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1 Introduction

The recent rapid technological development of self-driving cars led to today's situation in which tests with driver-less cars are performed all around the world. Lately, those developments are covered extensively in the news (Silberg et al., 2013; Fraedrich and Lenz, 2014). With increasingly autonomous driving assistance systems in mass car production the shift towards a fully-automated driving experience has already begun. While the progression into such a future might be gradual, autonomous vehicles are generally regarded as a disruptive force (Maunsell et al., 2014) with the potential to drastically change not only the traffic environment, but also the way we see mobility, we design cities and, consequently, work and live in an increasingly connected society with huge economic implications (Shanker et al., 2013).

The great challenge of research today is to develop coherent scenarios of a driver-less future by the means of historical analysis, concise assumptions, predictions and simulations. This report gives an overview about current results and forecasts around autonomous vehicles (AVs).

For that matter, it is necessary to define what exactly is understood as an autonomous vehicle (AV) in this report. While the technology can be adapted to a great variety of different vehicle types, here road-based transport is considered specifically, covering adaptations of self-driving technology to private cars and public transport solutions. In that regard the terms "autonomous", "self-driving" and "driver-less" are used interchangeably as is often the case in the existing literature in distinction to CVs (conventional vehicles).

Furthermore, it needs to be defined on which time scope the review addresses. While the technological development is already making progress, the adoption of self-driving cars is just beginning. There are plenty of scenarios on how the route towards a large-scale use of AVs will look like, with technological, societal, legal and economic barriers. While those aspects will be covered briefly in the next sections, the main part of the report will focus on the ideal scenario where AVs have become a fixed part of the traffic environment.

1.1 Technological Progress

The very reason that questions regarding the societal impact of AVs need to be asked, is that the enabling technologies are advancing with great pace. As evidenced by the DARPA challenges on autonomous driving (DARPA, 2014), huge progress has been made just in the last decade. In order to standardize discussions about AV technology, the NHTSA defined 5 levels (from 0 to 4) of automation in self-driving cars (NHTSA, 2013).

With autonomous driving on highways as released by Tesla or soon to be tested on a large scale in Gothenburg (City of Gothenburg, 2016), level 3 (autonomous driving in specific environments and situations) on that scale has already been reached. Gradually, AVs are expected to cope with less and less confined conditions such as highways or parking lots until a fully autonomous driving in all environments and situations can be provided in a safe manner (level 4).

In order to grasp the challenges within this development, it needs to be broken down what "self-driving technology" is actually referring too. On the software side, it relies on artificial intelligence, sensor fusion, machine learning and big data, where huge advances have been made in recent years. On the hardware side one needs to consider vehicle-to-vehicle and vehicle-to-infrastructure technology, which is developed by the ICT industry, on one hand, as well as sensors and their respective processing units on the other hand. In general, one needs to distinguish between connected and autonomous vehicles. While AVs are likely to be dependent on communication technology, it could also be possible that AVs will work truly "autonomous" in the sense that no communication with external vehicles and infrastructure is needed. Furthermore, it is often implied that AVs are powered by electricity, rather than fossil fuels (Litman, 2014), therefore the electrification of private cars and the development of powerful battery solutions are also main components of AV development.

Predicting the speed with which all the related technologies will converge towards level 4 autonomy is still a difficult task. For instance, the comparably slow progress in battery technology might be a main restriction for the technological development and, even more so, the large-scale adoption of self-driving vehicles.

Nevertheless, the existing literature agrees that fully autonomous cars are to appear within the next decade and that within the next 50 years a large number of vehicles on the road will feature fully autonomous driving. Numerous predictions include Bansal and Kockelman (2016) who are predicting 25% of vehicles being level 4 autonomomous by 2045, Lavasani et al. (2016) inferring a saturation by 2050 using a simulation on technology diffusion, Litman (2014) stating that AVs would become affordable for a broad majority between 2040 and 2060 and Bierstedt et al. (2014) predicting that AVs will be available in convined environments by 2040 and on public streets from 2050 on. Further time stamps are the introduction of full AVs, predicted at 2025 by Mosquet et al. (2015) and Bernhart et al. (2016), and from 2030 onwards in Bertoncello and Wee (2015). In general it is expected that personal and freight transport will follow similar patterns, though differences in technology exist. Since long-haul freight traffic is mostly taking place in better controlled highway situations, AV technology for trucks is expected to appear first. This thought is motivated by the large amount of savings that AVs can bring to the freight industry as will be outlined in a later chapter.

In terms of technological progress and acceptance of the technology, the German industry is leading the Automated Vehicles Index (Bernhart et al., 2016), followed by the United States, Sweden, and France on sixth place.

1.2 Adoption Forecast

While there is a range of predictions from optimistic to conservative on when exactly AVs will be an established element in the traffic environment, the path to that point seems to be clearer in the literature. Generally, legal, societal and infrastructural realities in different countries define what is necessary to do in order to arrive at fully autonomous vehicles on the roads and how easy or difficult this transition will be. Country-specific analyses have been done for Australia (Maunsell et al., 2014), the Europe-wide CityMobil2 project (Alessandrini et al., 2015), Austria (Azmat et al., 2016), Korea (Kim et al., 2015), the United Kingdom (Clark et al., 2016), Singapore (Tan and Tham, 2014)), the Netherlands (Milakis et al., 2015) and the United States (Fagnant and Kockelman, 2015; Burmeister et al., 2014).

Besides the technological challenges mentioned before, there is a number of additional barriers that need to be taken until AVs will be an integrated part of everyday life. The following paragraphs will give a short overview about those limiting factors, while prospective solutions will be described in the respective chapters:

Legal issues and questions of liability need to be answered in order to allow for autonomous vehicles. As of today it is not completely clear, who will take responsibility if property is damaged or people are hurt by autonomous vehicles. This also highly depends on the actual level of automation, since a user who has no possibility to interfere with potential harmful manoeuvres of the car, cannot be held accountable. On the other hand, service operators might be reluctant to take more and more responsibility off the driver when there is still an option to interfere. Therefore legal issues can be seen as a major challenge in the adoption phase, while the situation might become easier once a considerable share of autonomous vehicles is reached. Pathways into viable legal and liability scenarios, including privacy issues (Schoonmaker, 2016), are discussed in Sheriff (2016), Schellekens (2015), Lederman et al. (2016) and NHTSA (2013).

