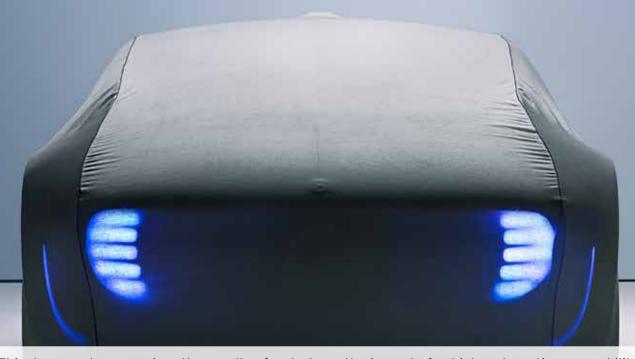ifmo

Institute for Mobility Research

AUTONOMOUS DRIVING

The Impact of Vehicle Automation on Mobility Behaviour

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This document summarises the results of a study on the impact of vehicle automation on mobility behavior. This research was sponsored by the Institute for Mobility Research (ifmo) and conducted by the German Aerospace Center (DLR), the Humboldt-Universität zu Berlin, as well as additional support by the Tongji University (Department of Urban Planning), Stanford University (Center for Automotive Research), and Inovaplan GmbH.

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Foreword

Automation is playing an increasing role in various different modes of transport. Driverless trains are already in operation, the degree of automation in cars is continuously rising, and even the air transport sector is discussing the use of pilotless aircraft at some time in the future. Still, there are many technological, regulatory and legal hurdles to be cleared, before autonomous vehicles (AVs) can be put into large-scale operation. Moreover, societal fears and ethical concerns could limit the acceptance and market penetration of these new technologies. Although it is still uncertain how fast and how strongly automation technologies will spread through the transport sector, they are very likely to make a large impact on mobility, over the coming decades, especially when it comes to AVs.

With this background in mind, the aim of this study is to evaluate how self-driving cars might impact people's travel behaviour and mode choices, focusing particularly on three markets: Germany, the United States and China. How much we travel, and the way in which we do so, is in today's world subject to substantial constraints.

Some of these constraints might be substantially influenced by AVs. What if...

- ...we could make efficient use of the time we spend travelling because of the ability to take our hands off the wheel and give our attention to other activities?

- ...individuals with physical challenges – or children – are enabled to travel unaccompanied, thanks to an AV that takes them to their destination?

- ...the availability of a vehicle at a certain location is not an issue because a driverless vehicle comes to pick us up and take us to our destination?

These examples illustrate the potential revolution in our travel behaviour that autonomous driving might bring about. For this reason, the project team developed an aggregated travel demand model to quantify the effect of self-driving vehicles – both private passenger cars and autonomous car-sharing fleets – on passenger-kilometres travelled by different modes of transport. The focus was more on obtaining an approximation of the magnitude of the observed effects on a national level, rather than making an attempt to suggest apparently accurate figures for individual cities. Expert discussions and focus groups in each of the three countries set the basis for the derivation of qualitative scenarios, and subsequently for the quantification of the required model input factors.

All in all, the value of this study is its special interest for the transport industry and policymakers dealing with the development and implementation of self-driving technology over the next ten to fifteen years.

Dr. Michael Halbherr
Consultant
Chairman of the ifmo Board of Trustees

Acknowledgments

Executive Summary

Objective

The aim of this project is to examine the potential impact of autonomous driving on the future of mobility behaviour, focusing primary on passenger cars and levels of automation sufficient to permit drivers to undertake other activities while travelling in an autonomous car. Three lead questions guide the project:

1. What if we could make efficient use of the time we spend travelling because of the ability to take our hands off the wheel and give our attention to other activities?

2. What if individuals with physical challenges – or children – are enabled to travel unaccompanied, thanks to an autonomous vehicle (AV) that takes them to their destination?

3. What if the availability of a vehicle at a certain location is not an issue because a driverless vehicle comes to pick us up and take us to our destination?

We selected three countries for our analysis, which we believe to be suitable for developing a good understanding of the global impact of automation: firstly Germany and the USA, because they are both highly developed mobility markets evidencing signs of saturation, and yet differ significantly in their mobility cultures, and then also China, as the world's largest mobility market, and one that is growing at a rapid rate.

To analyse and quantify the possible impact of autonomous driving on mobility behaviour, we used an approach that combined both qualitative and quantitative methods. In the first phase of the project, we analysed the status quo in our selected countries and the expected developments in autonomous driving, and identified potential user segments and influencing areas related to autonomous driving which affect mobility behaviour. The insights were drawn from expert workshops, and from focus groups with potential users. In the second part of the study, using the results derived from the first phase of the project, we developed three scenarios to be examined with respect to the selected countries, which differed in the projected share of AVs within the vehicle fleet, as well as the way in which they are used as shared vehicles. Using a travel demand model, the impact of autonomous driving on mobility behaviour has been quantified.

