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Autonomous vehicles: theoretical and practical challenges

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Abstract

Autonomous driving is expected to revolutionize road traffic attenuating current externalities, especially accidents and congestion. Carmakers, researchers and administrations have been working on autonomous driving for years and significant progress has been made. However, the doubts and challenges to overcome are still huge, as the implementation of an autonomous driving environment encompasses not only complex automotive technology, but also human behavior, ethics, traffic management strategies, policies, liability, etc. As a result, carmakers do not expect to commercially launch fully driverless vehicles in the short-term. From the technical perspective, the unequivocal detection of obstacles at high speeds and long distances is one of the greatest difficulties to face. Regarding traffic management strategies, all approaches share the vision that vehicles should behave cooperatively. General V2V cooperation and platooning are options being discussed, both with multiple variants. Various strategies, built from different standpoints, are being designed and validated using simulation. Besides, legal issues have already been arisen in the context of highly-automated driving. They range from the need for special driving licenses to much more intricate topics like liability in the event of an accident or privacy issues. All these legal and ethical concerns could hinder the spread of autonomous vehicles once technologically feasible. This paper provides an overview of the current state of the art in the key aspects of autonomous driving. Based on the information received in situ from top research centers in the field and on a literature review, authors highlight the most important advances and findings reached so far, discuss different approaches regarding autonomous traffic and propose a framework for future research.

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1. Introduction

Seen yesterday as a dream, autonomous vehicles (AVs) are closer and closer to become a reality. As time goes by and in parallel to technological advances, research on AVs is bringing to light the huge impacts that they might imply for different fields. Consequences of vehicle automation on global mobility, on traffic efficiency, on competitiveness, on the labor market, on the occupancy of the territory, etc., although unforeseeable with a high confidence level, are already being outlined. Current studies lay the foundations for future investigations and point out possible weaknesses that must be borne in mind as technology and vehicles evolve. Guaranteeing users' privacy and protection against hacking or terrorism are only some examples. However, the most controversial topic has to do with vehicle decision-making process. Controversy emerges in case of danger, as the AVs behavior will not be based on individual moral or impulsive reactions, but on ethical guidelines previously coded in the vehicles' software. Focusing on passenger transport, this paper provides an overall picture of the current state of the art on AVs that can help researchers to obtain a broader point of view in this topic. The paper is based on an exhaustive literature review and on the information gathered by the authors during the visits to top research centers in Germany and Switzerland, and it is complemented by authors' perception regarding AVs future evolution. The paper is organized as follows: Section 2 includes the state of the practice regarding AVs' technology. Next, Section 3 addresses the impact of AVs on traffic efficiency and mobility patterns. Other topics like AVs implications for the environment, users' acceptability as well as the legal and ethical challenges to overcome are discussed in Section 4. Finally, some conclusions are drawn in Section 5.

2. AVs technological perspective

The vehicle automation classification defined by the Society of Automotive Engineers (SAE, 2016) has been adopted worldwide. Six automation levels (from 0 to 5) are distinguished depending on the on-board driver assistance systems, i.e. on the distribution of the driving tasks between the vehicle and the driver. Vehicles of levels 0 to 2 are called "traditional", because the environment is still monitored by the driver. From level 3 onwards, this task is performed by the vehicle. This is a key frontier, as it involves that the vehicle must collect all the necessary data from the environment and interpret it. Furthermore, the vehicle can take responsibility for the driving task to certain limits. The culmination of automation is reached at level 5, where vehicles are called to perform the whole driving task autonomously, on all types of roads, in all speed ranges and with any weather conditions. Apart from prototypes, only AUDI offers at present a SAE3-level model to the public. Other automakers currently work on SAE3- and SAE4-level vehicles, which are likely to be available in the short-term. On the contrary, in spite of the optimistic announcements made by some companies, most forecasts agree (see Table 1) that it will take long time to make SAE5-level vehicles technologically available, and much more to achieve a significant implementation rate within the whole vehicle fleet.

Table 1. Autonomous vehicles implementation previsions.