Societal barriers arise mainly from the restructuring of the labour market. Along the general decrease of industrial work due to more and more automation, AVs will lead to a reduction of the number of jobs in transport and logistics (Spinoulas et al., 2015; Guerra, 2016). This mainly covers driving personnel for public transport, taxis and the freight sector and doesn't stop at related sectors such as for the maintenance of the vehicles, or at emergency room personel due to the reduced number of car crashes (Shanker et al., 2013). What is common in these

reductions is that mainly jobs with low wages and limited expertise are eliminated, while few are created, which require advanced technological knowledge. Facing these adverse effects of AVs it might be a risky step to politically support the development of AV-centred infrastructure in the traffic system today. While the technology is available, close to no metropolitan planning efforts are revealed publicly (Guerra, 2016) due to the high uncertainty about public perception. It is conjectured that in order to transform individual benefits of single users into population-wide societal benefits, regulatory actions, which will be explained later, need to be taken (Anderson et al., 2016; Lamotte et al., 2016). However, it is also argued that "aggressive regulatory action is premature and can probably do more harm than good" (Anderson et al., 2016).

Behavioural barriers are defined by the will and motivation of people to engage in autonomous mobility. While at early stages, people with high interest in the technology might be the only adopters, the progressive cost reduction and increased availability will eventually make AVs more attractive than conventional transport (Chen, 2015; Mosquet et al., 2015). Even though it might be the rational choice to use an AV at this point, it is not clear if people actually want to switch. After all, it seems, that the attachment to the own private car as a kind of status symbol, might be a challenge to overcome for the large-scale adoption of autonomous vehicles (Krueger et al., 2016). On the other hand, in case that AVs are used as private vehicles, owning one's own autonomous car might work even better as a status symbol. Again, the main challenge lies on the way to full autonomy. As long as conventional traffic is the majority on the road, behavioural aspects are expected to have an inhibiting effect on the adoption. Once a major share of autonomy is reached, it will be easier to argue for infrastructure, taxing and pricing decisions which favour autonomous vehicles.

Looking at these major barriers, it becomes clear, that the adoption of AVs will by far not be a linear process. Depending on the future developments in a multitude of aspects, highly optimistic scenarios with fast adoption rates, as well as highly conservative ones with a minimum diffusion can be argued for. The main driving forces are identified as technology, polcy, personal attitudes, the economy and the environment in Milakis et al. (2015), similarly Maunsell et al. (2014) define standards, drivers' concerns, customer rights and regulatory decisions as major stepping stones. In general, it should be much more difficult to predict exactly how the adoption process (Fraedrich et al., 2015) will look like, rather than how society will make use of autonomous vehicles when they are extensively available. Therefore, this report will focus, though not exclusively, on such a scenario of high availability.

Still, such a scenario comes with a great amount of uncertainty due to the outlook being heavily characterized by rebound effects. For instance, while a cheap AV service might attract CV users, the capacity in the road network could be drastically increased due to closer distances between vehicles (Shi and Prevedouros, 2016) and intelligent crossings (Yang, 2016). However, if the

service is similarly attractive to public transit users, their mode choices might lead to an increase of AV trip demand with more vehicles on the road (Litman, 2014), effectively competing for capacity. Therefore, it is necessary to study the net effects of the introduction of AVs with many components of the traffic network, which cannot be examined as an isolated system. For the assessment of the impacts of AVs on the traffic environment, understanding and quantifying these equilibria, is a crucial task.

1.3 Methodology

Research around autonomous vehicles is conducted using a variety of methods. By combining all the different results, it is possible to arrive at scenarios, which are backed by qualitative reasoning and predictions while providing numbers and measures, which are consistent with those prospects. The different techniques being used can be roughly categorized as follows:

Narrative approaches, mainly based on previous experiences, expert opinions and reasoning, are the foundation of the research. By examining similar technological developments in the past, imagining the advantages of AVs and inferring ways of implementing them, future scenarios are compiled. Influential documents include Litman (2014), Anderson et al. (2016) and Fagnant and Kockelman (2015).

Historical data can be used in a statistical way to get insights into the adoption process. By examining former diffusion processes of certain technologies, the adoption of AVs can be predicted and likely time frames can be derived (Lavasani et al., 2016; Nieuwenhuijsen, 2015; Silberg et al., 2013). Furthermore, aggregation techniques of websites, blogs and Twitter are used in order to statistically capture public opinions and concerns on the topic (Bazilinskyy et al., 2015).

Questionaires and surveys allow the generation of data to examine the motivation of people, including acceptable pricing structures of AVs, their will to give up their private or family car, their expected usage patterns and their general attitude towards the new technology. As a requirement to create meaningful stated choice experiments, already well-thought scenarios are necessary, which are built by combining the findings from the narrative approaches. An overview on existing surveys is given by Becker and Axhausen (2016). Additional results have been obtained by questioning metropolitan traffic planners (Gruel and Stanford, 2016) and international traffic experts (Alessandrini et al., 2015).

Simulations offer the possibility to test specific scenarios and therefore give quantitative insights into the adoption of AVs. As stated previously, implementing AVs in the traffic system will give

rise to a vast number of simultaneous, partly mutually cancelling and competing effects. While qualitative reasoning can acknowledge their existence, simulations are able to yield measures on their magnitude. However, in order to arrive at meaningful results, realistic narratives about AVs are needed, as well as concrete data input from questionnaires and surveys. Simulations on AVs are numerous, starting from qualitative network-based approaches (Gruel and Stanford, 2016), systemic optimization techniques (Kang et al., 2015) to the application of agent-based traffic models (Hörl, 2016; Fagnant and Kockelman, 2014; Boesch and Ciari, 2015).

Finally, though in their infancy, actual experiments in driving behaviour can be conducted in physical simulators, as done by Jamson et al. (2013).

1.4 Current Situation

Before the state of the art in the scientific literature will be presented, an overview of the automotive industry and related companies will be given.

Self-driving technology has been announced by virtually all car manufacturers. The introduction of semi-autonomous functions, for instance on highways or parking lots, is expected to be introduced by 2018, whereas full autonomy might first appear around 2021. Those years are given for instance by *Audi* (Pachal, 2016), *BMW* Baldwin (2016a); Nica (2016), *Ford* Thompson (2016), *PSA Peugeot Citroen* (PSA Group, 2016), *Mitsubishi* (2025AD, 2016), *Honda* (Baldwin, 2016b), *Volkswagen* (Cremer and Schwartz, 2016) and *Renault Nissan* (Abutaleb, 2016).