Automation technologies in transport

Today, high levels of automation technologies in transport can be found in aviation, maritime transport and rail-based public transport systems. Land transport, in contrast, has not yet reached a high degree of automation. This is equally true for private vehicles and public vehicles. One of the main reasons for this is the fact that navigating on roads requires much more complex interaction with other users.

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However, despite the technological challenges that need to be overcome before AVs become a reality on public roads, the degree of automation in road vehicles is continuously rising. Advanced driver-assistance systems, such as lane-keeping assistants and adaptive cruise control, are already available in currently produced vehicles, and this is moving the technology development forward.

Drivers behind the implementation of systems providing higher levels of automation are manifold, but can be grouped into the following categories:

- increased safety;
- improved energy efficiency and emissions;
- provision of a flexible mobility option to people currently unable to drive because of physical or age-related constraints; and
- enhanced comfort and a more effective/pleasurable use of the time spent travelling.

At the same time, the main barriers to the implementation of the technology are related to technological challenges that need to be solved, and to legal and regulatory issues. Analysing the legal and regulatory framework in the three selected countries, we found that the regulatory bodies are currently addressing the topic of autonomous driving, and are working on adjusting the legal framework to pave the way for this innovation. However the legal adjustments and the required regulatory discussions were found to be at different stages of development in the three countries.

Key influencing areas related to vehicle automation development

When analysing potential changes in mobility behaviour by autonomous driving, we identified the following three influencing areas:

1. (New) user groups: Certain user groups benefit more from autonomous driving than others, for a variety of reasons. The first group includes people with medical or age-related mobility constraints, such as disabled people, elderly people and teenagers. Autonomous driving can give them independence in their mobility, easier access to essential services, and a reduced likelihood of social isolation. Hence, more people among these groups might prefer using AVs to other modes of transport. Furthermore, since they would no longer have to rely on other people in order to travel, they might take more trips than they currently do. Another potential user group of AVs includes people with high annual mileages, such as long-distance commuters. Autonomous driving would enable them to use the commute in a more productive or pleasurable way, since many of them today spend much of their time in dense traffic, or find long routine road trips both exhausting and tedious. As a result, more people could be willing to commute longer distances, and existing long-distance commuters might switch to AVs.

2. Use cases and business models: Use cases and business models of autonomous driving are strongly linked to the different levels of automation. Use cases at lower levels, where the driver still has to pay attention to the traffic and intervene if required, are not expected to change mobility behaviour significantly. Higher levels of automation, on the other hand, which enable fully autonomous driving in certain situations, have the potential to change users' mode preferences for certain trips. The highest level of automation, which enables zero-occupant trips, might lead to new business models offering services similar to a taxi (known as 'autonomous vehicle-on-demand', AVoD) at costs lower than those of today's car-sharing services, and might therefore have the greatest impact on mobility behaviour.

3. Generalised costs of travel and value of time: Autonomous driving might change the generalised costs[1] of driving, especially the value of travel time, and thus also change users' mobility patterns, since time costs and monetary costs are important determinants of mobility behaviour. AVs can reduce the value of time spent on trips by car, since they enable people to undertake other activities while travelling. We suggest that the reduction of the value of time will be the most significant influencing factor among the generalised costs of trips by car. As a result, people might prefer driving autonomously to using other modes of transport, and also choose to take more trips or travel longer distances. This will be more relevant for certain kinds of journeys, such as commuting or long drives. Further expected changes are reduced access/egress times, a reduction in the overall travel time, and the lowering of variable costs for privately owned vehicles. Additionally, autonomous vehicle-on-demand services might significantly reduce car-use costs by reducing the operating costs for the provider of such services.

Scenarios for autonomous driving for the year 2035

We used a scenario approach to better demonstrate the possible impact of autonomous driving for the three countries for the year 2035 and developed the following three scenarios:

- "Evolutionary automation"
- "Technology breakthrough"
- "Rethinking (auto)mobility"

We quantified the impact of autonomous driving on mobility behaviour for each of the scenarios using a vehicle technology diffusion model[2] in combination with a travel demand model. The changes in value of time when driving an AV instead of a conventional one, together with the consideration of new user groups, are key elements of modelling the impact of AVs. Due to the lack of data, the scenarios for China have not been modelled and therefore follow a more qualitative approach, reflecting the results from focus groups and expert workshops conducted in China.

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[1] The concept of generalised costs is briefly explained in Appendix A.

[2] Diffusion models aim to determine how new products get adopted in a population.

The scenario **"Evolutionary automation"** describes a possible future which envisages a more evolutionary development of AVs in the overall fleet. In this scenario it is expected that the first highly automated vehicles (Level 4) come onto the market from 2025 onwards, and the first fully automated vehicles (Level 5) from 2030. The technology will be introduced first in the luxury segment and later in the smaller vehicle segments. The share of AVs in the fleet is higher in Germany than in the USA, reaching values of 17% and 11% respectively in 2035. Teenagers from 14 years of age are allowed to use AVs. The increase in vehicle-kilometres is moderate, at 2.5% and 3.5% respectively in Germany and the USA.

