, F. Yao et al. (2020) conclude that as conventional vehicles are replaced by AVs, emissions decrease up to reductions of 12.3%.

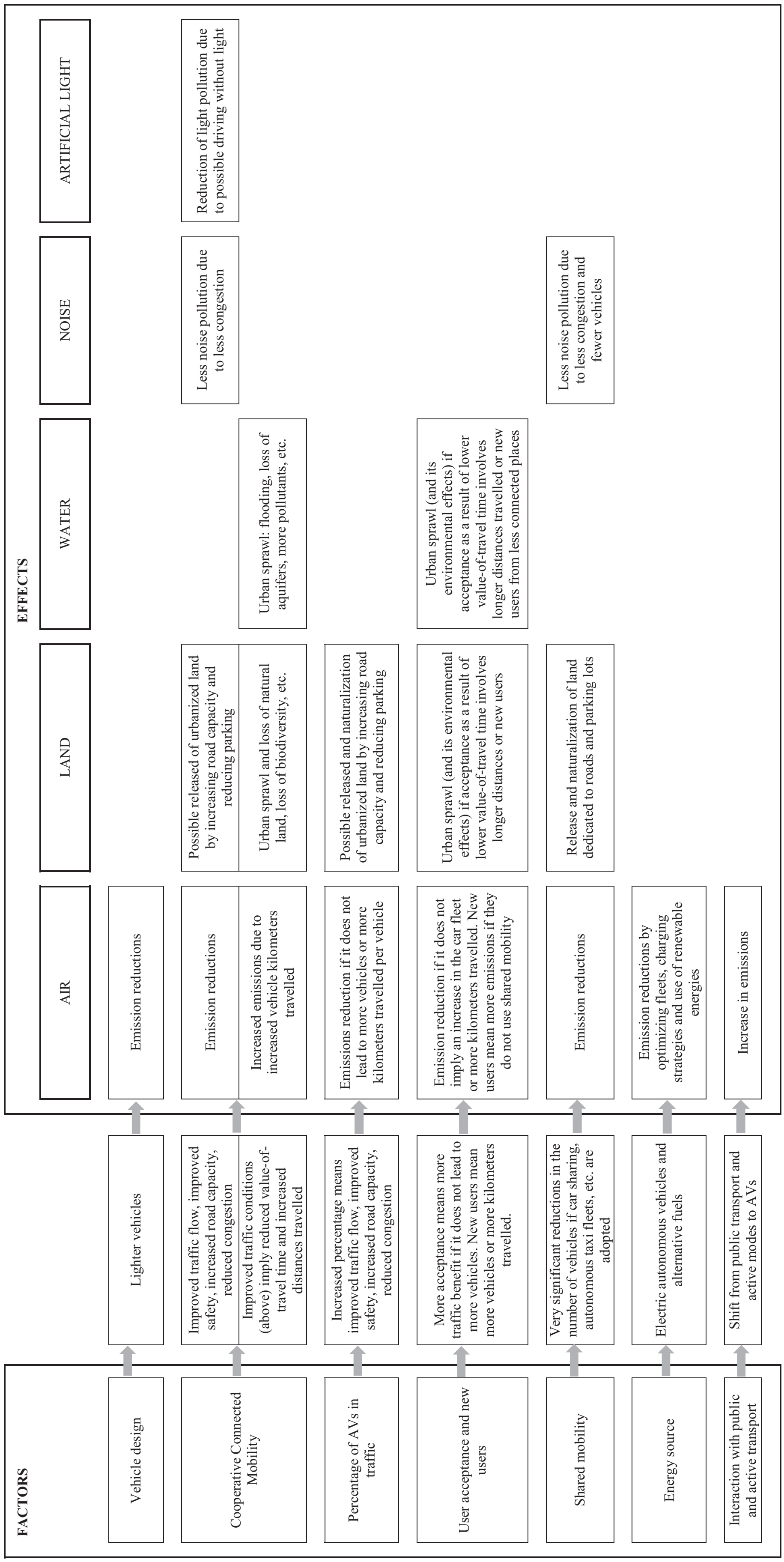

Fig. 1. Summary of the effects of Autonomous Vehicle on the Environment.

