Connected & Autonomous Vehicles – Environmental Impacts – A review

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Abstract.

Over the last decades the vehicle industry has shown interest in integrating new technologies on vehicles' design. Such technologies are used in autonomous, connected and electrical vehicles with the primary hope of improving road safety and the environmental impact of road traffic.

Regarding the environmental impact, the transport sector has been considered responsible for Greenhouse Gas emissions for the past thirty years or more, and efforts have been made to reduce impacts of such emissions on the environment. The environmental noise is also associated with road traffic and its effects on public health, along with ways of scaling them down, have been under investigation.

Taking into consideration worldwide efforts on climate change and new vehicle technologies that are being introduced, this paper attempts to provide a review on the studies concerning the environmental and traffic noise impacts anticipated by the implementation of these kinds of vehicles in the market and in road traffic.

Two types of studies are included in this review: studies that use logical estimates to draw conclusions on how Autonomous, Connected and Electrical vehicles will alter fuel consumption, gas emission, etc., as well as studies that make use of mathematical frameworks and the data available to extract numerical results.

A comparison of the different procedures is attempted, in order to identify the factors that are influencing the emergence of anticipated environmental impacts as well as their variety and extent.

Keywords: Autonomous Vehicles, Connected Vehicles, Environmental Impacts.

1 Introduction

As transportation technology evolves, more and more car manufacturers are announcing their will to introduce new kinds of vehicles into the automobile market. Such vehicles include Autonomous (AV) and Connected Vehicles (CV) as well as Electric Vehicles.

According to [14] Connected Vehicles are considered *"vehicles that use any of a number of different communication technologies to communicate with the driver, other cars on the road (vehicle-to-vehicle [V2V]), roadside infrastructure (vehicle-to-infrastructure [V2I]), and the "Cloud" [V2C].*" The U.S. Department of Transportation's National Highway Traffic Safety Administration (NHTSA) defines Autonomous or fully automated or "self-driving" vehicles as "*Automated vehicles are those in which at least some aspects of a safety-critical control function (e.g., steering, throttle, or braking) occur without direct driver input"* [45]. In 2014 the Society of Automotive Engineers (SAE) classified AVs in 6 different levels of automation, from level 0 - where no systems interfere with driving tasks, to full automation level 5 [52].

While the terms Connected Vehicle or Autonomous Vehicle refer to the way a vehicle's course is controlled, the terms Plug-in Hybrid Electric (PHEVs), Battery electric vehicles (BEVs) or Hybrid electric vehicles (HEVs) refer to the way the vehicle is powered. Literature defines that Electric Vehicles or EVs are those that are powered solely by electric rechargeable batteries. On the other hand, Plug-in Hybrid Electric vehicles are those that are powered by a combination of both electric batteries and a petrol or diesel engine [66]. Therefore, both Connected and Autonomous Vehicles can either be Electric, Plug-in Hybrid Electric or conventional gasoline/petrol empowered.

When it comes to transport, some of the basic motives, driving scientists to improve vehicle technology, are improved vehicle and road safety and less vehicle emissions. Especially when it comes to CAVs, much effort has been given to define the environmental outcome of their implementation both concerning ghg emissions and noise.

2 Environmental issues due to traffic

Traffic sector has an impact both on air and noise pollution [8, 2, 62, 63, 48 and 61]. In order to be able to fully understand and interpret the environmental impact of new kinds of vehicles, gas emission standards, environmental regulation and ghg emissions impacts on the environment should be taken into consideration.

According to literature [8, 18, 41], there are four major greenhouse gasses that are responsible for the earth's temperature. These major GHGs are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and fluorinated gases; CO2's enters the atmosphere basically as a product of fossil fuel (coal, natural gas, burn process), Methane is emitted during the production and transport of coal, natural gas, and oil and Nitrous oxide comes from agricultural and industrial activities, while fluorinated gases are synthetic gases emitted from a variety of industrial processes [18]. In a study conducted by Policy Department A at the request of the European Parliament Committee [43] authors acknowledge the existence of a variety of air pollutants, such as carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), particulate matter (PM), which are products of the automotive sector.

According to [8] *"the transport sector is a major contributor to CO2 emission because of its dependency on fossil fuels"*. As mentioned in (European Commission, 2012) almost 23% of CO2 gases produced in all 27 EU member countries has its origin in the transport sector, while the equivalent percentage for the US reaches 34 % [18].