The scenario **"Technology breakthrough"** assumes a more progressive development of the AV fleets, with the first AVs coming to market from 2022 onward. Using an AV is legal for all persons of ten years and older. The higher diffusion rates of AVs lead to a share of AVs in the fleet amounting to 32–42%, and to 75–80% of new car sales. By implication, there is a greater impact of autonomous driving on modal shift and vehicle-kilometres (VKT) travelled than in the previous scenario, with an increase of vehicle mileage of about 8.5% in both countries.

In the scenario **"Rethinking (auto)mobility"**, AVs are, in addition to their private use, part of new mobility-on-demand concepts. Regulations have changed such that vehicles are allowed to move without humans inside. We therefore model autonomous car-sharing (ACS) and autonomous pooling (AP) systems, respectively, with autonomous repositioning of vehicles giving rise to low access times. The ACS system allows at most one party in the same car at all times. The AP system allows more than one party in the same car, i.e. a sharing of trips and out-of-pocket costs; however, passengers have to expect detours for picking up and dropping off others. Vehicles are on the move for a maximum of 50% of the time, balancing operating costs and waiting times of passengers.

Conclusions

This study has investigated possible changes in travel behaviour and mode choice that are expected to occur when autonomous vehicles become available as private vehicles, and/or as part of a car-sharing fleet. For this purpose, it looks at Germany, the USA and China. Since the introduction of autonomous vehicles into the transport system is expected to have a wide range of impacts on the mobility behaviour of the population, we have developed three different scenarios and used a transport model to quantify these impacts. The key findings are the following:

By 2035, we expect to see about 17% AVs in the private car fleet in Germany, and 11% in the US. Depending on the assumptions that underlie these figures, these shares could be higher, but 42% and 32% (in Germany and the US respectively) are the realistic upper limits for the proportion of AVs in the fleets by 2035.

The rate at which AVs will enter into the market, and the speed with which they will then diffuse throughout it, are both still subject to high levels of uncertainty, and are particularly dependent on overcoming technological, regulatory and legal issues, with societal acceptance of automation technology also playing an important part. Analysing the legal and regulatory framework in different countries, we found that regulatory bodies are currently addressing the topic of autonomous driving, and are working on adjusting the legal framework to pave the way for this innovation.

By 2035, we expect to see a moderate increase in vehicle-kilometres travelled by private cars – about 3% – as a result of the introduction of AVs. Assuming the maximum share of AVs in the private car fleet that is realistic, the upper bound of this increase is estimated at 9%.

While we found a small increase in vehicle-kilometres travelled owing to a decrease in the (perceived) cost of travel, the main driver behind the overall increase in distance travelled consists of new groups of users who have not had access to a car before. This includes, but is not limited to, disabled individuals, elderly people and teenagers – and even children. Furthermore, people who had formerly been regular car passengers now more often 'drive' themselves. As a result of the effects above, the increase in vehicle-kilometres travelled is expected to be 3–9% (depending on scenario and country) compared to a case without any automatisation in the private car fleet. This resulting increase comes at the cost of a reduction in public transport usage, particularly in very short- and very long-distance trips.

Between now and 2035, autonomous car fleets have great potential for increasing the market share of mobility-on-demand systems, taking them up to perhaps 8–10% of all trips in Germany.

Autonomous car-sharing (ACS) and autonomous pooling (AP) each have a great potential for bringing car-sharing systems from a niche to a mainstream market. This is especially true in urban environments, where they can operate very efficiently. Our analysis reveals that under the defined input assumptions, ACS could be profitably operated at €0.30–€0.35/km. It is even possible that AP systems could be cheaper still in urban areas, reaching price ranges of around €0.10/km, i.e. similar to public mass transport systems. In particular, AP could in this way act as an attractive public transport service to supplement existing ones. It is estimated that total ACS trips might reach a modal share of approximately 10% of all trips in Germany by 2035. Looking at the AP option, the potential market share of trips in Germany is estimated at around 8%, but AP's benefit over ACS systems vanishes in rural areas. Both ACS and AP are expected to attract trips from all other transport modes, overall increasing vehicle-kilmetres travelled on the road.

1.1 Motivation

How much we travel today, and the way in which we do so, is subject to substantial constraints, amongst which are the following:

- limits on the proportion of time that we want/can dedicate to travel;
- the limited ability of some, such as children or individuals with certain disabilities, to travel;
- the availability of travel modes and/or vehicles that we have at our disposal.

Alongside other constraints, these three lead to a situation in which travel by individuals is limited. Some analysts argue that the current observed tendencies towards saturation in travel demand in some mature mobility markets are caused – at least partly – by such constraints.

However, all three of these illustrative restrictions might be substantially affected by automation technologies. In this project, we want to examine the impact that autonomous road vehicles might have on future mobility behaviour in Germany, the USA and China in the year 2035. Three lead questions guide the project:

1. What if we could make efficient use of the time we spend travelling because of the ability to take our hands off the steering wheel and give our attention to other activities?