On the supplier side, the main players are *Continental*, *Bosch* and *Delphi* as "traditional" car industry suppliers, which are supplemented by younger companies specialized in AV technology. Especially around the essential LIDAR[1] components the companies *MobilEye* and *Velodyne* have gained great importance over the last years, further players in this field are *Quanergy* and *ASC*. Specifically for AVs, one can also name companies like *HERE*, who are generating high-resolution maps or *Nvidia* (Korosec, 2016a) and *Intel*, who are providing high-performance computing units, as relevant suppliers.

Recently, the market around AVs shows numerous movements, with many new collaborations being planned:

- A collboration between *BMW*, *MobilEye* and *Intel* for the development of an autonomous mobility platform (Sloat, 2016) for which *Continental* is expected to set up a competing collaboration with *ASC* (Behrmann, 2016).

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[1]Word combination of "light" and "radar". Technology used to create an online 3D model of a car's environment.

- *Volvo* is providing 100 self-driving cars for the US market to *Uber* in a research collaboration (Volvo, 2016b) and joined up with Swedish supplier *Autoliv* (Etherington, 2016) for the development of AV technology.
- *Toyota* is engaging in a leasing deal with *Uber* (Buhr, 2016), though the former recently announced that they want to follow a "Guardian Angel" approach with AVs only interfering in case of emergency rather then offering full autonomy (Anders, 2016).
- *Delphi* cooperates with *MobilEye* to set up a nearly self-driving car by 2019 (Hawkins, 2016c).

Notable is the collaboration of established car manufacturers with the ride- and car-sharing industry here. Ford specifically stated that they aim to produce cars for services such as *Uber* and *Lyft* (Neate, 2016), the latter one receiving considerable funding by *General Motors* (Solomon, 2016). *GM* itself, on the other hand, is planning to setup an own AV service (Ramsey and Nagesh, 2016). Also *Volkswagen* invested $300M USD in *Gett*, an upcoming competitor to *Uber* (Lunden, 2016).

Another trend in the recent developments has been the acquisition of and investment in hightech-centered companies, mainly in the LIDAR business:

- *Velodyne* received a considerable investment by *Google* competitor *Baidu* and *Ford* (Ackerman, 2016).
- While *Continental* invested in lidar producer *ASC* to produce cheaper sensors (Ramsey, 2016), *Delphi* acquired *Quanergy* for the exact same purpose (Truett, 2015).
- Mapping service *HERE* is expected to receive large funding by *Amazon* and *Microsoft* (Hawkins, 2016a).
- On the other hand, *Tesla* just split up with *MobilEye* to facilitate its own lidar production (Moon, 2016).

Understanding that all these changes have just taken place in the first half of 2016, it is evident that the market around AVs is extreme volatile and predictions on which collaborations and efforts will survive and succeed is extremely difficult.

Nevertheless, it can be said that the hype in the market at least for Western countries is mainly fostered by a couple of companies such as *Google*, *Tesla* and *Uber*. In China, ride-hailing service *Didi* just pushed *Uber* out of the competition and received an investment of $1B from *Apple* (Wakabayashi and MacMillan, 2016). *Google*'s competitor *Baidu* plans to release autonomous cars on Chinese roads by 2021 with tests already taking place in Beijing (Korosec, 2016b) and soon in California (Hawkins, 2016b). Furthermore, *Google*'s Russian competitor *Yandex* just announced a cooperation with *Daimler* and truck manufacturer *KAMAZ* to develop a self-driving

shuttle bus (Fingas, 2016).

Apart from AVs for personal transport, much research and development is taking place in the logistics sector, the most prominent example being the *FreightLiner* Inspiration, the first autonomous truck that has been approved for highways in Nevada (Halpin, 2015). *Uber* just entered the logistics sector by acquiring *OTTO*, an innovative producer of autonomous trucks and *Google* received a patent for autonomous minivans delivering just-in-time orders to customers (D'Onfro, 2016).

While all the technological developments and strategic decisions are going on, specific tests of AV technology on public roads slowly become normal. Recently, *Mercedes'* Future Bus has been demonstrated on a 20km route from Amsterdam to Schiphool Airport (Bell, 2016), autonomous transit pods are already roaming the city of Milton Keynes (Transport Systems Catapult, 2016) and Rotterdam (Atra, 2008) for a while and *Volvo* is planning to let 100 autonomous cars drive on the highways around the city of Gothenburg in 2017 (Volvo, 2016a). *Uber* just opened a fully functional autonomous car hailing service in Pittsbugh for a chosen audience (Brewster, 2016) and Singaporean startup *nuTonomy* started an autonomous taxi (Patel, 2016), which is planned to cover the whole island by 2020 (Abdullah, 2016). Also in Singapore, *Delphi* will gradually build up a commercial AV taxi service by 2022 (Warren, 2016).

A self-driving shuttle bus by the French startup *Navya*, which already has been tested in Sion, Switzerland (Navya, 2015) has just been opened to the public in Lyon (Navya, 2016). This is possible due to the recent opening of French roads for the testing of autonomous vehicles (Le Monde, 2016). In general, with one of the largest figures in electro-mobility sales in Europe (EV Volumes, 2016), France is expected to have great potential for the AV market (Nouvelle France Industrielle, 2015) with a number of research and development projects taking place today (Janin et al., 2016).

2 Impacts on Mobility

Autonomous vehicles will become highly attractive compared to established travel modes at some point in time and are regarded as a disruptive force in the transport market (Maunsell et al., 2014). On one hand, this will be pushed by highly competitive prices (Chen, 2015) and on the other hand through increased comfort and the possibility to pursue useful activities while travelling (Litman, 2014). It is expected that different forms of autonomous travelling will converge towards a universal travel mode of on-demand autonomous vehicle services (Enoch, 2015), which can be seen as a completely new mode of transport (Skinner and Bidwell, 2016).

Given those assumptions, one can infer a picture of the traffic situation in the future. The expected improvements in mobility can mainly be explained in terms of capacity, which is either increased, leading to a more fluent traffic flow or decreased, leading to congestion and lower travel speeds. Weighing the net effects of those influences is an integral part of assessing the economic efficiency and welfare effects of AV-related projects.