Source	SAE4-level	SAE5-level	CAVs environment
Underwood, 2014	2019-2024	2025-2035	2040-2060
Godsmark, 2015	2020	2020-2025	2020-2030
Shladover, 2016	2020-2030	2075	?
Zmud, 2017	2021	2025-2030	?
Bloomberg, 2017	2018-2020	2028-2030	2040-2060
Litman, 2018	2020-2030	2020-2040	2060-2080
Kuhnert, 2018	2020-2030	2025-2030	?
Gehrke, 2018	2018-2021	2018-2021	2040-2050
SSCTCC, 2018	2018-2020	2040-2050	2040-2060
Shaheen, 2018	2018-2021	2023-2040	2045-2070

The main agents in cooperative autonomous driving are the vehicles, the infrastructure, the cloud and the passengers' personal devices, which must perform accurately and coordinately, supported by reliable communication systems. The vehicle's provisional architecture varies among companies and research centers. However, four distinct parts can be found in any design: the sensing system, the client system, the action system and the human-machine interface (HMI).

The sensing system is responsible for the data collection from the environment and from other vehicles. Data must be collected in real time and for all types of boundary conditions. Sensing refinement has been achieved by using a diversity of sensors in the vehicle, all of them with different strengths and weaknesses and thus appropriate to support particular aspects of driving assistance. For example, equipping vehicles with a LIDAR sensor lead to significant progress, as it provides 360° of visibility and measures distances with a precision of ±2 cm. Up to distances of 60 m LIDARs are able to accurately generate 3D maps of the nearby objects, and with less precision for distances up to 500 m. Therefore, LIDARs allow mapping and navigating, but also detecting and tracking obstacles, other cars, pedestrians, etc. A global navigation satellite system is the complement to self-localize the vehicle.

The client system consists of the hardware and operating system needed to process the data. This computing framework plays a key role, as it must in real time *i*) extract relevant and accurate information from the raw data supplied by the sensors (perception task) and *ii*) tell the vehicle how it must proceed (decision task). Very different types of hardware platforms are being designed: some companies opt for computing boxes containing distinct processors and accelerators. Others are developing system-on-chip (SoC) solutions, which are tiny integrated circuits with a microprocessor and advanced peripherals, the latter consuming less energy and having less space requirements, but still without enough computing capabilities to allow both fast and continuous sequential and parallel data processing. The support of cloud computing will be essential in this regard and will also add robustness to the system, which must continue working even after a failure. The perception task includes three parts: localization, detection and tracking, all of them achieved through data fusion performed at different levels. Localization is usually performed by algorithms that fuse data from GPS, IMU and LIDAR, resulting in a high-resolution ground map. Vision-based deep-learning technologies are achieving accurate results for object detection, as they are able to autonomously handle huge amounts of data. Deep Learning techniques have also demonstrated their suitability for object tracking relative to approaches based on computer vision. Decision-taking is one of the most challenging tasks that AVs must perform, especially in awkward situations. It encompasses prediction, path planning and obstacle avoidance, all of them performed on the basis of previous perceptions.

The action system consists of the mechanical parts of the vehicle (steering system, braking system, etc.) which will be probably improved with respect to traditional cars, in line with the other parts of the AV architecture. And finally, the HMI which is called to be minimalist in SAE5-level vehicles, basically oriented to provide information about the driving.

