

Dawn of autonomous vehicles: review and challenges ahead

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ABSTRACT

This article reviews the state-of-the-art on autonomous vehicles as of 2016, including their impact at socio-economic, energy, safety, congestion, and land-use levels. This impact study focuses on issues that are common denominator and are bound to arise independently of regional factors, such as (but not restricted to) change to vehicle ownership patterns and driver behaviour, opportunities for energy and emissions savings, potential for accident reduction and lower insurance costs, and requalification of urban areas previously assigned to parking. The challenges that lie ahead for carmakers, law and policy makers are also explored, with an emphasis on how these challenges affect the urban infrastructure and issues they create for municipal planners and decision-makers. The article concludes with a summarising SWOT analysis that integrates and relates all these aspects.

Keywords: Reviews, transport planning, town and city planning

1. Introduction

The automotive industry is currently undergoing two major transformations, which will arguably shape the future of this industry and modern societies. The first of these transformations is the energy challenge, triggered by sustainability worries and environmental concerns, which calls for the industry to develop powertrains to replace the current *status-quo*, almost entirely dominated by the Internal Combustion Engine (ICE). The second, which is the main topic of this article, and is linked to the first, is the autonomous driving.

The last decades witnessed massive advances in computers, software, sensors and communications. This progress provided the necessary technological support for taking on the challenge of making an autonomous vehicle (AV). Sensing that such an artefact could open new markets, major technological companies, such as Google or Apple, took on the AV challenge, with car companies following closely. As of today, just about every major car manufacturer has its own AV programme.

From the business perspective, new business models appeared for the transport sector, such as car/ride-sharing services and modern on-demand, vehicle-as-a-service companies (UBER, Lyft, etc.). A combination of autonomous driving with the emerging business models may bring a new, disruptive mobility paradigm that has the potential to overcome many current and future mobility challenges.

The new mobility paradigm can significantly alter the current car ownership model, replacing possession/renting with on-demand services, which are expected to become more affordable in the future. It should integrate AVs with public transport systems and non-motorised transport modes, combining them efficiently, with business services bridging the gaps between modes.

Regardless, the mere existence and use of AVs can, as will be argued below, impact societies, the economy, cities, and the environment at many levels. Everything will, of course, depend on policy, consumer acceptance and market penetration. It is the purpose of this article to expose and discuss these impacts and, where possible, to explore further and quantify them.

2. State-of-the-art

Present state and levels of automation

Fully automated driving has been pursued in a stepwise approach by carmakers, who have been developing and implementing ever-more complex driver assistance systems (DAS), in an effort to offer their customers plus-values.

As of today, many conventional cars are already equipped with multiple DAS, which assist driving and manoeuvring (e.g., cruise control, lane assistance, fatigue monitoring, park assistance, traffic signal recognition, emergency braking, evasive steering, night vision, blind spot monitor, 360° cameras, traffic jam assist). See Bengler et al. (2014) for review on DAS and its goals.

Integrating the various DAS leads to a certain degree of driving autonomy, making it necessary to define automation levels. Gasser and Westhoff (2012), NHTSA (2013), and SAE International (2014) define these according to both the capabilities of the available technology and the tasks performed by the human driver (see appendix 1 for a description of SAE levels). The Society of Automobile Engineers (SAE) defines six different levels while both the USA National Highway Traffic Safety Administration (NHTSA) and the Federal Highway Research Institute (BAST) in German define only five levels (ERTRAC, 2015). The SAE distinguishes high automation (fifth level) from full automation (sixth level) since the automation level depends on the driving scenario. It should be noted that in every definition, there is a key distinction between the third and fourth level. In the third level, human driver performs part of the dynamic driving task while in the fourth level that is performed by the automated driving system.

Present day DAS are usually at the first three automation levels. Systems at upper levels are almost entirely in the development stage.

Experiences on high/full automation

Leading the pack on the quest for AVs are Google and Tesla, but there are many automakers and satellite companies in the race, some of them in cooperation (CB Insights, 2016). While high/full automation is still at a pilot stage, it is only a matter of time until the concept becomes a reality, as companies' commitment and recent examples below show:

In August 2013, the Mercedes-Benz S-Class S500 Intelligent drive completed the 'Bertha Benz memorial route' in fully autonomous mode (103 km of rural roads, small villages and major cities) (Ziegler et al., 2014).