Table 3
Summary of the impacts of AVs on emissions.

	Cases	Type of study/context	Emissions variation	Reason for variations	References
Operational concepts/cases, 100% AVs traffic environment	Cooperative strategies, intersections	Micro-simulations on hypothetical road sections/intersections	−13.8% to −59%	Different Management Systems/Control Strategies. Results dependent on: Theoretical principle/approach; Signalized/Unsignalized intersections, roundabouts, isolated intersections; communications V2V, V2I; vehicle parameters considered; trajectories; traffic volume; etc.	Bento et al. (2019) Bichiou and Rakha (2019) Chen and Liu (2019) Feng et al. (2018) Filocamo et al. (2020) Z. Li et al. (2015) Lin et al. (2017) Stebbins et al. (2017) C. Wang et al. (2020) Z. Wang et al. (2020b)
	Speed strategies	Simulation on theoretical lane-drop bottleneck/capacity drop	−10.29% to −44.6%	Under the same traffic demand, different duration of an incident	Guo et al. (2020)
	Eco-routing/ eco-driving	Theoretical simulations, macro-simulations based on real urban networks (e.g. Toronto, Shanghai), micro-simulations on different terrains; field experiment (fuel consumption)	above −40%	Road network and parameters considered: real time emissions, traffic state, traffic demand, delays, velocity, direction… Type of terrain (rolling terrain, slopes)	Djavadian et al. (2020) C.L. Liu et al. (2019) J.Q. Ma et al. (2019); Tu et al. (2019) Zhai et al. (2019)
Mixed traffic environment	% traffic demand; % AVs, connected AVs, Human drivers	Simulation with specific traffic software and emission model on a real road network (Antwerp´s ring road).	−5% w/ 100% connected AVs, +11% w/ 80% AVs	Market share of manual vehicles, AVs, connected AVs; time gap (1.6 s for emissions results); traffic demand (selected 120% to show the widest variation in results)	Mattas et al. (2018)
	30% AVs; electric or conventional AVs	Simulation with micro-simulation traffic software and emission model on a real road section (a main avenue in Aveiro, Portugal)	+0.7% or − 29% w/ electric AVs	In a given day (with specific conditions); time period; traffic composition: 30% conventional AVs or 30% electric AVs; traffic parameters variation: demand, capacity, driving dynamics (acceleration)	Rafael et al. (2020)
	% AVs, % capacity, driving speed	Simulation with traffic demand model and virtual speed-emission function on a virtual transportation network (76 links and 24 nodes)	−30% at optimal speed w/ 80% AV market share	Speed, capacity, market share but assuming certain fixed parameters and conditions (no speed variance in the same link, stop-and-go emissions ignored, same vehicle characteristics, flat network, etc.)	Hwang and Song (2019)
	Different % AVs and capacity (traffic congestion)	Microscopic traffic simulation w/ emission models based on a bottleneck in a 5 km SH16 Auckland motorway stretch w/ on-off ramps	−58% to +48% depending on road capacity (70% to very heavy congestion) and market penetration	Non-congested to heavy congestion and future scenarios (very heavy congestion); market penetration rate; variable speed limit (VSL) control or no control applied	Li and Wagner (2019)
	Operational concepts, different % AVs	Micro-simulations on hypothetical road sections/intersections. Simulation on real freeway corridor (Los Angeles I-5)	−7.8% w/ speed strategies 10% AVs; up to −33.26% w/ eco-driving system and 40% AVs at intersections; up to −10.2% w/ cooperative strategies	Different management systems/operational concepts (eco-driving, coordination heuristic, speed control, platoon). Different models with different assumptions. Results dependant on: theoretical approach, congestion levels, AV/connected AV market penetration, position in the platoon, time lags, capacity	Jiang et al. (2017) McConky and Rungta (2019); Huang et al. (2020) Yu and Fan (2019)
Shared and on-demand mobility	AV fleets, different urban networks	Modeling (mainly agent-based) of shared/taxi AV fleets, with different compositions, scenarios, and assumptions on large-scale real road networks: Austin-TX (period: 2020–2050), Austin-TX (2020), NYC, Manhattan (NYC), San Francisco Bay Area, Lisbon, Austin-TX (horizon 2050)	−16.8% to −87% depending on urban environment, composition of power grid, fleet size, charging infrastructure, pollutant fees, etc.	Travel demand, waiting time, scenario length, VKT per vehicle, complete life-cycle/certain phases, lifetime per vehicle, powertrain (internal combustion vehicle, battery electric vehicle), fuel consumption, range, charging infrastructure, population distribution, travel distance, fare levels, fleet size, power composition, parking requirements, carbon policy, etc.	Gawron et al. (2019) Liu et al. (2017b) Lokhandwala and Cai (2018) Bauer et al. (2018) H. Zhang et al. (2020) Miao et al. (2019) Martínez and Viegas (2017) Jones and Leibowicz (2019)
	Shared mobility on commuting trips	Agent-based modeling of commuting with AV taxis in real road network (Ann Arbor, Michigan)	+25%	Assuming end-to-end trips and optimized fleet size (waiting time, in-vehicle time, VMT). Without variation for electric taxis because of power grid mix.	M. Lu et al. (2018)
	Large-scale mobility services	Agent-based simulation model in Hangzhou (China), hybrid ride--hailing scenario (human driving/-automated vehicles) based on December 2018 real travel orders	−12.3%	For the same order success rate, AV scenario results outperform in fleet size (less vehicles), working vehicles, waiting time, total VKT, cruise VKT, pickup length, deliver length, total profit and total emissions	F. Yao et al. (2020)