In spite of all this in-vehicle technology, AVs would not lead to an efficient autonomous driving per se. AVs need external support for the computing tasks, and in addition, efficient and safe mobility will not be possible if AVs behave individually. A cooperative environment is needed involving communications. AVs must at least communicate among them, with the infrastructure, with the cloud, with pedestrians, mobile phones and other personal devices, becoming CAVs (Connected Autonomous Vehicles). All these information exchanges are globally known as V2X communications. The establishment of a robust, powerful, safe and reliable communications network is still a main concern. This network must be able to transmit huge amounts of data at very high speed, with low latency, in all conditions (weather, traffic state, etc.) and without interferences. Additionally, it must be safe against hacker or terrorist attacks, and it must be able to work to some extent even in failure conditions. Interoperability between different countries must also be ensured. Two tendencies are being followed all over the world: the use of evolutions of the wireless standard 802.11p or of mobile networks, especially 5G (Intel, 2016; Arriola, 2017; Shaheen, 2018). In fact, most governments opt for their combination, as both have advantages and disadvantages. Under such a powerful communications network, the "cloud" will play a fundamental role supporting vehicles in the data storage and computation (e.g. updating of high definition maps, distributed processing, etc.). Several tasks assigned to the vehicle could also be temporarily transferred to the cloud in case of failure. Also, the communications network will lead to the development of Vehicular ad hoc Networks (VANET) on the basis of V2I and V2V communications, created by vehicles within the same area, which act as nodes (Zeadally, 2010). Because vehicles move and VANETs become instable and only cover an arbitrary range, they are considered to support

uncomplicated tasks related to safety, automated toll payment or navigation. VANETs could be linked to the cloud, which would be responsible for the most important tasks. This combination is called Vehicular Cloud Network (VCN) (Gerla, 2014; Ahmad, 2015). Another ambitious approach is that of the Internet of Vehicles (IoV) (Yang, 2014), based on the idea of the Internet of Things and not expected to materialize in the medium-term.

Finally, technological improvements in the infrastructure will also be necessary. First, those aimed at helping AVs to perform the perception tasks: horizontal and vertical road signs must be clear and complete, road layouts should be as smooth as possible, etc. (Bosetti, 2015, García et al., 2017). Second, V2I-related technologies must be deployed. Again, different administrations work together trying to design a system with continuity across borders.

3. Effects of AVs on mobility

3.1. Traffic efficiency

The first prototypes of AVs were designed with extremely conservative parameters to guarantee safety and convenience. Take as an example the time gap, set to 2 s for AVs in front of the 0.8-1 s typical in human driving (Diakaki, 2015). Furthermore, AVs accelerations and decelerations should be smooth and lane changes would take place only under very favorable conditions. Numerous studies conclude that, if quite a significant rate of AVs were introduced in the traffic stream with this driving behavior, congestion would increase due to capacity reductions. The loss in capacity has been estimated to be approximately 600 vehicles/hour/lane for an average freeway (Ntousakis, 2015). The solution is not evident, as few people would dare to travel in vehicles which autonomously drive in an aggressive way like humans do. The solution lies in cooperation between vehicles, i.e., vehicles would exchange information and make cooperative decisions looking for i) safety and ii) global efficiency of the system, despite their particular interests.

The context of driving automation implies an opportunity to finally succeed in the implementation of dynamic traffic management strategies, with the necessary technology and in a coordinated way. These strategies should be developed together with vehicle automation and implemented as the AV penetration rate grows. Traffic management strategies must be designed to deal initially with a mixed traffic environment and being gradually adapted according to the increase in the percentage of AVs. Freeway traffic is probably the first scenario to address, the reason being twofold: *i*) it represents the most controlled traffic environment and thus more suitable to make the first tests and *ii*) several freeways already have part of the required technology available. Freeway platooning could be one of the first traffic management strategies to deploy in the presence of AVs. This implies forming a sort of road train in which AVs will travel safely with very small spacings (smaller than that of human-driven vehicles) at high speeds. The idea is not new, and field experiments exist back to 1997 under the PATH program at UC Berkeley. Back then, technological limitations hindered the generalized implementation of the platooning strategy. Today, the strategy is being used by several freight truck companies in specific scenarios, with SAE2-level vehicles which usually have additional ad-hoc platooning equipment. However, there are still a lot of doubts with respect to generalized freeway platooning: minimum required vehicle automation level, type of vehicles (cars, vans, trucks, their combinations, etc.), platoon average gap, average speed, maximum length, etc. Also with respect to their interaction with traditional vehicles: shared lanes, dedicated lanes, dedicated roads, etc. Another key issue is the way in which vehicles should joint or leave the platoon. For instance, the “Traffic Engineering” research group of the Institute for Transport Planning and Systems (IVT) at the ETH Zürich developed a hybrid platooning formation strategy to optimize this process (Saeednia and Menéndez, 2016). Additionally, they proposed a distributed cooperative approach to constitute/modify truck platoons based on consensus algorithms. (Saeednia and Menéndez, 2017). These contributions could be particularized for passenger vehicle platooning. Very soon, technology will no longer be a problem either for platooning or for other advance traffic management strategies, and research in traffic management is needed more than never before. This need is even more pressing and challenging in a mixed traffic environment: safety and comfort of human drivers must be ensured while improving the overall efficiency in the presence of AVs. In fact, it has been demonstrated that traffic efficiency improves together with the increase in the penetration rate of CAVs. Enhancements become already noticeable when they reach 30% of the flow (Guériaud, 2016). The design of advanced traffic management strategies is challenging, and as fully AVs are still not available, semi-autonomous probe vehicles or simulations are being used to analyze their effects. In fact, most research