Looking at the sheer number of vehicles needed to cover today's demand, numerous studies can be cited. While mostly not taking into account induced demand (generated traffic) (Weis and Axhausen, 2009; Litman, 2016), they give an insight into the magnitude of the number of cars that will be populating tomorrow's roads. A study by the OECD (OECD/ITF, 2015b) comes to the conclusion that 10% of today's car fleet is needed to cover the existing demand in Lisboa, Portugal. Likewise, Bischoff and Maciejewski (2016b) estimate that 10 cars in Berlin can be replaced by one AV, and Fagnant et al. (2015) estimate a ratio of 9:1 for Austin, Texas. A more recent study in the same city with added simulation components such as a recharging infrastructure estimates that 6.8 private cars can be replaced by one AV (Chen, 2015). For Singapore, a study came to the result that 30% of the available fleet size would be needed (Spieser et al., 2014)a nd a possible reduction of up to 90% of fleet size in the Zurich region has been found in (Boesch et al., 2015).

An **increase in traffic capacity** is expected to occur because of a couple of different factors (Litman, 2014):

- **Connected AVs** will make it possible for vehicles to communicate and thus decrease the necessary distance for safe driving (Shi and Prevedouros, 2016). Likewise, having information about other vehicles intentions, accelerations and braking makes it possible to avoid the emergence of traffic jams and suggest a much better traffic flow than is present today. One example being the intelligent control of intersections (Yang, 2016).
- **Crashes** today reduce the road capacity. Assuming AVs are much more safe and reduce the number of crashes significantly, this will also allow for a higher average capacity in the traffic network. Bertoncello and Wee (2015) expects a reduction of traffic crashes by 90%. Also, Fagnant and Kockelman (2015) suggest that a penetration level of 10% AVs would lead to half the number of crashes today, while a level of 90% they would remove 90% of accidents.
- A redeveloped **infrastructure**, aimed at supporting a traffic system mainly consisting of AVs will have the potential to create huge gains in capacity by making use of several AV advantages, such as the ability to autonomously drive to parking spaces or the possibility to optimally dispatch vehicles according to the current demand at a certain time of the day. Those infrastructure changes will be described in a later chapter.

The number of trips taken due to the **induced demand** of AVs will make any higher capacity. This means that by introducing the new travel mode, more trips with different characteristics are being taken and thus the network is slowed down if no capacity gains happen in parallel. This induced demand emerges for a couple of reasons:

- Many barriers for the participation in the traffic network today will be removed when AVs are established. Younger people, as well as persons without driving licenses will be able to engage in more individual travel, not being constrained to fixed public transit schedules. The elderly for which the same point applies, gain increased access to travel since AVs are able to pick them up at their homes. The same is true for disabled persons. Therefore the bare number of trips being taken by newly acquired user groups is likely to increase, creating more demand on the network (Litman, 2014).

- The mode shift from collective traffic such as busses and trains towards AVs, which presumably will feature smaller passenger capacities will generate additional demand on the network (Bierstedt et al., 2014). For instance, a bus today with 50 seats could be replaced by 13 AVs with four seats. Given that all travels on that route remain the same, there would be 12 additional vehicles in terms of flow capacity. Looking at the needed storage capacity in the network with one bus being equal to three cars, one arrives at an increase of 400%. In a number of scenarios, public transportation as we know it today is expected to vanish (Gruel and Stanford, 2016). For the city of Poznan, Poland, Owczarzak and Żak (2015) come to the conclusion that a only-AV scenario or AVs in combination with specific bus lines would be the most effective combination of travel modes.

- The increased comfort of AVs is likely to generate more trips simply because it is more convenient to travel. While it may be easier to walk for grocery shopping for some people today, because one would need to go to the parking lot, go there by car, find another parking space and do the same on the way back, just calling an AV in advance might add the critical comfort that would make the customer opt for using the vehicle instead of walking (Christie et al., 2016). Since such use cases would constitute short trips, the gain in in-vehicle productivity is not the main issue here, what actually matters are the waiting times and reliability of the service (Heinrichs and Cyganski, 2015). Spinoulas et al. (2015) estimate that an increase of AV availability by 25% corresponds to the trip generation that would be like the effect of five years of population growth. Burmeister et al. (2014) expect an increase in travels by 150%.

- Depending on the service level of the AVs, the relocation phases, where AVs drive without any passenger will use up capacity. If there are numerous AVs taking part in the traffic, for tasks such as going shopping for the customer or searching for parking space, there will effectively be more vehicles on the road than before.

It is not clear, whether these effects will lead to an overall increase or decrease of road capacity,

because of the contradictory effects mentioned above.

This is also true, because it is not clear what the driving characteristics of AVs will be. While AVs might be able to drive faster than today's cars, the question is whether this is actually desired, taking into account that people want to engage in different activities on board (Diels and Bos, 2016). Le Vine et al. (2015) calculates AV benefits given the longitudinal and lateral acceleration constraints of today's trains, as well as distance-keeping regulations (Le Vine et al., 2016) on highways to conclude that capacity gains are possible even with these restrictions, but that they may be lower than expected. Furthermore, arguments for lower AV speed can also be made regarding safety for other participants in traffic.

While changes in capacity might be positive or negative, the literature on AVs agrees that there will be an increase in vehicle kilometers travelled (VKT). Numerous simualtion studies exist, which give numbers for the expected increase:

- Bierstedt et al. (2014) expect an increase of VKT between 5% and 20% with a 50% market share of AVs, later up to 35%
- Chen (2015) estimates an increase in a similar range from 7% to 14%.
- Fagnant et al. (2015) estimate an increase of 8% and Fagnant and Kockelman (2015) system- wide up to 37% at 90% market penetration.
- Increases in VKT are also observed by Hörl et al. (2016) and Gruel and Stanford (2016)

Autonomous vehicles are expected to be most efficient in areas with a dense traffic demand (Bischoff and Maciejewski, 2016a), which is true in urban areas. Therefore, their implications on city planning will be examined in the next section.

3 Impacts on City Planning

What is clear today is that increased automation will define how cities are planned, changed and built in the future. Among the expected effects are the removal of most of traffic signs and lights and the redevelopment of abandoned parking spaces, as shown in a recent UK case study (Skinner and Bidwell, 2016). While AVs are only one component of that process, a large variety of effects can be anticipated on their account. Likewise, the way cities are structured today will mainly influence how fast and efficient AVs will be implemented. Most probably, AVs will need to adapt to the current situation in the beginning, while planners and designers can then shape the city for the use of AVs, once they are about to become a fixed part of urban life. This includes infrastructure decisions, the restructuring of land use as well as leveraging positive effects on the

environment.

3.1 Infrastructure

The urban infrastructure is a limiting factor for the adoption of AVs. The more understandable and predictable a traffic environment is for an AV, the easier it will be to operate in that area and the faster it will gain acceptance. Therefore, the existing infrastructure and investments in infrastructure will significantly shape how AVs will be used in the future. On the other hand - especially when considerable shares of AVs are reached - the new technology will guide infrastructure considerations and offer great societal benefits.