3.1.4. Overview of effects on the transport system. Compatibility with other modes of transport

Although modeling based on real city networks generally yields positive results of AVs in terms of emission reductions, the conclusions cannot necessarily be extrapolated to other cities. In a more general analysis by establishing different categories of cities, Oke et al. (2020) find that the introduction of mobility services with AVs in cities with large public transport networks is counterproductive for congestion, while in denser cities with moderate use of public transport, the penetration of shared mobility with AVs is more successful in reducing congestion. Today, 96% of the daily transport emissions generated in a large metropolitan area such as Toronto correspond to private vehicles and with the introduction of AVs, it is observed that kilometers travelled, and emissions could increase. However, it can be achieved regional emission reductions of 5% with electric AVs (A. Wang et al., 2018).

Studies on wider transport systems, such as the EU-28, show positive results by 2050 but a "selfish" use of the technology would compromise these outcomes (Noussan and Tagliapietra, 2020). Likewise, in China, only from 2045 onwards, with improved consumption parameters and increased penetration of AVs, could be seen reductions in global emissions (F. Liu et al., 2019).

As many studies advance about the interaction among different modes of transport, by 2050, vehicle kilometers could increase by 50%, the use of public transport could decrease by 18% and the use of active modes (cycling and walking) could decrease by 13% (May et al., 2020). Considering the shift that the AV may cause on active and public transport modes, some authors conduct surveys and interviews with different population samples. A survey conducted by Booth et al. (2019) show that 48% of respondents would be willing to replace public transport with an autonomous vehicle, as would 32% of those who cycle and 18% of those who walk. Issues related to safety and the use of the urban space by AVs and cyclists remain unclear (Blau et al., 2018; Latham and Nattrass, 2019). Also, studies about AVs acceptance show that a positive attitude towards environmental protection and innovation do not predisposes towards AVs (Potoglou et al., 2020; Müller, 2019; Lang and Mohnen, 2019). Surveys on shared mobility in a 100% AVs scenario show a majority of respondents in favor of choosing a SAV (Stoiber et al., 2019).