developed so far has used microsimulation software. Since macroscopic studies only consider traffic average parameters, this micro approach is initially more logical to study cooperation between vehicles, to define optimal gaps and speeds, etc. However, there is a need for a huge amount of different parameters and, even worse, empirical calibration is not possible nowadays. This does not mean that research developed so far is not valid, but that the accuracy of the results will depend on the adequateness of the chosen parameters. In order to overcome some of these limitations, researchers at the UPC-BarcelonaTech work on a project that addresses the influence of AVs on traffic flow from a mesoscopic point of view. The project COOP “Cooperative freeway driving strategies in a mixed environment with driverless and traditional vehicles”, is particularly aimed at defining platoon traffic management strategies in a mixed environment. In simple words, the mesoscopic approach consists in a macroscopic study at the lane level. Several micro hypotheses are still necessary, but they are much less than that required by a microscopic model and all of them have a physical meaning, being easier to foresee. Current results are promising.

3.2. Influence on the mobility rate and on mobility patterns

The number of users of car-sharing, ride-hailing and ride-sharing systems is continuously increasing. More and more, and particularly young people find unnecessary or even unadvisable to own a vehicle for many reasons: private vehicles typically spend more time parked (20-23 hours per day according recent analyses) than in motion, their acquisition and maintenance costs are high, parking and congestion in urban areas is highly problematic, efficient mobility alternatives in urban areas exist, the sustainability awareness is growing in developed societies, etc. This trend towards vehicle usage instead of vehicle ownership is expected to significantly intensify in the coming years: firstly, the availability of sharing and hailing services will grow and they will become cheaper due to the economies of scale. Secondly, AVs are ideal to support these mobility initiatives because already having a large technological component, the savings in labor costs will be appealing for entrepreneurs. In addition, the higher costs of AVs will favor their shared use instead of private ownership. Sharing systems based on electric AVs are expected to be promoted by administrations and well accepted by the public. The first conclusion that could be drawn from the former considerations is that the overall vehicle fleet will tend to decrease (Grosse-Ophoff et al., 2017; Litman, 2017; etc.). The vehicle fleet reduction has already been estimated in 22-25% in Europe and the U.S. by 2030 (Kuhnert and Stürmer, 2018). Regarding the mobility rate, there is no agreement: several researchers estimate a reduction of the vehicle-km per passenger but an overall increase in terms of vehicle-km. Both together imply a much higher personal mobility of society. The former is linked to sharing, as vehicles would transport more people in each travel (current car average occupancy is 1.3 pax. and this is expected to increase for shared vehicles). However, the most recent studies (Correia and van Arem, 2016; Milakis, 2017) dispute this expectancy and point out that vehicle-km per passenger will probably increase too, because of private AVs making empty journeys for example to park once their owners are at the destination. Not only this, the configuration of the collective transportation systems will also be critical. Sharing systems will only make mobility more efficient and sustainable if they substitute private vehicle trips but not those made by mass transit, whose occupancy is higher and thus more favorable to sustainability. This will be achieved if sharing acts as a complement for collective transportation, aimed for example to cover the last km of a commuter's journey towards lower density environments. Mass transit must adapt to these new scenarios, by integrating on-demand services like MaaS. First analyses show that the trade-off between the necessary investment and the overall benefits is greatly positive (Barceló, 2016). Regarding the increase of the overall vehicle-km, this will be caused by the expected reduction of transportation costs due to the higher utilization rate of vehicles and their shared use. Therefore, both freight and passenger transport are expected to rise. In addition, the spectrum of users will grow, as non-drivers, very young or very old people, etc. will be able to use AVs.