- Especially in highly congested areas, **parking spaces** are expected to vanish, either to make space for additional roads or to be converted to a completely different use. This is possible since AVs do not need to stay at the customer destination. Either they can return to strategically positioned **mobility hubs** or roam through the city. In that case, Zhang et al. (2015) estimate a reduction of 90% in parking spaces for AV users at low total shares in the urban area. Since this reduction provokes an increase in vehicle kilometers travelled per day (VKT), it is argued that this reduction can be partly sacrificed against providing a considerable amount of parking space. In any case, most studies predict decreases in parking demand, e.g. by being able to pack AVs 15% tighter, Bertoncello and Wee (2015) estimate a reduction of $5.7m^2$ in the US per car, Skinner and Bidwell (2016) predict 15-20% more developable area in the city, which is in line with the expected reduction of Alessandrini et al. (2015) at 15%. For highly shared, roaming AVs, (OECD/ITF, 2015b) sees a decrease of 80% in parking demand. Furthermore, without even considering gains from reduced parking demand, Ambühl et al. (2016) come to the conclusion that with AVs, 12% of road space can be saved.
- Contrary to that, **extended spaces for picking up and dropping off** customers are needed. This is especially true for large event venues, where high numbers of travellers are expected at specific times.
- The **connected city** will emerge, managing traffic data on the fly and distributing information to allow for the best flow possible. This includes the implementation of intelligent traffic lights, which react to the current demand on the roads. Furthermore, automated crossings are discussed (Yang, 2016), where no traffic lights are needed at all, because AVs are able to negotiate on their own, who will cross first. Then, however, it is necessary to give pedestrians safe ways of interacting with such new traffic management opportunities. This leads research towards asking for a anthropocentric development of cities, offering equal opportunities for every participant (Mladenovic and Abbas, 2015;

Mladenovic and McPherson, 2016).

- The ongoing **electrification** of cities in terms of recharging stations will be a crucial support for the adoption of AVs. Since they are commonly expected to be powered electrically, the recharging infrastructure is not only an important factor to provide acceptable levels of availability, but also for shaping in which way and where AVs will be used (Maunsell et al., 2014). Still, it is not clear how this recharging infrastructure will look like. Options are large mobility hubs, stations distributed over the city or even electrified streets, which are able to recharge cars while driving.

All in all, it is clear that a future city will look different than today and that new developments in traffic, most notably self-driving cars, will have a big share in these changes. By making intelligent infrastructure decisions, a number of open questions on mobility, that have been posed before, can be narrowed down. For instance, the removal of parking spaces would create space for additional lanes, which would increase the road capacity and thus serve the induced demand that is generated by AVs. Maciejewski and Bischoff (2016) find that a moderate capacity increase of 50% by infrastructure has the potential to significantly decrease congestion for a fleet of AVs. If cities make sure they have a say in the communication of participating vehicles, it is possible to perform city-wide optimization of the traffic network rather than have single AVs compete against each other finding the fastest way possible for themselves (Lamotte et al., 2016). Given that customers might be willing to spend more time in the vehicle, this is a viable option. Similar results are found in Levin et al. (2016), where it is argued that smaller AV fleets might be able to handle the demand more efficient than over-sizes scenarios. The discrepancy between the individual optimal travel plan of one traveller and the collective optimal choices is a common and widely studied phenomenon in traffic engineering (Braess, 1968). Specifically for AVs, Lamotte et al. (2016) study the distribution of road capacity among shares of autonomous and non-autonomous participants in traffic.

However, Guerra (2016) found that AVs are not part of the metropolitan long-term plans on traffic infrastructure for 25 major US cities and states that thoughts about AVs are still discussed in the background due to the high uncertainties connected to the technology. Tools in order to assess qualitative effects of an introduction of AVs are in the making (Gruel and Stanford, 2016).

3.2 Accessibility

The implementation of AVs will have great impact on what people are able to do in the urban environment and beyond. By offering mobility to new users groups, decoupling travels from fixed schedules and increasing spatial availability by offering pick-up services, it will become

easier to reach more locations in the urban area than before. One major benefit can be seen if AVs are regarded as a means of covering the last mile between a public transit facility and peoples' homes or work places (Litman, 2014).

On one hand, as described before, this will lead to an induced demand and might have the negative effect of slowing down travelling. On the other hand, the increased accessibility is a huge societal benefit of AVs. In that regard both developments can be seen as antagonists if no infrastructural changes are being made (Meyer et al., 2016). Therefore, from a societal perspective, it will be a challenge to balance expected gains in accessibility (among the other benefits of AVs) with expected losses in speed through congestion.

Finally, one needs to think about how the increased accessibility will change the behaviours and decision making of the people. One likely development is that AVs will heavily encourage urban sprawl, giving the motivation to move outside of crowded city centers into the neighbouring areas (Anderson et al., 2016; Litman, 2014). This, if no tailored policy decisions are made, will drastically change how the urban environment changes and what can actually be considered as the "urban environment".

3.3 Emissions Environment

Looking at AVs from the an environmental perspective, a couple of positive and negative effects can be pointed out.

Given that AVs will be powered electrically, their reduction of **CO2 emissions** can be seen as a major positive effect on the environment with the right mix of electricity production. Still, by increasing the demand in electric energy due to a vast number of AVs, the question needs to be raised how this energy is produced. While the net emissions are likely to decrease, it is not clear if those effects are as large as thought. At the end, the effective benefits depend heavily on the development of sustainable ways of energy production (Greenblatt and Shaheen, 2015).

Furthermore, using electric engines, a reduction in **noise emissions** is possible at lower speeds. This may give rise to building roads closer to residential areas and to simultaneously decreasing the distances that one needs to travel. The land value for areas which are close to highways today is likely to increase.

Connected to those points are reductions in **light emissions** and savings of **electrical energy**. Since AVs are relying on sensors, which not necessarily need light on the road as human drivers do today, it is possible that tunnels and similar structures can be operated without any illumination

and thus with great energy savings. Furthermore, given that the necessary precautions for pedestrians', cyclists' and non-autonomous vehicles' safety can be met, night driving without light could become a reality.

Summarizing the environmental effects of AVs, it can be said that they are generally regarded as a positive development. However, Thomopoulos and Givoni (2015) state that positive effects will only become apparent if AVs are used in shared manner, resembling simulation results from Wadud et al. (2016), where emissions might either half or double, depending on the usage scenario of AVs.