The impacts of Greenhouse Gases on the environment, originating from the transport sector, are widely reported by authors. Climate change, air pollution, health problems, degradation of water and soil quality are among the most important ones [3 in 17, 51, 55, 53] with climate change being of high interest.

Treaties such as the Kyoto Protocol [33], established in 2005, and the Paris Agreement [33], established in 2016, are in force so as to enhance the fight against global warming. Furthermore, other legal frameworks, such as the European Legislation "2020 climate & energy package" [21], enacted in 2009, set goals for the reduction in CO2 emissions. Legislation on fuels can be found in the USA, dating back to 1975 (Corporate Average Fuel Economy CAFE standards [1]). CO2 emissions standards were introduced by the EPA in cooperation with NHTSA [43] in 2010 and re-adjusted in 2012, and are still into effect.

3 AV Adoption patterns and potential benefits - Low Carbon Mobility, Shared Mobility, On – demand Mobility

Apart from the legal framework that is set in order to reduce carbon emissions, other practices are introduced aiming to put a halt to the increase of CO2 emissions that originate from the transport sector. A shift to shared mobility or on-demand mobility is proposed by many authors, as an answer to the GHG problem. Such a shift is also suggested as the ideal way to enhance the positive impacts of new kinds of vehicles on the environment [26, 38, 32, 58, 39, 46, 19, 64,57].

CAVs' implementation in the market and traffic is supposed to bring a big number of potential benefits: user convenience, increased road and vehicle safety, reduction of crashes, decrease of congestion, improved emissions, equity, reduced cost of travel time, parking space saving [35, 11, 2 and 65]. Among the main anticipated benefits of the CAVs implementation stand the reduction of crashes, the increase of road capacity, the decrease of congestion and fuel consumption and change in travel behavior [22]. The last two aforementioned benefits are both able to affect the amount of GHGs caused by transport. Having this in mind, new ways of car use are introduced. In particular, shared mobility, low carbon mobility and on-demand mobility travel behaviors are strongly suggested by investigators around the world as the solution.

According to [23] *"Low Carbon Mobility (LCM) is defined as mobility that results in lower levels of carbon"*. Another term used in literature is that of Low Carbon Mobility Plans (LCMP), which are defined as a set of actions in order to achieve *"desirable accessibility and mobility pattern for people and movement of goods in the cities"* [60]. Philp and Taylor in [49] suggest that *"an optimum blend of technological development, infrastructure adjustment, innovative policy developments, and community behavior change is required"* in order to achieve the reduction of GHG emissions. On-Demand Mobility is described by [26] as *"the use of shared vehicles accessed on demand"*, and it can vary in forms, such as car sharing, ridesharing/carpooling, transportation networks and e-hail services. It is through such driving behaviors that a possible increase of the VMT, resulting from CAV implementation, can be counterbalanced.

4 Connected and Autonomous Vehicles' anticipated Environmental Impacts

As mentioned above, the implementation of CAVs as well as the use of alternative fuel as gas or electric power to empower vehicles, are supposed to have an impact on the amount of the GHG emissions originating from traffic. Due to the importance of this matter, many researchers have tried to estimate or quantify the size of the anticipated effects on the environment. In this section, a review of literature on the potential environmental impacts is presented and results are summarized. The papers reviewed are displayed on table 1.

Authors use different approaches. They either use previous works' estimates to reach conclusions or they use mathematical frameworks and data available to extract numerical results concerning gas emissions, energy consumption, etc. Research is done based on the fact that environmental impacts of autonomous technology originate from the vehicles themselves, the network system as a whole and from their users. Much research is done on how autonomous driving is going to affect vehicles' operation and fuel economy. Barth, Boriboonsomsin and Wu [7] use results from previous studies of the first two ([5 & 6] , to *"identify the general areas where vehicle automation can potentially impact energy and emissions"*. Results show that energy consumption and gas emissions are strongly influenced by a vehicle's speed. More specifically, they are high at low speeds, as in case of traffic congestion, they flatten out at average speeds, and then rise up again when vehicles are moving at higher speeds.