3.3. Safety-related aspects

The number of road deaths has been decreasing in most developed countries due to improvements in the vehicles' technology (e.g. driver assistance systems, stronger bodyworks, passive and active safety systems, etc.) and to the efforts of traffic administrations to fight the main causes of accidents (i.e. usage of safety systems, speeding, driving under the effects of alcohol/drugs, of the use of mobile phones while driving). However, the tendency in developing

countries like India is the opposite. Globally, the number of traffic related deaths is still huge and very far from the Zero Vision (i.e. no accidents) pursued by many countries. A cooperative autonomous driving environment will not be able to avoid all accidents. Nevertheless, taking into account that 90% of accidents derive from human errors, they are expected to be reduced to a minimum (Koopman and Wagner, 2017; Gear 2030, 2017). Two important conditions must be fulfilled in order to achieve such success: *i)* the penetration rate of fully AVs must be high and *ii)* cooperative traffic management strategies must work adequately. Otherwise, the increase in the number of vehicle-km travelled could offset to some extent the decrease in the number of accidents. Other types of risks must also be prevented. For example, the possibility that passengers of AVs become overconfident and give up using seat belts, or that pedestrians cross streets recklessly assuming that AVs will not run over them. More dangerous, AVs and V2X as a whole could be appealing targets for hackers or terrorists: ransomware or malware could be easily distributed through the networks (Douma and Aue, 2012; Litman, 2017). Governments are analyzing these issues and expect to build an extremely secure system that is resilient to this kind of attacks. Although some probability of communications being hacked will remain, it should be at least possible to resume the control in a very short time (BMVI, 2015; Shaheen, 2018, etc.).

4. Further considerations about AVs

Like in all previous transportation revolutions, the factors that will support or restrain the generalized implementation of AVs will transcend those directly related to mobility. For example, the rising awareness with respect to global warming and other environmental impacts will play a fundamental role. The number of EVs will grow together with vehicle automation, as their main disadvantages (e.g. the lack of an adequate charging network or the battery-related range anxiety) are expected to be attenuated in the short-term. Public incentives to EVs, their lower maintenance costs, the introduction of fuel economy standards and EV mandates, city access restrictions for combustion-engine-powered vehicles, among others, are factors which will surely affect the transition process towards AVs. With self-driving cars, EVs will definitively capture the market. Furthermore, well-developed management strategies including AVs can increase traffic efficiency and thus help to further reduce pollutant emissions (Ding and Rakha, 2002; Soriguera et al. 2017) and energy consumption (Wadud et al. 2016). In fact, automation is already boosting eco-driving (Barth and Boriboonsomsin, 2009; Yang et al., 2017).

AVs will also affect land use and could have a negative territorial impact. AVs are thought to provoke urban sprawl due to the lower transportation costs as well as to the possibility of using the travel time to work, rest, etc. (Meyer et al., 2016). Besides, 70% of the population is expected to live in cities by 2050. Urban planners must work to ensure that the urban sprawl will respect green, agricultural and leisure areas. Besides, on-demand well managed mobility based on organized, seamless combinations of different modes of transport is necessary to prevent congestion due to the longer commutes. As an example, park and ride facilities in the city periphery would generate free urban space and a more sustainable city.