2. What if individuals with physical challenges – or children – are enabled to travel unaccompanied, thanks to an autonomous vehicle (AV) that takes them to their destination?

3. What if the availability of a vehicle at a certain location is not an issue because a driverless vehicle comes to pick us up and take us to our destination?

What do we mean by 'automation' technology?

Automation technologies in road transport can be classified into various levels – what is more, there are various alternative definitions of these levels presently under discussion (Gasser et al., 2012; NHTSA, 2013; SAE, 2014; VDA, 2015) defining the degree of automation of a system. However, as this project's aim is to examine possible changes that affect mobility – or, more specifically, mobility behaviour – levels of automation are only considered insofar as they are expected to have a substantial impact on travel behaviour. That is to say, drivers are likely to perceive the time spent travelling in a different light only when they can take their hands off the wheel and transfer their attention to other activities – and this is what will ultimately lead to changes in the way in which they travel.

Referring to the definition given by the German Association of the Automotive Industry (VDA, 2015), this level of independence from the driving task would come about only in the case of levels of automation 4–5[3] (see Figure 1.1.1). We will therefore not consider intermediate levels of automation (0–2), although they may each constitute important entry points for further automation and thus pave the way to higher levels of automation, and eventually fully autonomous passenger vehicles. As for Level 3 systems, while it is true that they are capable of executing the complete driving task – longitudinal control (speed, acceleration and braking) and lateral control (steering), and navigation – they still require the driver to be constantly ready to intervene when needed. Results from focus groups that were conducted during this study suggest that acceptance rates, as well as the level of attractiveness of the technology, decrease drastically if the respondents are confronted with the need to intervene whenever requested. Therefore, for the future projections considered in this report we have considered only Level 4 (the system in charge, some driving use cases) and Level 5 (the system in charge, all driving use cases).

LEVEL 0 DRIVER ONLY	**LEVEL 1** ASSISTED	**LEVEL 2** PARTIAL AUTOMATION	**LEVEL 3** CONDITIONAL AUTOMATION	**LEVEL 4** HIGH AUTOMATION	**LEVEL 5** FULL AUTOMATION
Driver continuously performs the longitudinal **and** lateral dynamic driving task.	Driver continuously performs the longitudinal **or** lateral dynamic driving task.	Driver **must** monitor the system **at all times**.	Driver **does not** need to monitor the system **at all times**. Driver must be capable of resuming dynamic driving task	Driver is not required during **defined use case***.	No Driver required during **entire journey**.
No intervenign vehicle system active	The other driving task is performed by the system.	System performs longitudinal **and** lateral driving task in a defined use case*.	System performs longitudinal **and** lateral driving task in a defined use case*. Recognizes its limits and requests driver to resume the dynamic driving task with sufficient time margin.	System performs the lateral **and** longitudinal dynamic driving task in all situations in a **defined use case***.	System performs entire dynamic driving task on all road types speed ranges and environmental conditions.

* Use cases refer to road types, speed ranges and environmental conditions

Driver □ **Automation level of the function**

Figure 1.1.1. Levels of automation (VDA, 2015; SAE, 2014)

[3] Currently, there are various definitions on levels of automation for different countries that are similar in most aspects but vary in others. Note, that, for example, in Germany "high automation" usually refers to Level 3 (VDA, 2015). In this report we use the SAE automation levels´names, where „high automation" refers to Level 4 (SAE, 2014).

Automation systems expected to be available to consumers before 2020 showcase Level 3 automation applications. The aim of this level is mainly to ease highway travelling in dense traffic situations using the so-called 'Traffic Jam Chauffeur', or to assist in free floating traffic by allowing the driver to turn on the 'Highway Chauffeur', which combines cruise control and lane assist. These applications already allow the driver to engage in other activities, such as using their smartphone or reading a book, but only until the system demands that they take back control again. At Level 4, the 'Highway Pilot', as the successor to the Highway Chauffeur, enables the driver to completely leave the driving task to the vehicle from entrance to exit of the motorway or similar streets. The vehicle will not demand the driver to take over control, thus even allowing the driver to take a nap. The 'fully automated vehicle', featuring automation under all circumstances without any necessary input from the driver, is the most advanced form of automation (Level 5), and is expected to be more than a decade away from mass series production (ERTRAC, 2015).

Several roadmaps have been published describing several applications of automation (Levels 3, 4 and 5) and timeframes for their possible introduction. Most of them follow a distinctly evolutionary path (see Figure 1.1.2).

Figure 1.1.2. Roadmap of autonomous driving

The available roadmaps, together with discussions with experts in the field, formed the basis for the development of the scenarios within this report; the time at which the automation technologies become available is an important factor in calculating the possible fleet size of AVs in the timeframe analysed.