Likewise, among the experts surveyed by Nogués et al. (2020) there is a certain skepticism about the effects of AVs in urban environments, so to avoid sustainability problems in the future should be implemented policies that promote active modes of transport, improve the public transport, restrict city centers for private vehicles and design more compact urban forms. In this respect, Acheampong et al. (2021), based on survey data from Dublin, conclude that current attitudes towards a car-based transport system will be maintained in a future AV environment, but also suggest that alternative options in which car-sharing and public transport predominate are possible if appropriate transport policies and education strategies are implemented.

3.2. Effects on land

The environmental impact of AVs on land (and therefore on natural habitats) is not being studied at the moment, although several authors already indicate that one of the possible undesired effects is the intensification of urban sprawl, a phenomenon already studied in the scientific literature from the perspective of conventional vehicles.

As regards the impact of AVs on urban form, it is receiving increasing attention from researchers since, as has been said, its characteristics have the potential to multiply certain undesired effects or favor new, hitherto unthinkable, land-use possibilities. Among the former, by not having to drive, AVs' users will be able to use their trip time for work or leisure activities. For example, Bertoncello and Wee (2015) estimate 50 min free up time per user and day, reducing the cost of travelling and being more willing to travel longer distances, affecting decision-making regarding the place of residence or the location of companies. On the other hand, the improvements in traffic flow brought about by AVs make urban commuting easier and inner-city space more attractive, making it more desirable, under certain circumstances, for city dwellers to stay in the city rather than move to distant residential areas.

One parameter that will therefore define user behavior is the value of trip time, a subjective indication of how much the traveler is willing to pay to reduce the time allocated to travel. Several studies show that the introduction of AVs decreases the travel cost, to a greater or lesser extent, but this is true for urban, suburban and rural users, which may imply different trends in urban form, some of them opposing: suburban growth or the growth and densification of urban centers (Milakis et al., 2018). Gelauff et al. (2019) find that, in a scenario of high automation combined with good public transport performance in large urban areas in The Netherlands, population tends to increase in large metropolises and their suburbs, decreasing in smaller cities and their suburbs. Zhong et al. (2020) analyzing medium-sized metropolitan areas in the USA conclude that trip time reduction is most pronounced for private AVs and among suburban dwellers, reaching 32%, but is also significant among urban users, which does not result in appreciable population redistributions. Moore et al. (2020) also obtain trip time value savings of 30% but predict a horizontal urban sprawl of 68%. Bin-Nun and Binamira (2020) find that the implementation of AVs would lead to population gains in more urbanized areas (up to 12%) compared to population losses in less densely populated rural areas.

As can be seen in the different studies, the trend towards sprawl as a consequence of AVs penetration sometimes yields contradictory results. Although most models lead to sprawl, Larson and Zhao (2020) also analyze this ambiguity, concluding that it is produced by the tension between reduced commuting costs, increased costs due to the increase in both congestion and urban density as a consequence of the new residential use of parking space not needed with AVs. If shared use is not adopted and the parking space is not dedicated to residential use, the result is a dispersed urban pattern. This is similar to the result obtained by Kang and Kim (2019) in the case of Seoul.

On the other hand, several studies focus on another significant and positive aspect: the possibility of freeing up urban space currently dedicated to roads and parking. However, it is noted that only in combination with appropriate active policies, its full potential can be realized (González-González et al., 2020). Thus, the reduction of parking space can be very significant with the adoption of shared mobility (W. Zhang et al., 2015). However, some studies show that, at the same time as parking space is freed up in metropolitan centers, vehicles travel longer daily distances and there is an increase in parking space in the periphery (Harper et al., 2018; W. Zhang and Wang, 2020). Furthermore, Cugurullo et al. (2021), based on empirics generated in a survey, envision a future where a mix of human drivers, shared and private AVs, and artificial intelligences will compete for urban spaces, generating complex urban geographies with evident repercussions on the sustainability of the cities.