4 Impacts on the Car Industry

Generally, autonomous vehicles are regarded as a disruptive force, that will have significant effects on economy and industry. The main reason for that is, that a couple of innovative developments and thought experiments from recent years cumulate in the implementation of AVs. Those range from electric vehicles, increasing automation, artificial intelligence, sustainability to the emergence of the sharing economy and on-demand culture. Against this background, the following sections will cover scenarios on how AVs will be produced and maintained, how and by whom they will be operated and how legal and ethical question can be brought to consensus from the perspective of the car manufacturing industry.

4.1 Production, Operation Ownership

The production and research for AVs is done in start-ups and established car manufacturing companies alike. While start-ups have the ability to try new concepts with the prospect of failure, car manufacturers need to perform more conservative work, maintaining a stable economic situation. Nevertheless, due to great advance in technology the established companies increasingly engage in research around self-driving cars as the public interest and the feasibility becomes evident. The big question is, whether eventually car manufacturers will take the lead, because customers have more trust in their work, or whether the inspiring concepts of smaller start- up companies will occupy the market quickly, leaving no space for established companies. For now, it has been found that trust regarding AV technology is higher in new start-up companies (Silberg et al., 2013).

The car manufacturer in a future scenario with AVs can be seen in a variety of different roles:

- It will keep the classical **producer** role, where cars are provided as a good to customers, which is paid per unit. Looking at prospective developments in the ride-sharing market, a probable scenario is that those cars won't be sold to individual customers, but that whole fleets will be delivered to third-party fleet operators. These could act in the areas of car-sharing, ride-sharing or provide delivery services. The specific use case of the AV is defined by the operator.

- Therefore, the car manufacturer will more strongly than today act as the first support contact. Bertoncello and Wee (2015) state that 60% of customers would be willing to follow the maintenance recommendations of their autonomous vehicle, which could be the car producer itself. The technology built into the cars might become so complicated that only the producer of a specific car would know how to solve a specific defect. Furthermore, car producers are likely to become more focused on the **software** of the provided vehicles. Given steady changes in vehicle-to-vehicle and vehicle-to-infrastructure communication, frequent updates might be necessary or appreciated by the customer. In a way, rolling out a new AV would bear strong similarities to releasing a smart-phone today, where the customer not only buys the current phone, but also the prospect of future updates. According to this vision the software that is built into an AV is likely to become more difficult to handle than the hardware, which might increasingly be outsourced to suppliers.

- Going one step further, the car manufacturer might shift away from the classical per-unit sales model to a service based model. As a **service provider** the car manufacturer would not sell an AV, but AV hours. The car manufacturer would be responsible for setting the vehicle up with the appropriate driving logic, tailored towards a single user, a fleet operator for shared AVs, or even more specific scenarios. A fleet operator might buy "AV hours" from a car manufacturer with AV driving logic that is either optimized for dense downtown situations or rural areas. Another possibility would be to program the AV for the delivery of goods and provide the software to control the delivery process. In this scenario the car manufacturer would to a large extent become transformed into a "software developer".

- The last step towards the customer would be taken if the car manufacturer acts as a **fleet and service operator** itself.

Which model will dominate in the future does not only depend on the car manufacturers intentions, but also the trends in the whole automotive sector. For instance, a likely development could be that suppliers start selling usage times for the provided components (Wallin et al., 2015). That way the producer of the AV would buy lidar-hours or camera-hours from the supplier (Baines et al., 2009). Because suppliers are more and more focusing on the software and the "intelligence" within their provided components, such a scheme might become likely.

Regarding the speed of fleet renewal that is passed to the customer, different possibilities exist: Longer lifecycles for AVs might appear in the sense that AVs are expensive to assemble and

frequent software updates and maintenances might be more cost effective than building a new car. This is especially true given the strong dependence on suppliers for all the single components such as lidar and cameras. On the other hand, shorter lifecycles could be possible because of a fast progression of the technology. Depending on the number of competitors in the market and new developments in vehicle-to-vehicle and vehicle-to-infrastructure technology, the turnover might be quick. Furthermore, novel technologies such as 3D printing might further speed up the process.

Also, the use mode of the AVs needs to be taken into account. If AVs are used as car-sharing or ride- sharing vehicles, the usage per day will intensify. In that case a faster deterioration of the vehicle is likely and might impose new requirements on the producer.

The design of a new vehicle might be based on completely different criteria than today. Obsolescence strategies might be deprecated, vehicles might either be heavier (because of batteries and technology) or lighter (because of reduced safety requirements). The actual looks may loose importance due to AVs being less of a status symbol (Krueger et al., 2016).

From a customer perspective it is not clear yet, who will perform different tasks within the AV economy:

- The **maintenance** of AVs could either be conducted as it is today - with dedicated garages customers can turn to - or it could be done by the producing company or a large scale service operator. The technology is likely to become so complicated, that it could be the duty of the producer to take care of any problems in the vehicle. Furthermore, small garages are likely to disappear, if AVs are able to detect failures and drive themselves to a garage. Given a highly connected environment, where it is clear when and where repair slots are available, the maintenance could be highly optimized and centralized. Additionally, for the actual customer deficiencies will become less relevant, since an on-demand service would be able to provide him a different car quickly.
- Another question is **ownership**. In previous chapters already different usage models have been introduced, where either single persons, families, interest groups or the public is using an AV collectively (Silberg et al., 2013). Especially for family households, a significant lack of trip overlap has been pointed out (Schoettle and Sivak, 2015), where the family members' individual trips could be scheduled without interfering with each other. However, those schemes only indirectly answer the question of ownership. Even if a family or group decides to use an AV, this could be provided as a service. Looking at the fact that AVs need to be managed in order to satisfy the needs of all participants, this task could be given to an operator, who could also have the ownership of the AV.
- Closely related to that question is, given that AVs are used as a general service for society,

to which degree should private companies or the public sector be involved in the operation of the system. While at first, private operators are likely to appear (as is the case with car- sharing today), it could be beneficial to engage in autonomous mobility for public authorities (Lamotte et al., 2016). Not only will this more likely lead to a unification of standards regarding vehicle-to-vehicle or vehicle-to-infrastructure communication, but also could the authorities set up schemes for the assignment of vehicles, track travel for the charging of taxes and in general work towards a traffic environment that comes close to a social optimum (Bonnefon et al., 2016). After all, the same question can be raised for the infrastructure that is needed to operate AVs.