1.2 Focus and objective

The study focuses primarily on passenger cars, and on levels of automation (Levels 4 and 5) that allow drivers to take their hands off the steering wheel and transfer their attention to other activities. Moreover, we will focus our quantitative estimation of the impact of automation in transport on the impact on travel behaviour. Other consequences of automation, such as those affecting safety, the environment or the efficiency of road travel, might also be substantial – they are not, however, in the centre of our analysis.

Automation in road transport also has an unarguably high potential for the haulage industry. The main motivations behind this development are possible cost reductions that open up if the driver can be replaced, e.g. in interurban long-distance transport, and a reduction in accidents, which are often caused by boredom and falling asleep at the wheel. Nevertheless, this study focuses on private transport owing to the complexity of the haulage aspect of automation.

1.3 Approach

It used to be the case that questions about future technical or societal developments were addressed mainly by means of specific forecasts generated by modelling. Today, in contrast, thinking in terms of what might be plausible, rather than what we suppose to be certainties, has become the state-of-the-art methodology in futures research. The aim is no longer to attempt to precisely predict the future, but rather to determine key issues that might have effects on the topic of interest, to explore their interdependencies, and then go on to project various possible pathways along which events might unfold. 'Scenarios' can then be defined as descriptions of complex future situations that could (but do not necessarily have to!) take place, as well as the descriptions of plausible pathways that lead from the present to those possible futures (Gausemeier, Fink & Schlake, 1995).

In this report, we want to outline influencing areas and descriptors[4] related to possible changes in travel behaviour that are generated by automated driving. The aim is to derive scenarios for the year 2035 for three different countries (the USA, Germany, and China) with different penetration rates of AVs, and modelling possible changes in travel demand. The first two scenarios start with the foundation of today's use and ownership of cars, but with varying shares of AVs penetrating the countries' vehicle fleets. Our third scenario, however, follows a revolutionary path in the transport sector, showcasing the impact of autonomous vehicle-on-demand (AVoD) systems on mobility behaviour.

We believe that the three reference countries are suitable for developing a good understanding of the global impact of automation: Germany and the USA are both highly developed mobility markets evidencing signs of saturation, which at the same time represent different prototypes of mobility cultures; in contrast, China is largest among the world's rapidly growing mobility markets.

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[4] A descriptor can be characterised as an influencing factor that describes a specific aspect of an influencing area, and does so in a measurable way.
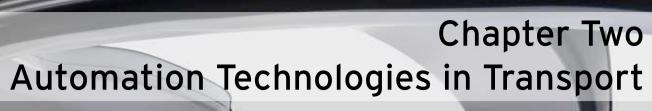
The automation scenarios have a strong link to ifmo's existing mobility scenarios, which are available for Germany (Phleps, Feige & Zapp, 2015), the USA (Zmud et al., 2013) and China (Ecola et al., 2015); moreover, they derive assumptions from them according to demographic, technological and economic developments. In addition, we identify influencing areas that are thought likely to have an impact on mobility in a future featuring autonomous road vehicles – more specifically, the influencing areas, their descriptors, and the projections too should all be strongly connected to the three focus areas of the project: travel time, new user groups and availability of vehicles. Each influencing area consists of various descriptors "that represent one specific element within the influencing area" (Zmud et al., 2013). To develop the influencing areas and descriptors, a qualitative approach was chosen. Expert workshops and focus groups were organised in each of the countries.

To model the impact of autonomous driving on travel volumes, a space-invariant travel demand model is used. The model was applied only to the USA and Germany; it was not suitable for China because of the lack of detailed and reliable data on travel behaviour at a national level. Its main components are the generation of the future population and calculation of total trip volumes, a diffusion model for AVs in different car segments, and a combined destination and mode choice model.

Figure 1.3.1 gives a graphic overview on the methodical phases of the project.

Figure 1.3.1. Methodological approach of the study

This chapter gives an overview of the state of the art of automation technologies in the field of transport and introduces the drivers of the implementation of autonomous driving for private vehicles, and the current barriers to it. In this context, we focus particularly on technological challenges and country-specific regulatory and legal issues related to highly autonomous driving in Germany, the USA, and China.

2.1 Application in the field of transport

Today, high levels of automation technologies in transport can be found in aviation, maritime transport and rail-based public transport systems. Road transport, in contrast, has not yet reached a high degree of automation. This is equally true for private vehicles and public transport vehicles. One of the main reasons for this is the fact that navigating on roads requires much more complex interaction with other users.

However, despite the technological challenges that need to be overcome before AVs become a reality on public roads, the degree of automation in road vehicles is continuously rising. Advanced driver-assistance systems, such as lane-keeping assistants and adaptive cruise control, are already available in currently produced vehicles, and this is moving the technology development forward. In the past, such advanced technologies have been available only in the higher vehicle segments, but today such systems are also available in medium-sized cars.

There are high expectations of automation technologies. Some experts envision autonomous driving as a comfort-enhancing feature for drivers, as it would enable them to focus on other activities. Other stakeholders, such as government officials involved in transport and traffic management, hope that the technology will reduce road fatalities and increase the efficiency of transport systems. In a more distant future it is possible to imagine fully automated vehicles complementing (or even replacing parts of) the current public transport system, supplying demand-responsive service, and serving individual mobility needs in the form of AVoDs in the way that taxis or car-sharing services do today. To achieve this, technological challenges need to be overcome, and also regulatory and legal hurdles cleared.