From an environmental point of view, the above effects or possibilities are transferred to their repercussions on energy consumption and GHG emissions but as the exacerbation of urban sprawl is one of the possible negative consequences of the implementation of AVs, it is necessary to consider the polluting effects not only on the air but on the rest of the environment, including the land. Johnson (2001) summarizes the impacts that different researchers identify in relation to sprawl and, among them, the following affect the land: loss of environmentally fragile land, smaller open spaces, loss of landscape attractiveness, absence of landscape views (mountains), monotonous or inappropriate landscape, loss of farmland, reduction of biodiversity, increased runoff and increased flooding, loss of native vegetation and fragmentation of ecosystems.

Many of the effects on land are more easily noticeable than measurable, hence the difficulty in studying them. It is also evident that there are impacts whose harmful effects are not appreciated until a certain period of time has passed, and furthermore, the perception of the risk associated with these impacts varies between different individuals. This is perhaps the reason why there are still no articles in the scientific literature that address the problem of polluting effects on the ground as a consequence of the introduction of AVs.

3.3. Effects on water

Changes in land use are one of the main factors contributing to water quality degradation. As seen in the previous section, suburban sprawl is one of the possible effects of AVs penetration and, therefore, in addition to impacting on air and land quality, it is recognized that urban and industrial land use is a determinant factor affecting stream water quality (R. Wang et al., 2021). Urbanization causes substantial changes in hydrogeological systems since, by increasing the impermeable built-up area, it increases the occurrence and intensity of flooding, decreases aquifer recharge, eliminates small surface watercourses, alters the permeability of the remaining natural terrain and increases the load of pollutants, while also increasing the demand for water for the population and its services. S. Wang et al. (2019) conclude that, analyzing the degradation and decline of water resources as a consequence of suburban urbanization in a megacity like Beijing since the 1990s, such levels may compromise the future sustainability of the city.

If, as some studies suggest, there is a link between a possible increase in low-density urban sprawl and the massive adoption of AVs (Milakis et al., 2018), its likely serious effects on the aquatic environment beyond the emissions generated should be considered. However, in view of the results obtained in the WoS and Scopus platforms, there is currently no literature that takes these effects into account.

3.4. Noise pollution

Noise and air pollution are the two most important risk factors for health in urban areas and are responsible for more than 75% of diseases attributable to environmental conditions (Hänninen et al., 2014), with road traffic being one of the largest emitters of noise.

For the analysis of the health effects of noise pollution, the parameters L_{dn}, day-night level, which is the 24 h equivalent sound level with night-time sound levels increased by 10 dB(A) and L_{den}, day-evening-night level, are commonly used. People living in urban environments in industrialized countries are exposed to L_{dn} levels above 50 dB (A) and there is sufficient scientific evidence that exposures above these levels can induce certain diseases (Passchier-Vermeer and Passchier, 2000). Despite the potential of AVs to change the future of transport and user habits, there is little literature studying the impact that its penetration can have on such important health risk factors. However, some early studies, such as the one by Patella et al. (2019b) analyzing the effects of AVs penetration on a real road network (Rome), indicate that in a scenario with a 100% presence of AVs, inner urban roads would benefit from 24% noise pollution reduction due to a 5% decrease in traffic volume.

3.5. Light pollution

Another pollutant associated with urban environments and transport routes is artificial light at night. Artificial light has negative impacts on ecosystems (Gaston et al., 2015) and some studies alert that it could be a risk factor among population (Flies et al., 2019). Besides, lightning consumes a large amount of energy, generating 1900 Mt. of CO_2 per year (IEA, 2006). As with noise pollution, little literature has been developed in relation to AV even though they could reduce the need for artificial light in certain environments. Although street and roads lightning are not only for driving issues, Stone et al. (2019) propose to study the design of AVs so that they can drive safely in low-light conditions to reduce lighting needs.