Volvo's 'Drive Me trial' already has test AVs driving on Swedish roads and by 2017 it intends to have real-world customers using a fleet of 100 AVs on public roads (VOLVO, 2016).

1 Tesla implemented autopilot technology in October 2015 (Tesla, 2015), one of the most
2 advanced assistance technologies, capable of replacing the driver in most situations.
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5 On September 2016, UBER launched its first driverless fleet in Pittsburgh, USA, the first time,
6 driverless cars are accessible to the general public (Business, 2016). Besides the customers, there are
7 two operators in the vehicle: a trained Uber engineer and a person taking notes.
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10 Lyft followed suit and associated with General Motors to deploy and test a fleet of self-driving
11 Chevrolet Bolt electric taxis on public roads (WSJ, 2015b).
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14 Many more companies are preparing their own AV testing. See e.g. driverless-future (2016) for
15 a roadmap of these companies.
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17 18 19 **Regulation**

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21 Legislators are becoming increasingly aware that AVs call for a revision of current regulation.
22 Accordingly, in 2014 the governments of Austria, Belgium, France and Italy submitted an
23 amendment to the Vienna Convention on Road Traffic (ECE, 1968), which stipulates that ‘every
24 vehicle shall have a driver who shall at all times be able to control his vehicle’, in order to allow for
25 “vehicle systems which influence the way vehicles are driven and to take account of recent technical
26 developments” (ECE, 2014). This amendment came into force on 23/March/2016 and allows for a
27 car to drive itself if the automated driving technologies are in conformity with the United Nations
28 vehicle regulations, or can be overridden or switched off by the driver. However, the driver must be
29 present and be able to take control at any time. A workgroup within the United Nations Economic
30 Commission for Europe (UNECE) is elaborating a further update to the Vienna Convention to enable
31 the use of driverless systems in future (Mercedes-Benz, 2016).
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34 Despite the above legal updates, at present in Europe AVs cannot be freely used on public
35 roads because regulation regarding steering equipment only permits fully self-steering systems for
36 speeds of up to 10 km/h (EU (European Union), 2008). Tests have been taken under *ad hoc* legal
37 permits, specific conditions and places.
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40 Regulating AV use is but one of the legal challenges that lie ahead. As will be shown below, AVs
41 have other implications that call for special legislation.
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43 44 45 **3. Impacts of AVs**

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47 Autonomous vehicles are expected to have a high impact on cities and societies. Societal
48 changes are however slow-paced and gradual, contrasting with nowadays evolution of technology,
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1 which is usually a swift affair. Nevertheless, it seems clear that AVs will, at some stage and to a
2 certain degree, make part our lives. This section discusses how they may impact that life, assuming
3 AVs reached full automation levels.
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7 ***Socio-economic impact***

8 *Vehicle ownership*

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10 This is possibly the biggest societal change AVs can bring. Currently people tend to have (or
11 long-term rent) a car of their own, so as to benefit from ownership advantages, such as availability,
12 flexibility, privacy, and comfort, unmatched by public transportation. Collective inefficiency is the
13 price to pay for individual convenience, as private cars are mainly inactive during the day. They are
14 essentially used in the peak hours (less than 1 hour per day – ITF (2015b); WSJ (2015a)), usually
15 running with just one occupant.
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22 On-demand services, such as the taxi, provide some of the benefits of personal vehicles,
23 without the nuisance of ownership responsibilities. The rise of mobile devices made it possible for
24 new business models to appear in this sector, such as UBER or car/ride-sharing services. For the
25 latter example, it is estimated that one vehicle can replace at four to eight personal vehicles (MOMO,
26 2010), while Sivak and Schoettle (2015) estimate that the use of household vehicles by multiple
27 residents could reduce vehicle ownership up to 43% (cited by Litman (2015)). Shared AVs have the
28 potential to reduce the cost of the current on-demand services, in many use scenarios to values below
29 the cost of ownership, thus fostering a change on the vehicle ownership paradigm. Indeed, even
30 nowadays is not uncommon for people to systematically opt for on-demand services in densely
31 populated cities, when they can afford it. Because AVs fleets have no expenses with driver salaries,
32 they can lower on-demand services prices to more affordable levels (Chen et al., 2016).
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42 To understand how plausible this paradigm change can be, an estimation was made on how
43 much taxi prices may come down considering a driverless fleet, based on simple assumptions and
44 field data from a study of taxi services in Lisbon, Portugal (IMTT, 2006). Assuming that the taxi
45 company passes 90% of driverless service savings to the customer, this results in a taxi fare
46 reduction of roughly one-third. Considering scenarios of commuting and all-purpose use of a car
47 (commuting plus three daily week-end trips), cost-comparison charts between three car usufruct
48 models, namely *small city car (ownership)*, *taxi*, and *driverless taxi*, can be derived. These are shown
49 in Figures 1 and 2 below, as a function of commuting distance. More details on how the chart was
50 derived can be found in Appendix 2.
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(INSERT FIGURE 1 ABOUT HERE)