Moreover, market acceptance will play a crucial role in the future market penetration of AV technology. Societal fears and ethical issues might decelerate their market adoption – these therefore need to be addressed before an AV product can enter the market. Additionally, higher retail prices might present a problem for many consumers. For instance, the willingness to pay for available assistance systems in the medium-sized car segment is lower than in the higher one, which suggests that the perceived benefits from the user's point of view are still on the low side. We make the assumption, however, that further development of the technology and its deployment in a wider range of vehicle segments will reduce its costs. Additionally, the user benefits of highly automated driving, such as enhanced comfort and the ability to use the time spent travelling more effectively, will increase consumers' willingness to pay for such systems.

In summary, there are large uncertainties about how fast autonomous driving will be adopted on public roads and how strongly the technology will spread out into the market. The following section investigates the drivers of its implementation within the transport system, and the current barriers that hinder this.

2.2 Drivers of and barriers to implementation

Potential benefits of automation systems

There are several potential benefits of automation technology in the transport sector, both for society as a whole and for the individual user. These are now discussed as the main drivers behind the development of this technology.

Safety: Experts expect that advanced driving technologies will be more reliable than human drivers, because the system will have the ability to make decisions within milliseconds and without any distractions. Hence, autonomous driving should be able to dramatically reduce the frequency of road accidents, since over 90% of them are caused by human error (Fagnant & Kockelman, 2015; Fraedrich, Beiker & Lenz, 2015). Furthermore, even if road accidents do still happen, AVs can mitigate the severity of crashes that cannot be avoided (McCarthy et al., 2015).

Energy efficiency and emissions: Automation technologies can improve fuel consumption by optimising operation of the vehicle. For example, the system will be able to accelerate and brake more smoothly than a human driver could (Fagnant & Kockelman, 2015). On the other hand, reducing fuel costs and enabling new user groups to travel by car might both lead to an increase in automobile usage, and thus to an increase in fuel consumption and emissions (Anderson et al., 2014; Fagnant & Kockelman, 2015). But then again, automation technologies can facilitate the use of alternatively fuelled vehicles, which would in turn reduce pollution. For example, Level 5 AVs can recharge themselves. Also, the reduction in crashes will allow the production of lighter vehicles, which can increase energy efficiency of the vehicle (Anderson et al., 2014).

Traffic congestion: The expectation that autonomous driving will have a positive effect on traffic jams is not universally accepted. On one hand, AVs will be able to travel closer together and this will increase the utilisation of capacity (Fagnant & Kockelman, 2015; Litman, 2013). Furthermore, accidents, which are a common reason for congestion, can be expected to happen less frequently. On the other hand, should AVs gain a substantial market share, this might lead to an overall increase in vehicle-miles travelled, which in turn could potentially lead to even higher congestion levels. As with the aforementioned safety and efficiency gains, the expected impact on traffic congestion is likewise also dependent on the share of AVs within the fleet. It is even imaginable that in a mixed-mode environment where AVs are in the minority, network speeds initially decrease, with an increase in traffic congestion, due to a minority of vehicles driving strictly according to the rules of the road.

Mobility: Autonomous driving could provide mobility options for people who do not hold a driving licence, or are currently unable to drive because of physical and/or age-related constraints. This includes, but is not limited to, disabled individuals, elderly people and teenagers – and even children. Automation technologies will provide these user groups with the means of independent mobility, will enable easier access to essential services, and will help reduce their social isolation (Anderson et al., 2014).

Comfort and use of time: A much-discussed benefit of autonomous driving for the user is the decrease in the perceived time costs, since vehicle occupants are enabled to transfer their attention to other activities during the trip (Sommer, 2013; Fraedrich et al., 2016; KPMG, 2012). Also, the 'driver' does not need to steer or brake any longer, and can hence travel in a more comfortable way. Moreover, the increasing digitalisation in vehicles, such as infotainment systems, can improve the overall travel experience and level of comfort.

Technological progress in automation and digitalisation

"It´s the end of the era of mechanical engineering and the beginning of the era of software engineered cars."

(an expert´s point of view expressed in the workshop)

There are two cultures of development of the technology. Car companies: "We are taking a car and we are putting a computer into it to drive." Zoox, Google and many academic labs: "We are taking a computer and putting wheels under it."