Reference	Factor											Results
	Alternative Fuel / ElectricVehicles	Vehicle Size / Vehicle Design	Platooning	Eco-Driving	Route Choice	Traffic Congestion Reduction	VMT	On-demand mobility / Car Sharing	Penetration Levels / Automation Level	Use by underseved populations	Consumer's Travel mode Choice / Willingness to pay	
Anderson, et al., 2014	√	√	√	√		√	√	√	√			
Barcham, 2014	√	√	√	√		√	√	√	√			
Barth & Boriboonsomsin, 2008				√		√	√					7-12% Reduction in CO_2 emissions
Barth & Boriboonsomsin, 2009				√		√			√			10-20% Reduction in CO_2 emissions
Bentley, et al., 2015		√	√	√			√	√	√			
Brown, et al., 2013	√	√	√	√	√	√	√	√	√	√		90% fuel savings / 250% increase in energy use
Brown, et al., 2014	√	√	√	√	√	√	√	√	√	√		
Chen, et al., 2017	√	√	√	√	√	√	√	√	√	√		
Department for Transport, 2016	√		√		√	√			√			
Fagnant & Kockelman, 2015	√	√			√	√	√	√			√	5.6 % GHG emissions reduction
Gonder, et al., 2012	√	√		√	√				√			30 -40% fuel savings
Greenblatt & Saxena, 2015	√	√	√				√					87-94% Reduction in CO_2 emissions
Greenblatt & Shaheen, 2015								√	√			16.77-18.65% Reduction in CO emissions
Guo, et al., 2013				√	√							
Hawkins, et al., 2012	√	√					√		√			
Igliński & Babiak, 2017		√	√	√		√		√			√	40-60% reduction in GHG emissions
MacKenzie, et al., 2014	√	√	√	√		√	√	√	√	√	√	5-20% reduction in energy intensity
Miller & Heard, 2016	√	√	√		√	√	√	√	√	√		
Morrow, et al., 2014		√	√	√	√		√			√		
Pakusch, et al., 2018				√		√	√	√			√	
Wadud, et al., 2016	√	√	√	√		√		√	√	√	√	
Zhang, et al., 2015							√	√			√	

Based on that fact they estimate that there are three possible ways to reduce both energy consumption and gas emission:

(a) Reducing traffic congestion, so as to allow vehicles to move at average speeds.
(b) Vehicle platooning, so as to reduce aerodynamic drag forces, and consequently reduce fuel consumption and gas releases, and
(c) Traffic smoothing, by eliminating stop-and-go driving behavior.

Although no numerical results are introduced, Morrow et al [40] present a list of eight key factors that could influence the environmental impact of AVs' implementation in traffic, using data drawn from previous research on AVs. The factors are classified in three categories, (a) vehicle characteristics, (b) transportation network and (c) consumer choice, based on their field of influence. On terms of vehicle characteristics, authors estimate that vehicle weight, performance and right-sizing could have a positive impact on energy reduction, based on the fact that AVs are supposed to diminish/reduce - if not eliminate - car accidents, thus making all vehicles' safety equipment unnecessary. As energy consumption is proportionate to a vehicle's weight, removing safety equipment will result in much lighter and less fuel consuming cars. Furthermore, the regulation of a vehicle's speed, through automatic control, and the introduction of smaller sized vehicles, more appropriate to specific uses, would enhance all efforts to weight reduction and thus energy consumption.

As reported by [59] the energy impacts of Light Duty Automated Vehicles depend on the number of miles travelled by a vehicle, its performance and consumer acceptance. Regarding the vehicle's performance and its effect on the environment, authors of [56], after reviewing literature, conclude that there are four factors contributing to gaining maximum results: (a) Vehicle Operation, associated with eco-routing or eco-driving, (b) electrification (c) vehicle design and (d) platooning.

Eco-driving is associated with automated acceleration and braking technologies applied on CAVs. Such technologies have the ability to reduce fuel consumption and, can result, according to [13] in a fuel consumption reduction of at least 20%. Authors of [24] state that eco-driving could reduce fuel use up to 20%, in the case of aggressive drivers, and up to 15% in the case of less aggressive drivers. According to [42], as mentioned in [2], fuel economy can be improved by a 4 to 10% through eco-driving. Other studies present estimates of energy reduction: researchers of [5] suggest that a reduction of 10-20% in fuel consumption is possible, those of [10] state that a percentage of 13% is achievable, while results of (Chen, et al., 2017) show greater benefits in fuel consumption ranging between 30 to 45%. Platooning is also expected to increase fuel savings, by reducing air resistance (air drag) for cars following the leader car of the platoon. Platooning gains are greater for the vehicles in the middle of the platoon and become significantly smaller for the vehicles at the front or at the end. Studies such as the SARTRE project estimate a possible reduction of up to 20% to fuel consumption due to platooning [50]. In [64] platooning benefits on energy reduction are estimated to be somewhere between 3% and 25%, while a percentage of 10% is mentioned in [13].