(INSERT FIGURE 2 ABOUT HERE)

Figure 1 shows that short-distance commuting (up to 5 km) becomes more economical if done resorting to a driverless AV on-demand service. If parking costs are considered, the advantage rises to commuting distances of up to 18 km. It is only when a vehicle is used for all-purposes that ownership becomes the more economical choice, and even then only if parking costs are not considered.

The main conclusion of this analysis is thus that AVs extend the range of situations where using on-demand services is advantageous. These advantages will become even more obvious if on-demand service fleets opt for electric AVs, which are cheaper to run. Although this study reflects the reality of a particular city and country (Lisbon, Portugal), it is plausible that its main assumptions, and thus its conclusions, hold in more general contexts.

Whether AVs will trigger an usufruct model change is another story because week-end and vacation trips may be considered by each consumer. Also, as there is no human surveillance, driverless taxis are more prone to be vandalised, which increases running costs due to risk (Litman, 2015). Still, AVs create a context where it becomes favourable for people to change their vehicle ownership model. This is especially true for households which currently have two vehicles (the average is 2.28 in the USA (Noor, 2008)), which can keep a family car for week-end and vacations and let go their smaller, commuting vehicle.

Unemployment

Unemployment is a major problem that can arise from automation advances. AVs will threaten the job of professional drivers (see e.g. CNBC (2016)) and change the required skills for workers linked to mobility systems. Taxi and other on-demand services drivers may be the first to experience this threat, as corporations already began driverless experiments. The UBER experiment in Pittsburgh is one such example. Truck drivers may come next, as the sedentary and predictable driving style makes it “a job ripe for disruption” (The Guardian, 2016a). Also, as will be discussed below, automation allows the efficient technique of platooning of heavy weight vehicles, whose fuel efficiency gains may further encourage trucking companies to go AV. Even if the more demanding task of driving on national/municipal roads is, at a first stage, better done by a human driver, it is likely these become completely expendable as time goes on.

Companies related to vehicle repair and maintenance may experience a reduction in demand for services, due to less accidents (see below).

Automation of manual labour work leads to more value for businesses, making the country, as a whole, richer. It also allows for creation of better, qualified jobs, as the increase in job offers for AV-related work shows (KPMG, 2015). However, more education and skills upgrade will not solve problems faced by displaced workers, a general socio-economic issue which AV dissemination will aggravate, and the solution to job losses lies in economic restructuring - cited by Palvia and Vemuri (2016). Several strategies have been proposed to solve this problem (Peters, 2016).

Accident reduction and insurance premiums

About 90% of all accidents are due to human-error (Bengler et al. (2014)). AVs have the potential to drastically reduce accidents, as AV driving is not subject to distraction, bad driving behaviour, and slow human reaction times. Consequently, it is expected that AVs have lower insurance prices (The Guardian, 2016b). Insurance companies will have to face up to new challenges such as accident liability. Schroll (2015) suggests the elimination of liability for any accidents involving self-driving cars, and recommends the creation of a National Insurance Fund to pay for all damages resulting from those accidents. In addition, other risks will arise, which will need to be evaluated by these companies, such as cyber risk and system failures.