3.6. Environmental impacts correlation

This review classifies the effects of AVs according to the various physical components of the environment and explains these impacts separately, although they are all clearly related. For instance, if emissions are soaring, many other effects are likely to occur. It should be noted that if a triggering factor such as the value of travel time decreases enough for users of AVs to travel longer distances, in addition to increased emissions, more natural land would be consumed for housing and companies, in turn fragmenting and degrading the landscape and ecosystems, reducing biodiversity, etc. The sequence continues to affect natural waters, increasing flooding and runoff, degrading aquifers, and increasing water demand. It also generates light and noise pollution where it did not exist before.

Mobility benefits entail certain costs for society, in addition to GHG emissions, such as air, noise and water pollution, but also road accidents and collisions, congestion and biodiversity loss (European Commission, 2020). The solution must therefore be multi-objective taking into account the potential cascading effect of these impacts.

4. Conclusions

This literature review has highlighted the increasing attention that the likely environmental impacts of AVs are receiving from the scientific community, albeit mainly focused on analyzing energy consumption and emission levels.

New design and driving possibilities, the ability to operate in coordination with other vehicles and the infrastructure itself, the use of electric motors, their potential to optimally manage shared and on-demand mobility are some of the factors that researchers analyze in many different contexts. The optimal management of almost any kind of vehicle movements in the traffic environment thanks to cooperative driving systems results in lower emissions. Similarly, when considering mixed scenarios with conventional and autonomous vehicles, pollution decreases as the presence of AVs in the traffic flow increases. Nevertheless, some studies suggest that, depending on the ratio of AVs, emission reduction could be not significant or even negative because improvements in road capacity could lead to more traffic density and, therefore, more emissions. Similarly, with low levels of presence, AVs could worsen the inefficient behavior of human drivers.

As many authors advance, autonomous vehicles aptitude for a more efficient driving combined with shared mobility could bring the most significant reductions in emissions. Simulations of autonomous taxi fleets in real urban environments show remarkable results in terms of emission reduction (Greenblatt and Saxena, 2015; Gawron et al., 2019; Liu et al., 2017a), that even could be better if power generation is mostly based on renewable energies. However, some articles alert that outcomes seem dependent on the size of the fleet and the number of charging points (H. Zhang et al., 2020). Factors such as pollutant fees could enhance environmental benefits of shared mobility (Jones and Leibowicz, 2019) but, opposite, empty trips could lead to more emissions (M. Lu et al., 2018).

The presence of AVs is expected to affect not only road mobility but also the whole transport system. Thus, when researchers consider the interactions among autonomous vehicles and public transport, find that part of the users are willing to change their habits and to adopt that new technology. Likewise, AVs could be attractive to active transport users with negative consequences on the global assessment of emissions (May et al., 2020). Few models analyze emissions involving the rest of the transport modes in a large scale such as a whole country. Positive results are only seen on the long-term, with no major emission reduction and highly dependent on a wide range of factors.

In this article, it has been considered the passengers transportation and more specifically, passengers' vehicles but not the freight transport despite its growing importance in the urban traffic. In this respect, some researchers have point out the current significance of the logistics and their opportunities (Savelsbergh and Van Woensel, 2016), the relevance of the last-mile logistics and their inefficiencies (Ranieri et al., 2018; Digiesi et al., 2017) and more effective and sustainable approaches (Perboli and Rosano, 2019; Gružauskas et al., 2018; Haas and Friedrich, 2018, Bucsky, 2018), but further research about the impact of the autonomous driving on this sector and its environmental repercussions should be considered in future analysis.