Vehicle design is also considered important when it comes to fuel consumption. Authors of [38, 4, 36, 30, 12, 9], mention that lighter vehicles could decrease fuel consumption and contribute to the reduction of GHG emissions, as an indirect effect. Given the fact that CAVs are expected to reduce crashes and improve overall road safety, safety equipment would no longer be necessary, resulting in light-weight vehicles, which will consume less fuel. Such alterations in vehicle design are expected to be greater as the level of automation increases. Small vehicle mass reduction in levels 1 to 3 and great for level 4, which may even result in vehicles shaped as "*ultralight, aerodynamic pods"* [2]. Based on scenario projections, authors of [42] estimated reductions in fuel consumption between 4% to 7% in case the vehicle's weight was reduced by 25%. An estimate of 6-7% reduction in fuel consumption is presented in [44], resulting from a 10% weight reduction.

Changing fuel type, from gasoline to electricity, is assessed to be another way of reducing GHGs emissions [25, 64, 24, 29]. Studies on the environmental impacts of Electric vehicles found in literature examine the possible outcomes concerning GHG emissions through the use of Plug-in Hybrid Electric Vehicles (PHEVs), Battery electric vehicles (BEVs) or Hybrid electric vehicles (HEVs). Environmental gains from electricity powered vehicles depend both on the vehicle's power consumption as well as GHG emission reduction during battery production. Authors of (Hall & Lutsey, 2018) compared life-cycle emissions of BEVs and PHEVs to those of a conventional European car. They concluded that both BEVs and PHEVs emit less GHGs than conventional cars with BEVs being the less polluting of the two, producing up to 50% less GHGs through its life cycle compared to a conventional car. A possible further reduction was suggested to reach up to 41% through battery recycling and battery improvements technology. Similar statements are to be found in (ICCT, 2018). In the report it is stated that though battery manufacturing emissions play a significant role in the overall environmental gain, benefits from the use of electricity as engine power vary from 28 to 72% depending on the power source.

Another indirect effect on the environment is through maximizing routing efficiency. Based on the fact that CAVs are equipped with technology enabling interaction with infrastructure systems or other vehicles and providing real-time information on congestion levels, accidents etc, they could contribute to right decision making concerning route selection, thus avoiding traffic congestion and reducing emissions. In their research, authors of [27] found that fuel consumption could be reduced up to 12% when algorithms, used for modeling route selection, aim at emissions reduction. Though travel time and vehicle fleet can be increased through green route selection, the overall outcome on the environmental impact is assumed to be positive [67].

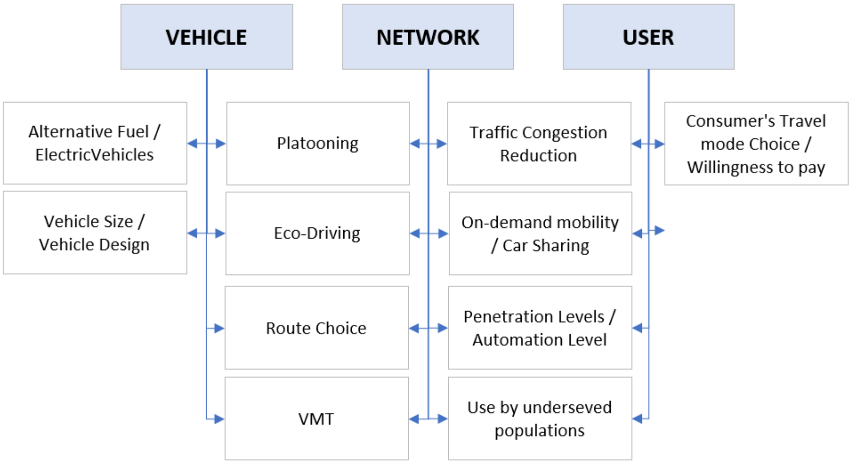
One of the most widely mentioned benefits of CAV implementation is considered to be the reduction of traffic congestion. Being able to keep smaller distances from each other, CAV use is likely to increase road capacity and decrease congestion levels. It is during peak hours that congestion reaches the highest levels. Iglinski and Babiak mention in [32] that fuel consumption can be increased up to 50% during this time. As GHG emissions and fuel consumption rise in congestion situations, a decrease in traffic congestion could result in a decrease in fuel consumption varying between 15% and 60%, depending on the AV penetration level [22, 54]. In the case of traffic congestion and traffic flow, the CAVs penetration level is of great importance, as *"at low penetration levels the benefits of CAVs are likely to be constrained by the limitations of the existing vehicle fleet"* [16].