Equity

Private AVs bring mobility to people who would otherwise be unable to drive such as e.g., teenagers, elderly, people without driver's licence. Disabled people may also benefit from AVs, depending on their degree of disability. In a context of ageing population, they may contribute to solve some mobility problems of older people (EC, 2014).

Energy/emissions and traffic impact

Vehicular communications and platooning

Vehicular communications have the potential for improving traffic efficiency and consequently reducing traffic delay. They can advise other AVs and non-AV drivers in advance about traffic events, optimising their driving by reducing stop times and unnecessary accelerations/decelerations, and lead to other ways of obtaining efficiency: Luo, Xiang et al. (2016) proposed a dynamic automated lane change manoeuvre based on vehicle-to-vehicle (V2V) communication, whereas Zohdy and Rakha (2016) developed a tool that optimises the movement of vehicles equipped with cooperative adaptive cruise control in the vicinity of intersections, which can reduce average intersection delay and fuel consumption by 90% and 45%, respectively. Again, the advantages of

these technologies are strongly dependent on their penetration rates. If all vehicles were autonomous, intersections could become fully smart, with traffic flowing in an interwoven way, for almost zero delay (Tachet et al., 2016). Since this situation is not expectable in the near-future, research has been done on how to best harmonise intersection flow with incoming AVs and non-AVs (Yang and Monterola, 2016).

Vehicle-to-vehicle and vehicle-to-infrastructure (V2I) communications, whose reaction times are much shorter than human times, make platooning possible, i.e. to have vehicles riding very close to each other, reducing aerodynamic drag and consequently fuel consumption. Zabat et al. (1995) showed that fuel efficiency could improve up to 30% - cited by Alessandrini et al. (2015). In addition, close riding reduces congestion. Platooning requires however legal changes for road cruising, as nowadays it is mandatory to keep a distance to next vehicle.

The greater the market penetration of AVs and vehicular communications, the more effective platooning will be. Wang et al. (2015) found in simulations that both emissions and total travel delay of the platoon were reduced as market penetration of AVs increased. The same conclusion was reached by Li et al. (2015), who studied a fuel-saving strategy (Pulse-and-Glide) in a platoon with AVs and non-AVs.

Electric vehicles and on-demand services

On-demand services are also a natural stage for the massification of electric AVs (Chen et al., 2016), as these are cheaper to operate and maintain (Egbue and Long, 2012), have zero emissions (important in an urban environment), and automatically look for a charging station when low on battery. If the above-argued rise in vehicle-as-a-service use becomes a reality, it will have as by-product a speed up of vehicle fleet replacement, thereby facilitating the introduction of new, more fuel-efficient vehicles and technologies. More on-demand services usage also translates to less fuel used in seeking for a parking place, an activity which can represent 40% of fuel use in congested urban areas (Mitchell, 2007).

Smaller and lighter vehicles

OECD average car occupancy rate is about 1.5 (ITF, 2015a). Since AVs have a permanently vacant seat, vehicle-as-a-service companies are likely to invest on fleets of smaller, lighter two-seater cars, which are more efficient than general purpose vehicles with respect to costs, energy and space.

Built-in safety and crash resistance features is one of the reasons conventional vehicles get heavy. As automation increases, AVs became safer and consequently some of these features can be

removed, reducing fuel consumption and emissions. According to MacKenzie et al. (2014), safety features contributed 112 kg out of 1452 kg (7.7%) of the average new USA car's weight in 2011. The removal of safety weights would decrease fuel consumption by 5.5% - cited by Wadud et al. (2016).

Automated eco-driving

Eco-driving is a driving pattern which avoids high speeds and sharp accelerations/breaking. It can reduce fuel consumption and emissions by 5-20% (Barth and Boriboonsomsin, 2009) and improve safety. Eco-driving patterns can be programmed into AV control systems, which additionally can operate them more efficiently than human drivers.