(an expert´s point of view expressed in the workshop)

Moving from a world of fully manually driven cars to a situation in which we see more and more AVs, software development has become as important as hardware development and machine engineering (KPMG, 2014; Mosquet et al., 2015). As a result, the development of automation technologies faces technological challenges in terms of both hardware and software. The main challenges for the various levels of automation arise from the complexity of the driving environment. The vehicle has to be able to operate autonomously in numerous situations – for example, in a complex urban environment. The system therefore has to make complex decisions based on the information available (sensor data and/or real-time streamed data) using algorithms (Bernhart et al., 2014). Current technological challenges facing autonomous driving are related mainly to the further development of precise (affordable) sensing technologies (e.g. radar, camera, LiDAR[5]) and software solutions that reliably process the information. Appropriate systems are expected to be available on the market within the next few years (VDA, 2015). Experts predict that highly automated driving under specific driving circumstances will be technically possible before 2020. However, it could take up to twenty years or more (from today) to complete the market maturity of fully automated vehicles (Mosquet et al., 2015). The estimated additional costs per vehicle of the technology according to current analysis are between US$3,000 and US$6,000 (Bernhart et al., 2014).

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[5] LiDAR = Light Detection and Ranging

There are two main technological trends related to autonomous driving – automation confined to onboard systems, and automation supported also by communication between vehicles (V2V), as well as between vehicles and other systems (V2X[6]), for example roadside infrastructure (V2I). Some experts suggest that car connectivity is crucial to the achievement to the full potential of autonomous driving (USDOT, 2015). However, efficient information exchange between vehicles and other systems is only possible when there is large market deployment of vehicles with onboard communication capability. Furthermore, V2X communication requires physical as well as digital infrastructure. At the same time, V2X capability is not mandatory for autonomous driving (Bernhart et al., 2014). Hence, these two technological streams – automation and vehicle communication – continue to develop as two separate approaches that might, but will not inevitably, converge in the future (Zmud et al., 2015).

Another consequence of car digitalisation is that not only traditional car manufacturers, but also new players such as the ICT (information and communications technology) sector, are taking a key role in the development of automation technologies (KPMG, 2014). These two sets of developers often have different approaches to the development of technology. While OEMs improve automation systems in conventional cars, new entrants work on AVs, capable of driving fully autonomously in a limited context, with the aim of gradually expanding the range of driving conditions under which the vehicle can operate autonomously (OECD/ITF&CPB, 2015).

Legislation and regulatory framework

"We´ll see way better technology way before we see a better law."
(an expert´s point of view expressed in the workshop)

The legal and regulatory framework is one of the main hurdles to be cleared before autonomous driving can be introduced. The first steps to be taken by the regulatory bodies in paving the way for AVs are the development of a legal framework to permit tests, followed by the actual operation of AVs on public roads. The following section introduces the current status of the discussion in the selected countries.

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[6] V2X communication means vehicle-to-X communication. The term summarises various vehicle technologies that enable a vehicle to communicate, i.e. exchange information, with other systems (the 'X'), e.g. with other vehicles (V2V, i.e. vehicle-to-vehicle), with systems integrated into the infrastructure (V2I, i.e. vehicle-to-infrastructure), with pedestrians' mobile devices (V2P, i.e. vehicle-to-pedestrian), or to a database (V2C, i.e. vehicle-to-cloud).

GERMANY

The Vienna Convention on Road Traffic (VC) and the UN ECE Regulation Nr.79 (ECE-R 79), to both of which Germany is a signatory, have to date been the two primary pieces of legislation which concern autonomous driving. Recent amendments to the VC (23 March 2016) permit a car to drive itself, as long as the system can be overridden by the driver or the car conforms to the UN vehicle regulations (UNECE, 2016). Prior to that, according to the VC, the driver was obliged to remain in control of the vehicle at all times. The first draft for the integration of the amendment into the German national law has been proposed. However, the revision permits automated driving only with a human driver inside the car who can override the system at all times (corresponding to Levels 3 and 4). The next step is further amendment of the VC that will permit the use of driverless cars, i.e. Level 5 AVs which do not require any human intervention. Moreover, a proposal to amend the ECE-R 79 has already been introduced. The recent amendment should allow the system to operate up to a defined maximum speed (130 km/h is under discussion). The amended regulation is expected to come into force in 2017 (UNECE, 2016; Lutz, 2016).

In 2015 the German government published a national strategy on autonomous and connected driving, based on results from the expert Round Table "Automated Driving". According to the strategy, Germany aims to become lead provider and also lead market for AVs. To achieve these goals, the next steps are planned in five fields of action: infrastructure, legislation, innovation, cyber security and data privacy policy (Bundesregierung, 2015). For example, nationally funded projects with a focus on further development of autonomous and connected driving systems are in preparation. The first test tracks for highly automated vehicles have been set up, and are open for use by domestic OEMs and research labs to test their prototypes in a real operation. For instance, the A9 auto-bahn is the first 'Digital Test Field Highway' in Germany, in operation since 2015, and planned to be fully digitalised soon with a 5G network, the successor of the current LTE standards, to enable V2V and V2I communication in real time (Bundesregierung, 2015).