A recent field of study is the potential of AVs to change the land use. Many models suggest that one of the likely consequences is urban sprawl, yet others suggest a possible increase in urban density, or even both. As a consequence of the decrease in the cost of travelling, commuters could be willing to travel longer distances, affecting the place of residence and location of companies. Articles on land use changes also highlight positive aspects like freeing up urban space currently dedicated to parking or even roads, among others (González-González et al., 2020). Improvements in urban traffic flow could lead to more livable cities, discouraging population to move to residential areas. Notwithstanding, population redistribution because of AVs depends on many aspects so results of the studies are not interchangeable. Anyhow, there are few analyses on the environmental aspects of land use change and only focused on energy consumption and emissions.

Noise and light pollution are barely mentioned in the literature on autonomous driving. However, as other studies advance, these impacts have notable repercussions on natural habitats and population (Hänninen et al., 2014; Gaston et al., 2015). Quieter and efficient driving, and less vehicles could improve noise pollution. Also, as AVs could drive in darker environments than human drivers, artificial lightning could be partly removed. Among it benefits could be counted the reduction in the power generation emissions.

The present review has also identified gaps and scarcely explored fields of study regarding the potential environmental impacts of AVs. New and further research on these areas would allow to a comprehensive understanding of the effects of AVs and an overall assessment of their implications.

To date, many studies analyze in detail the technical possibilities to improve the traffic flow in a 100% autonomous vehicle environment but models also involving conventional cars need further research. That period of mixed traffic composition could be critical in the acceptance of the new technology and the short-term impacts, moreover when some studies alert from some undesired effects. The interaction among AVs, conventional cars and other modes of transport in this intermediate phase would be also necessary. Shared autonomous vehicles and autonomous taxi fleets show very significative emission reduction but if users of public transit and active modes swift their habits, global assessment could be different. As some studies suggest, when considering the whole transport system, results could be less attractive than when considering just a part (Noussan and Tagliapietra, 2020).

As this review observes, environmental impacts of AVs are focused on emissions but to understand the true impact of AVs on the environment, researchers should broaden their vision to the other environments that could be affected. For example, the negative effect of urban dispersion would not only affect emissions, but would also lead to land degradation, loss of ecosystems, depletion of aquifers and natural watercourses, increased runoff, and denaturalization of the landscape. Conversely, the release of land currently occupied by car infrastructure can lead to more compact urban patterns, avoiding the occupation of more land. Moreover, to transform this space into green areas could trigger positive effects on urban air quality.

To sum up, it is needed a more comprehensive assessment of the environmental impacts of AVs. Improvements in the traffic flow in an intersection or even significative emission reductions of an autonomous taxi fleet do not lead to the same results if it is considered the whole transport system. Equally, an overall analysis of the beneficial and detrimental effects of AVs on different natural environments (air, water and land) can provide useful information for researchers and policy makers. Such information would be very useful in supporting long-term decision making in line with sustainable development and climate change mitigation goals.

A limitation of this study, partly due to the broader perspective and the multitude of dimensions and aspects considered, is the difficulty of identifying the influences that aspects such as the size and location of the case studies, the temporal context and the basic methodology used in each study have on the variations in the results advanced by the researchers. Nevertheless, the aim of this review is to provide a first general overview of the studies conducted on the total environmental impacts of AVs. This has allowed to know better the main expected effects and their potential magnitude, and to identify those dimensions or aspects that are still little explored in order to understand the overall repercussions that these vehicles may have in order to try to avoid or mitigate the most problematic ones.

CRediT authorship contribution statement

Conceptualization, R.C., E.G.-G and S.N.; methodology, R.C., E.G.-G and S.N.; formal analysis, O.S.; investigation, O.S.; writing—original draft preparation, O.S.; writing—review and editing, O.S, R.C., E.G.-G and S.N.; supervision, R.C., E.G.-G and S.N.; project administration, S.N.; funding acquisition, S.N. All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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