Traffic congestion and transport infrastructure

Since AVs can provide mobility for more people, travel demand may increase. Sivak and Schoettle (2015) estimate this increase to go as high as 11%. The potential of AVs to reduce travel costs and travel time may also induce people to make more, and/or longer, trips – Jevon's Paradox (Norton, 2015). However, more travel demand does not necessarily implies more vehicles on the road. Dynamic ride sharing schemes can be used to collect unable driving people in the same neighbourhood and working/undertakings (leisure activities) in the same place (Fagnant and Kockelman, 2015). This increase in demand will depend on the new mobility pattern/vehicle ownership pattern.

This demand increase can, to some extent, be accommodated by the infrastructure because AVs are more traffic-efficient, due to platooning and vehicle communication. In the same spirit, price decrease of on-demand services can make these more attractive as a hub transport mode between public transport modes, which are more space-efficient, further reducing congestion.

It is therefore not clear whether AVs can ultimately lead to more or less traffic congestion. The land-use discussion below brings even more uncertainty to this issue.

Land-use

Mobility and land-use have been inherently intertwined. There has been much speculation concerning the land-use impacts of AVs (Heinrichs (2016); Alessandrini et al. (2015); Bajpai (2016)), as it may trigger multiple effects. For example, a reduction in vehicle ownership will arguably decrease parking requirements, while a reduction of travel costs and travel times might induce more urban sprawling.

Parking

Currently cars are used only for short periods of time. Most of the time, they stay parked (WSJ, 2015a). Finding a parking spot may, in addition to fuel waste, increase traffic up to 15% (Alessandrini et al., 2015). Fully AVs can mitigate these problems since they can drive passengers to their destination, and then drive home or to a parking area further away. It is however not clear whether society will accept empty AVs squandering fuel and polluting while looking for parking far away. On-demand services or shared AVs are more efficient in this respect, as they do not need parking.

Nevertheless, AVs do have potential for saving parking space, not only by increasing the use of on-demand services, but also by reducing space required for self-parking, should it be necessary. According to Safdie (1998), compact storage of AVs in specialized depots requires only one quarter of the space currently required in a conventional parking (cited by Alessandrini et al. (2015)).

Urban environment

The increase of urban sprawl that lower travel costs/time may induce can be partly compensated by judiciously relocating space freed up from the decrease in parking needs. If this extra space from e.g., supressing a parking lane, is used to construct quality bikepaths, an increase in bicycle use can be expected (Cervero et al., 2013), decongesting the streets and possibly contributing to break the vicious cycle of automobile use (UN, 2012) and bring people to the city centres. An architectural study on possible street configuration changes for the city of San Francisco, USA, was presented in (Tierney, 2014). One of the examples given in that study featured a 100 ft wide street with eight lanes converted into a four-lane street with bike lanes and double the green space.

Political decision making is crucial here: if freed-up space is not used to foster active travel modes or public transportation, it may be used for something else that goes in the opposite direction.

Risks and Challenges

Although the potential benefits of AVs are likely to be substantial, their use will pose several risks and challenges. The adoption of AVs will greatly depend on the way in which those risks and challenges are managed. It will not be an easy task since technologies have been evolving faster than the regulators can keep up.

Technological barriers/developments

Prior to massification, AVs need to be able to operate competently in the heavily constrained 2D environment that is traffic, especially urban traffic. Reaching navigation proficiency in this environment is much more complex than in the case of airplanes, which is the main reason auto-pilot appeared for airplanes much sooner than for cars.

AVs use various sensors systems and digital maps to scan their nearby environment. All information is combined in an on-board computer system that uses sophisticated algorithms to determine if the vehicle can move to a new position, in a continuous process which makes decisions many times per second. This navigation system must be reliable in all weather conditions and environments for that, there is still a lot of work to do.

Vehicle map position must precise and reliable in real-time, as well as environment information. Some situations have proved very challenging, mainly because technology is based on optical systems. For example: hidden lane markings, night-time, bad weather conditions, bridges, blinding light from the sun, obscured lights, unusual signage, four-way junctions, hand gestures, head nods and hand gestures, blocked GPS signal, etc. In addition AVs will need to be able to recognize and deal appropriately with unforeseen situations.