Another important aspect that must be considered is people's acceptability of AVs. Some people distrust leaving their life "in the hands" of a machine, others are reticent to share personal data, most fear cyber-attacks, etc. In addition, some lobbies may see AVs as competitors: taxis, professional drivers, traditional garages, etc. are called adapt or disappear. In fact, the modification of the labor market is another impact of AVs that must be borne in mind. On the contrary, other sectors will take advantage of vehicle automation, like those related to informatics and communications. Supporters are also found among technology lovers, people with great environmental awareness, and of course, by those groups that nowadays have reduced mobility. The acceptability of AV by other stakeholders, like pedestrians, cyclists or drivers of traditional vehicles, must also be considered. Finally, it cannot be overlooked that age, gender, social environment and education also play a role in this regard. The most probable outcome of this discussion is that progress it is always eventually accepted. In spite of this, educational campaigns should be promoted aimed to clearly inform people about the advantages and disadvantages that AVs can bring to society,

Last but not least, vehicle automation requires significant policy changes as well as a new legislation. In fact, legal aspects are expected to postpone the introduction of self-driving vehicles much more than technological challenges. For example, an agreement ratified by 74 countries in Vienna in 1968 and modified in March 2014, maintains that drivers are responsible for controlling their vehicles. Thus, SAE5-level vehicles are not included in this regulation. The definition of the type of driving license that will be necessary and the conditions to obtain it

should also be addressed. It seems necessary that people in charge of AVs know the driving rules and how to operate on-board technologies. Mandatory periodical vehicle revisions will also radically change. These are the required regulations for tomorrow's AVs. However, we also need to face the regulations for today. Regulations aimed at facilitating the test of automated vehicles in real environments must be developed. Liability in case of accident is possibly the most controversial topic regarding AVs regulation. The problem is even more complex if one takes into account that during a long period driverless vehicles will share roads not only with traditional vehicles, but also with automated vehicles of different levels subject to different regulations. One could think that automakers should bear the responsibility if a SAE5-level vehicle is involved in an accident, as the presence of a human being is not even mandatory. This assumption would not only be unfair, but it could even prevent fully AVs from entering the market. Improper maintenance or usage could also be the culprit. Also even if everything works fine, some unavoidable accidents will occur. In such situations, the vehicle will have to make a decision. The decision-making process that researchers try to introduce in the software of AVs is supposed to mimic that of human beings. But to this end, some guidance must be programmed, which implies moral dilemmas. In fact, ethics and philosophy are already being applied trying to find a solution to the most intricate situations, like the "trolley problem" (Foot, 1967). Stakeholders, authorities and user associations already work together trying to reach a common agreement. For example, the need for a "black box" in the vehicle is seen by all parties as essential to support legal decisions in case a contingency occurs. However, only Germany has released specific guidelines on these points. The German Ethical Guidelines (BMVI Ethics Commission, 2017) highlight for example that human life has priority over that of animals or over things. They also demand fully AVs software to make the decisions that involve less damage, etc. Responsibility will also affect insurances, which are expected to be cheaper for passengers and more expensive for other stakeholders like automakers or software developers. Policies in this regard are also essential.

Finally, data treatment must also be regulated. Security and privacy are the main goals, while ensuring the data sharing required by a cooperative driving environment. For example, the German automotive industry already developed in 2014 a set of principles as a basis for secure and transparent data processing (VDA, 2016). The aforementioned German Ethical Guidelines also address this topic and in fact support the former principles. The right of users to retain the control over their data as well as the engagement of carmakers, software developers, authorities, etc. to protect data against hackers and terrorists stand out as indisputable requisites.

5. Conclusions

The paper explains how AVs could contribute to make future mobility more efficient, safer, cleaner and more inclusive. However, also highlights that several conditions must be fulfilled to achieve this goal. Otherwise, the introduction of AVs in traffic streams could not bring the desired benefits. Fully self-driving vehicles will not be commercialized soon. Meanwhile, the time needed to overcome the technological challenges must be used to design cooperative traffic management strategies which will guarantee success upon their introduction. Also, special attention must be paid to legal and ethical issues, which will determine when the society is ready for the future autonomous driving environment.

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