As a summary one can say that regarding the manufacturing of AVs, established companies and innovative start-ups are in competition for the market. In any case, and this seems to be the current development, combining knowledge and expertise from both is most likely to speed up the development and adoption of self-driving cars.

The need for drastic changes in infrastructure raises the question, who will pay for it. While authorities have an interest in providing a stable traffic infrastructure, more work is to be done in convincing them of the benefits of AVs. At the moment one problem in this regard is the immaturity of binding standards in vehicle ICT, which will be solved soon. For instance, Mersky and Samaras (2016) investigate new approaches of drive cycle testing in a scenario where car-following benefits should be accounted for specifically.

4.2 Law, Liability and Insurance

As stated before, the speed and acceleration of AVs might be limited by the user experience (Le Vine et al., 2016). Especially on the way to full autonomy great concerns are raised about the shift of automatic to control when cars are not level 4 autonomous (Louw et al., 2015; Aria et al., 2016; Merat and Jamson, 2009). This - in turn - raises questions about the responsibility of AV manufacturers and to what degree they can be hold accountable for eventual crashes. Since the research on safety measures in an autonomous car is just starting, manufacturers are reluctant to accept binding mandates to introduce those measures into their cars due to unresolved liability questions (Anderson et al., 2016).

Liability for manufacturers is first expected to be based on the specific base technology such as navigation and collision avoidance (Lederman et al., 2016), while it is gradually seen to span over the whole vehicle operation (Anderson et al., 2016). Extensive analyses regarding insurance and liability are already available (Sheriff, 2016; Yeomans, 2014; Schellekens, 2015).

The general tendency in these essays is that crashes with AVs will bear a moral component (Goodall, 2014a,b). In that regard considerable thought is not only put into who would need to pay in case of an accident, but also what would be a morally feasible way to determine which action to take, given that either the driver or third persons outside of the car are at severe risk (Bonnefon et al., 2016; Hevelke and Nida-Rümelin, 2015). Consent on these problems has not been reached yet.

5 Impacts on Work Organisation

The general trend towards an increasingly connected society allows for more flexibility in choosing working times. Since automation allows for larger fractions of work being done online the need of physical presence at a certain work place is not mandatory any more. While the current traffic infrastructure allows for a shift towards such flexibility by providing earlier and later transit possibilities, AVs are likely to benefit from these developments (Litman, 2014). Especially business sectors, which depend heavily on their employees travelling, could benefit from the introduction of AVs, because some work does not need to be done at a centralized office, but in the vehicle.

Due to the possibility of AVs picking up customers, the catchment area of a work place is increased, as well as the number of work place options a customer has from his home. This way, the general accessibility is increased (Meyer et al., 2016) and longer distances to work are tolerated (Shanker et al., 2013). That on one hand can lead to urban sprawl, letting people live further away from urban work hubs than today. On the other hand, it also allows for the movement of companies towards outer regions of a city, since being located at a central, easily accessible spot in the city centre does not have as much value as it does today.

Looking at the scenario from the opposite perspective, AVs might increase work efficiency by providing the customer more time to engage in relaxing free-time activities. Bertoncello and Wee (2015) expect leisure time to increase by at least 50 minutes a day.

6 Impacts on User Profiles

Looking at today's choices, there are privately owned cars, which allow for high flexibility and individually planned travel. However, one has to buy a car in the first place, pay yearly insurance premiums, maintenance costs parking costs and fuel. All of that while the time spent in the car

cannot be used productively. Public transit services offer more transparent pricing by allowing easier controllable per-trip, monthly or yearly fares. In general, this means that the user is paying for the travel itself, rather than for the possibility to do so. The main disadvantage of public transit is the restriction to a confined set of routes, potential problems of getting to and form the stop facilities, which both limit the temporal and spatial availability of mobility.

In that regard, the choice between a car or public transit can be seen as a question of availability. Recent developments in on-demand systems find a compromise here. When using a car-sharing service with a sufficient fleet size, users are able to take individual trips with payments per use. Albeit the problem of temporal and spatial availability can only be solved in a dense city environment, car-sharing is expected not to produce great demand in remote areas as long as there isn't extensive coverage (Litman, 2000).

Autonomous vehicles, in contrast, solve the problem of spatial availability by making it possible for a car to autonomously drive to its user. At the same time, this resolves the problem of having to search for parking space, since the AV is able to perform this task on its own, as well as finding a place to recharge itself. Therefore, AVs build on the advantages of mobility-on-demand services, but with increased availability. What comes on top of that is that time in the vehicle can be spent effectively pursuing another activity than driving, thus making that in-vehicle time much more productive and worthwhile (Litman, 2014).

Looking at privately owned AVs, the aspect of running costs has to be considered again, though. While prices for AV technology are expected to decrease, the question must be stated whether it is still attractive to own a car then. Even in a non-autonomous scenario with highly developed mobility-on-demand services offering 24/7 possibility of travelling, that is bought by owning a car, this might not be a rational decision anymore. Therefore, it is expected that AVs will be used in a shared fashion.

Different sharing schemes are possible though. One perspective, especially during the onset of level 4 autonomy, are family-based AVs, which could drive each family member to their school / work location and pick them up one after another in the afternoon. The time in between could be used to automatically go on errands such as picking up goods from the grocery store (Litman, 2014).

The most probable and versatile scenario features fleets of autonomous vehicles, which can be used as a mobility-on-demand service. For such a setup, waiting times (i.e. temporal availability) would be the main quality factor (Heinrichs and Cyganski, 2015). On the other hand, the pricing scheme would be what defines which user groups are most effectively engaging in the new service (Chen and Kockelman, 2016).

Especially young people without a driving license, old people, which are not able to drive by themselves any more and disabled people would gain improvements in their travel possibilities. In that regard, AVs are not only supposed to bring advantages to the trips that are taken today, but will also generate new ones. While this might have a negative impact on the traffic network, one can argue that AVs can play a huge societal role in increasing accessibility throughout the population. This, in turn, is linked to the question of liability, since the "duty to act" for avoiding an accident cannot be enforced as soon as young, elderly or blind people are allowed to use AVs (Hevelke and Nida-Rümelin, 2015). Furthermore, the question can be stated, how many of those trips can actually be performed 100% autonomously, since elderly and disabled passengers might still need to be supported by a human assistant.

Even in an intermediate state towards fully autonomoy, AVs have the potential to strongly support the given public transit infrastructure, by acting as transit feeds, offering the possibilities for customers to cover the last mile from the stop facility.