As mentioned in section 3, on demand mobility and carsharing can have a positive impact on GHS emissions especially when Autonomous technology is engaged. As authors of [56] state: *"Shared mobility is an effective way to reduce VMT by combining trips that are temporally and spatially similar, generating many benefits including efficiency improvements, fleet downsizing, congestion reduction, energy conservation, and emissions alleviation"*. Carsharing can contribute to fuel and gas emission reduction, by eliminating unoccupied vehicle time, representing almost 90% of a vehicles' lifetime, and reducing the vehicle fleet. Martin and Shasheen estimated a reduction of 9 to 13 vehicles per vehicle sharing [37] while Greenbalt and Saxena point out that Autonomous Taxis could help drop down average energy consumption, through the use of right-sized vehicles and car-sharing, by 3% [25]. Barcham [4] notices that it is of great importance to adopt policies that would avert possible increase of the Vehicles' miles travelled (VMT), as it is that increase that would prevent any positive climate impact of the AVs' implementation [22, 67, 2] .

However, many researchers point out that the risk of Vehicle Automation can actually result in an increase of vehicle fleet number and a consequent increase in fuel consumption and GHG emissions. Although a shift to shared or on-demand mobility is desired or even necessary, the possibility of private-owned vehicle patterns prevailing could lead to an enlargement of the vehicle fleet number, more VMTs, resulting to an increase in both fuel consumption and GHG emissions. Furthermore, it is suggested that when AVs are on the road there is a possibility that VMT will increase because of the increase of road users like people with disabilities, young and elderly people. A possible increase in VMT could eventually lead to an increase in gas emissions and fuel consumption.

Consumer choice is crucial when it comes to both AVs penetration levels and adaptation of shared mobility models. Authors of [47] conducted an online survey aiming at discovering user driving preferences and future travel modes. Taking into consideration that human behavior can dramatically alter potential benefits of AVs' implementation, specifically those originating from reduced fleet number, authors performed a research in order to include human driving behavior as a significant factor. Based on the answers of 302 participants, the authors analyze user preferences on private car use, automated private car use, traditional carsharing, automated carsharing and public transport. Although it is widely discussed in literature that the implementation of AVs is going to promote car sharing, results of the research show that private car use is most preferred, followed by automated private car and public transport, while at the same time carsharing, both automated and conventional, are the least preferred. Consequently, authors doubt the fact that autonomous driving will encourage the reduction of vehicle fleet and all the environmental positive effects coming from it and suggest that autonomous carsharing is the way of achieving the best positive effects.

All key factors that are to be found in literature are summarized in the following diagram and categorized based on which component they refer to, vehicles, transportation network or user.



5 Discussion

Based on existing literature, CAVs are expected to bring noticeable changes to the transportation system and through them a reduction of the environmental impacts of the transportation sector. Many key factors will contribute to the realization of these changes. Studies show that expected reduction in CO_2 emissions varies between 7 and 94%, depending on the factors taken into consideration. GHG emissions are also expected to decrease at a lower rate though, varying between 5 and 60%, while fuel consumption seems to be the most influenced with a reduction rate between 30 and 90%.
One of the most important key factors affecting the environmental impact of CAVs, is considered to be their penetration level. Simulation studies and theoretical researches show that at lower levels of CAV penetration, positive effects tend to be less remarkable and become greater as the penetration rate rises. Penetration level affects other key factors as well, with congestion reduction being one of them. If electrification of CAVs is taken into consideration along with high penetration levels, reduction of traffic congestion is estimated to reach its maximum rate.

Though existing studies cover to a great extent the aspects of environmental impact of CAVs, more research is needed, especially in relation to public opinion on CAVs and market penetration. Users' opinion is of great importance as it affects both penetration levels and the shift to on-demand mobility and car sharing. Furthermore, new studies should be conducted taking into consideration all the key factors and combinations of them in order to detect any controversies between them. Finally, it is important that available real world data be used as to have a more realistic evaluation of the upcoming/potential positive effects.

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