Overcoming these situations reliably requires improving maps, sensors and computer algorithms. Deep learning systems (TechCrunch, 2016) may help dealing with unpredictable environments, as they can pass human-like decision making patterns to vehicles. This requires however a long learning period, which may delay time-to-market. Instead, some improvements can also be made to fix the infrastructure in order to be as predictable as possible (WIRED, 2016).

In the quest for high-precision maps and GPS data, which are essential for AVs, the Japanese government and the European Union plan integration of their GPS satellite constellations (NIKKEY Asian Review, 2016). An alternative to GPS (or complement to it) was developed a team of USA researchers, exploiting existing environmental signals such as cellular and Wi-Fi (TECH i.e., 2016). Detailed street-level maps of cities using vector-based graphics have also been developed (Road Show, 2016). With this technology, AVs determine their position by calculating their distance to known objects, instead of using GPS.

Other technological developments include: software for vehicle guidance without GPS by Oxbotica (Popular Science, 2016); a localizing ground-penetrating radar (LGPR) that works well in all weather conditions, day and night, developed by the MIT Lincoln Laboratory (MIT News, 2016); LIDAR technology, which allows AVs drive in the dark as in daylight (Fortune, 2016) (electrek@, 2016). This technology has become increasingly cheaper and smaller (Autoevolution, 2016).

Challenges for municipalities

As recognized by Fox (2016), “Currently, little planning is being done to prepare for driverless technology”. But municipal decision-makers will soon be prompted to plan the city for AVs. They will face both technical decisions (e.g., transport infrastructure issues) and political ones (e.g., land-use policies), whose outcome may either favour a smooth AV transition or complicate matters. A breakdown of possible issues that municipalities may encounter can be found in (Guerra, 2015).

Legal, liability and ethical issues

Along with regulatory legislation on how AVs are to be used, the Highway Code and certification standards will need to be revised. The Gear 2030 (EC, 2016) presents a review of the EU legislation related with AVs, with special attention to the challenges that such vehicles will pose.

Of particular importance is liability in accident cases. If an accident occurs, who is liable? The car’s owner, or the automaker? Some automakers (Mercedes, Volvo and Goggle) said they will accept responsibility and liability if their technology is at fault once it becomes commercially available (Jalopnik, 2015). Hevelke and Nida-Rümelin (2015) present a discussion about who should be held responsible for accidents of fully AVs from a moral stand point. According to them, automakers responsibility should be limited to not obstruct AVs improvements.

As to ethical problems, these may arise before imminent crashing, with algorithm behaviour having to decide which humans to endanger (Goodall, 2014).

Cybersecurity and data privacy

Like with all electronical devices, AV cybersecurity is a serious issue. In 2015 two hackers remotely took control of a Jeep Cherokee (WIRED, 2015) and this year a team of hackers did the same for a Tesla Model S (The Guardian, 2016c), raising fears that a large-scale attack could bring a city to a halt. As result, some carmakers and service companies resorted to crowdsourcing, rewarding hackers who find bugs in theirs software. A set of automotive cybersecurity best practices was also published (AUTO-ISAC, 2016).

AVs collect massive amounts of data as they operate, data which can be “foodstock” for business opportunities (Financial Post, 2016). Associated to this are data privacy and security issues. Authorities are becoming aware of these issues and draft regulations are starting to appear (DMV, 2015).

4. SWOT analysis

The SWOT table below summarises the discussion of previous sections. It is presented from a general, holistic perspective, not specifically a business-oriented one. One of its key features is that congestion and traffic demand could be interchanged, depending on the political choices made by municipal decision-makers.

(INSERT TABLE 1 ABOUT HERE)

5. Conclusions and future

The usually hard task of anticipating the future becomes even harder when a large change, such as the appearance of autonomous vehicles, is looming. Many consequences of their appearance are, at best, nebulous at the present stage, along with how deep they might reach. What seems to be consensual is the fact that AVs will bring, sooner or later, a paradigm change in transport. Whether this change will come from widespread adhesion to new car usufruct models, traffic efficiency, electric powering, other factors or any combination of former is not clear. Neither is what practical implications it will have on cities, especially if one considers that cities change due to many factors.