An overview and discussion about literature on behavioural experiments of potential AV users has been provided by Becker and Axhausen (2016). The main benefits that are seen in AVs are fewer crashes and multitasking, the strongest concerns lie in the areas of liability and insurance and loss of control across several behavioural studies (Bansal et al., 2016; Howard and Dai, 2014; Mosquet et al., 2015). Academic concerns about the IT security of AVs (King et al., 2016) are also reflected in customer opinions (Kyriakidis et al., 2015). Further behavioural experiments have been conducted by Piao et al. (2016), Krueger et al. (2016), Zmud et al. (2016), Cyganski et al. (2015), Schoettle and Sivak (2014) and Payre et al. (2014).

Specific studies have been conducted on the use of AVs within families (Schoettle and Sivak, 2015), revealing a strong lack of trip overlap with an increase of vehicle occupancy of 75% if an AV is used per family. Also, the attitudes of the elderly are investigated specifically by Souders and Charness (2016).

The main user groups that are attracted by AVs have been found to be young people in urban environments (Deloitte, 2014; Becker and Axhausen, 2016) with a stronger interest among males (Becker and Axhausen, 2016) and non-drivers (Sivak and Schoettle, 2015). Furthermore, adoption highly depends on the customers' social networks (Bansal et al., 2016).

A general deficiency of most of the available studies, as pointed out by Becker and Axhausen (2016) and Nordhoff et al. (2016), is that mainly drivers have been asked.

7 Impacts on the Delivery of Goods

The demand in freight transport worldwide will increase by a factor of three until 2050 (OECD/ITF, 2015a). Maunsell et al. (2014) expect that the costs can be reduced by 40%, once fully autonomous trucks are available:

- The main contribution to those reductions would be the missing driver wages, which today are estimated to be 30% of the total transport costs in the logistics sector (Trego and Murray, 2015).
- Removing the driver from the delivery process would also remove the need of breaks due to working time restrictions and therefore make the whole shipment more efficient.
- This, in turn, leads to the scenario where highways will be crowded places at night, because there is simply no reason not to use the late hours to move large amounts of goods with autonomous freight vehicles.

Clearly, those developments will lead to great concerns among employees in the logistics sector.

DHL Trend Research (2014) states that "self-driving vehicles will change the world of logistics". Several use cases ranging from efficient logistics within confined warehouse situations, unload operations in harbours and logistics hubs, long-haul transportation with less risk of fatal accidents and delays are covered. Similarly to the case for private passengers, the last-mile problem is examined from a logistics perspective: With an autonomous delivery vehicle, parcels could be delivered directly to one's door within short times at day and night. Mobile parcel stations, as they are stationary available in Germany, could move across the city for people to pick their deliveries up from them. Similar use cases are presented by Van Meldert and De Boeck (2016), Savelsbergh and Van Woensel (2016), Lee et al. (2016) and Flämig (2016), along with the general remark that scientific literature on the impact of AVs on logistics is still scarce.

A general reduction of freight traffic can be imagined to occur because of goods being transported as a side task by AVs in the urban environment. Similar projects of facilitating existing public transit lines for the just-in-time delivery of goods are already tested today (Kell, 2015). On the other hand, the phenomenon of induced demand should also be applied to the freight sector: If it gets cheaper and more convenient for the customer to ship things, an increase in deliveries can be expected. Looking at just-in-time delivery services as they are developing with manned vehicles (Dinham, 2016), such a scenario seems probable. The effects might be twofold: Not only the flow capacity of the traffic network would be used up by more deliveries, but also the capacity of the transport network itself, including delivery stations and logistics hubs. Therefore

similar considerations as for the induced demand in personal transport need to be taken in the existing supply chains.

In general it can be assumed that a separation between last-mile and long-haul deliveries will persist. Introducing AVs will not change the fact that large-scale trucks are efficient for covering long distances, but difficult to operate in crowded neighborhoods, while agile light-duty transport vehicles are less cost efficient than bigger solutions on long routes. This leads to the phenomenon that AVs might speed up long-haul and last-mile delivery by themselves, but that one still needs to consider time losses at the bottleneck between the two modes when assessing the net customer benefits (Merchán and Blanco, 2015).

Finally, the question arises, whether different means of transport will be more successfully than road-based autonomous vehicles. Especially in dense urban areas the introduction of autonomous drones for the delivery of goods might engage in a serious competition with AVs (Amirtha, 2016).

8 Impacts on Price

At the end the developments described before will depend on how much it will cost to use an AV. Numerous estimates have been done so far, of which the most recent are presented here.

Bansal et al. (2016) estimate an average willingness to pay (WTP) for AV technology of $7253 across all user groups, with values of $5551 and $14589 for additional level 4 and level 5 automation technology among users who are willing to pay at all (WTP > $0) (Bansal et al., 2016). Mosquet et al. (2015) arrive at a WTP value of $5000 for adding autonomous driving technology to today's vehicles. Looking at shared AVs, Chen (2015) expects AVs to be operable at a price of $0.42 to $0.49 per occupied mile travelled, which is competitive to today's car-sharing services. Also, Mosquet et al. (2015) expects shared AVs with at least 2 passengers to be competitive with mass transit by 2035.

What those studies have in common is that at some point, AVs are expected to become cheaper than conventional means of transport (Mosquet et al., 2015). This will lead to a conversion of trips towards the new travel mode. Once this happens, customers benefit from a couple of factors, which will also shape their travel behaviour.

The cost awareness will increase, because straight-forward pricing structures such as per-distance or per-duration schemes are expected to evolve. This means that customers have a much more direct understanding of the costs of travel than today (Chen, 2015). While for immediate mode

choices, the perceived costs of the actual are trip are most important, investment costs as for a private car are often ignored or underestimated. On the other hand, it is likely that subscription schemes will appear, similar to today's monthly or annual offers. Still, compared to a private car, the estimation and assessment of personal travel costs will be simplified.

From a welfare perspective it is important to weigh monetary efforts against benefits and losses on a societal level. There it is interesting to investigate how valuable the time spent in an AV is for the customer. This is strongly related to the offered comfort and is likely to correlate with for instance the number of passengers in a car. Knowing this valuation, it will be possible to assess, how much more and/or longer trips customers will take, compared to today, which in terms allows for the estimation of negative impacts on the traffic environment. With a conservative \$0.85 per mile and valuing losses due to travel time at 30% of today's value, Chen and Kockelman (2016) arrive at an already strong AV taxi mode share of 27%.

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