This research summarised the possible impacts of AVs and the state-of-the-art with respect to academic research on the subject. It also argued that AVs can make alternative car usufruct models more affordable, possibly to an extent large enough that these can subsequently shape the city and traffic. However, technological hurdles must be surpassed before any of these come to fruition. Recent Tesla auto-pilot crashes prove even the more basic AV functions need vital upgrades, leaving harnessing of all AV potential still far away.

An AV-based society requires a different collective mind-set. People will need time to adapt, and it is likely that some die-hards will never give-up being at the helm. Nevertheless, with big companies so committed to AV development, it is only a matter of time before some of the aforementioned impacts unveil. Some forecasts as to what the future may bring can be found in the recent work of (Litman, 2015).

With research on AVs impacts still at its infancy, the field is ripe for exploring and modelling them in a quantitative way, anticipating their extent and side effects. Research on usufruct model changes, traffic demand and congestion, and how to best integrate AV with normal traffic rank on top of this to-do list, given their potential to shape the city and its urban way of life. Extending the study presented in this article in section 3 to more cities and countries may help estimate short- to mid-term regional penetration rates.

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APPENDIX 1

SAE level	Name	Narrative Definition	Execution of Steering and Acceleration/Deceleration	Monitoring of Driving Environment	Fallback Performance of Dynamic Driving Task	System Capability (Driving Modes)
Human driver monitors the driving environment						
0	No Automation	the full-time performance by the <i>human driver</i> of all aspects of the <i>dynamic driving task</i> , even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	Driver Assistance	the <i>driving mode</i> -specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the <i>human driver</i> perform all remaining aspects of the <i>dynamic driving task</i>	Human driver and system	Human driver	Human driver	Some driving modes
2	Partial Automation	the <i>driving mode</i> -specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the <i>human driver</i> perform all remaining aspects of the <i>dynamic driving task</i>	System	Human driver	Human driver	Some driving modes
Automated driving system ("system") monitors the driving environment						
3	Conditional Automation	the <i>driving mode</i> -specific performance by an <i>automated driving system</i> of all aspects of the dynamic driving task with the expectation that the <i>human driver</i> will respond appropriately to a <i>request to intervene</i>	System	System	Human driver	Some driving modes
4	High Automation	the <i>driving mode</i> -specific performance by an automated driving system of all aspects of the <i>dynamic driving task</i> , even if a <i>human driver</i> does not respond appropriately to a <i>request to intervene</i>	System	System	System	Some driving modes
5	Full Automation	the full-time performance by an <i>automated driving system</i> of all aspects of the <i>dynamic driving task</i> under all roadway and environmental conditions that can be managed by a <i>human driver</i>	System	System	System	All driving modes

Source: SAE International (2014)

APPENDIX 2

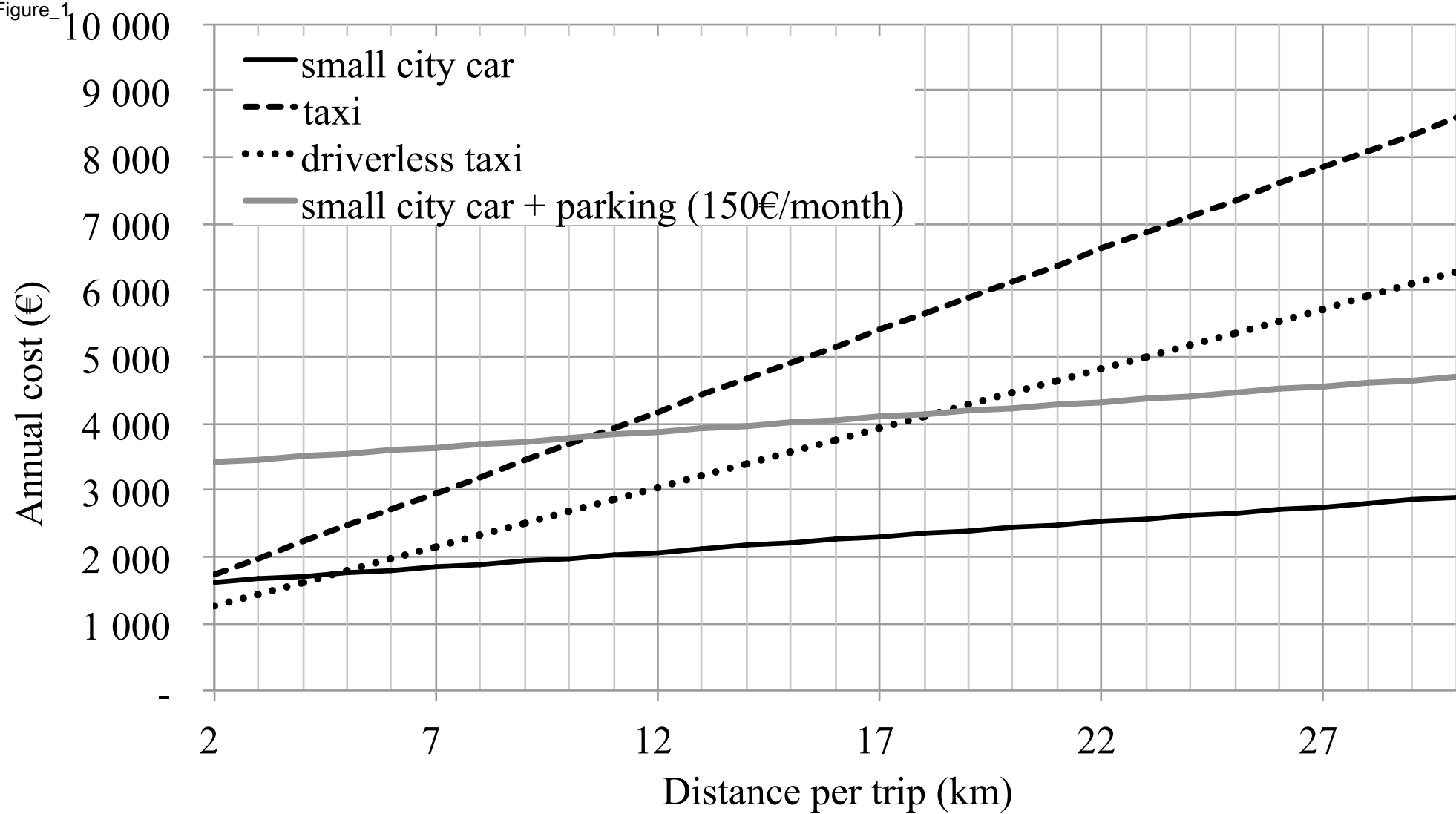
This appendix discusses the assumptions made for the usufruct model study. For the three different car usufruct models, *small city car (ownership)*, *taxi*, and *driverless taxi*, these assumptions were made as follows.

First, taxi company income and expenses were taken from the IMTT taxi study for the city of Lisbon, Portugal (IMTT, 2006). Driver salary was removed from the expenses and depreciation was increased to that for a vehicle costing an excess 10 000 EUR over a regular one (extra cost of driverless capabilities (Litman, 2015). Considering other variables as constant, e.g., service frequency; average service kilometres; occupancy percentage; day/night service percentages (respectively 65%/35%); fuel costs, it was calculated that a decrease of 32% on taxi fares was possible, assuming that the taxi company would want an increase of 10% on its profit margin.

Second, based on taxi fares for regular taxis and driverless taxis, yearly commuting costs were evaluated as function of commuting distance for both taxi types, assuming five days/week of commuting (two trips/day). For the all-purpose case, along with commuting, six week-end trips were also considered (three each week-end day). This resulted in the dashed lines of figures 1 and 2. Note that Portuguese week-end taxi fares are more expensive than week-days fares, which is why taxis are more advantageous for commuting only.

Finally, to evaluate ownership costs, it was assumed commuting would be carried out on a small city car (12 000 EUR cost), considering 7 litres/100 km consumption, 2016 gasoline costs, 200 EUR insurance costs, 100 EUR circulation tax, and yearly linear depreciation for 10 year vehicle life cycle with 10% buyback value. This resulted in the dark solid lines of figures 1 and 2. The grey solid lines on these figures show ownership costs if a flat rate of 150 EUR/month is added for parking expenses (average monthly parking cost in Lisbon).

Figure_1



Figure_2