USA

The topic of autonomous and connected vehicles has already been discussed a great deal on a national level in the USA. In 2013, the U.S. Department of Transportation (USDOT) published a national five-year programme on vehicle automation, which covers the development of automated driving at all levels of automation (ERTRAC, 2015). In 2016, the US Transportation Secretary introduced a budget proposal which would provide an investment of US $4 billion to accelerate the development and adoption of AVs over the next ten years. Meanwhile, USDOT and the NHTSA (National Highway Traffic Safety Administration) announced that they were working together with other government entities, as well as with individual states, to set up a regulatory framework for both testing and operational deployment of AVs. Moreover, NHTSA is currently working with different stakeholders on the development of model state policy on AVs that offers a nationally consistent approach on autonomous driving (USDOT/NHTSA, 2016). According to USDOT, vehicle connectivity plays a crucial role in achieving the full potential of AVs, so there are efforts by government to accelerate the deployment of the technology (USDOT, 2015).

A V2V government mandate has been announced and is expected to be established in the near future. Its purpose is to ratify requirements for new vehicles, saying that all new passenger cars and light commercial vehicles have to have V2V equipment (USDOT/NHTSA, 2014). At the same time, there are uncertainties about V2I technology because of the high costs of implementation. Another milestone toward the legalisation of autonomous driving is the NHTSA's statement, published in an official letter to Google in February 2016 (NHTSA, 2016), that a self-driving system could be considered as a driver under federal law.

Although legislative efforts on the subject of AVs have already been initiated at a national level, it is expected to be a state-by-state process. Several states – including Nevada, California, Michigan and Florida – have adopted the legislation for manufacturers' testing of AVs on public roads and proposed the first draft for operation regulations of AVs (Anderson et al., 2014). For instance, the public road testing of AVs has officially been permitted in California since 2014. Prior to that, companies and research labs had been conducting tests with AVs for years, as there was no state law that prohibited such practices. Regulations for operation of AVs on public roads are expected to be established later in 2016, which will actually permit the commercial sale of Level 4 vehicles. Initial test results, including accident reports, are important for the evaluation of the technology, and are the first step towards legalisation of highly automated vehicles. California is cooperating with other states and the federal government to develop regulations for AV operation at a national level. Still, most of the states have no regulations on autonomous driving as yet.

CHINA

China has its own regulatory framework for vehicle technologies, based on its national so-called Guabiao standards (Mosquet et al., 2015). This makes it difficult to analyse and compare China's standards to those of Western countries such as the USA and Germany (Cacilo et al., 2015; Dokic, Müller & Meyer, 2015). Safety concerns, and other traffic problems related to the rapid pace of motorisation in China, constitute important triggers for the government to start taking a regulatory framework for AVs into consideration (ERTRAC, 2015; Cacilo et al., 2015). In the past, the Chinese government has implemented regulatory restrictions in some areas in order to mitigate traffic problems (Ecola et al., 2015), which suggests that if automation technologies are assessed as a good solution for current traffic issues, they will be promoted strongly by the government.

The first steps have been already taken. The Chinese government has recently (March 2016) announced its initiative on improving regulations and establishing a testing environment to support the development of autonomous technologies (Hao Yan, 2016). The first draft roadmap, consisting of unified standards and regulatory guidelines that will allow AVs on highways within five years and permit AVs for urban driving by 2025, could be unveiled by the end of the year. The roadmap will also propose technical standards for AVs that include a common language for V2X communication. The efforts of the committee that is drafting the plan are backed by the Chinese Ministry of Industry and Information Technology (Spring, 2016). Also, there are already some autonomous driving R&D projects in China, funded directly by the government (Newcomb, 2016). R&D activities of foreign OEMs in China are severely restricted by government regulations. For instance, automated mapping activities are not permitted in China, which makes OEMs' tests of AVs on public roads possible only if they cooperate with domestic ICT companies. The first joint ventures have already been established. Moreover, the first test trials on public roads have been announced (Newcomb, 2016).

Liability and insurance issues

Although it is expected that AVs will be involved in road accidents less frequently than conventional vehicles, liability issues in the event of an accident need to be considered. In particular, it must be determined whether the responsibility lies primarily with the vehicle's user, with the owner, or with the vehicle's manufacturer (Dokic, Müller & Meyer, 2015). A variety of solutions have been proposed. For instance, some OEMs announced that they would take full liability in the event of an accident, a stand which might accelerate users' acceptance of the technology. Another issue in this context is the need for a significant change to insurance models when applied to AVs. Experts expect that the insurance costs may decrease as a result of a drop in the frequency of claims. On the other hand, repair costs for AVs after accidents might well be higher than for conventional vehicles because of their more expensive components (KPMG, 2015).

Chapter Three
Key Influencing Areas Related to Vehicle Automation Development

In this chapter we identify the following key influencing areas, which play a crucial role in how autonomous driving might change travel behaviour and mode choice:

(1) (New) user groups

(2) Use cases and business models

(3) Generalised costs of travel and value of time

We review past trends and consider future trends in the selected areas, and briefly discuss the possible impacts of AVs on mobility behaviour. The insights are drawn mainly from expert workshops and from focus groups held with potential AV users which were conducted in the three countries during the project. Additionally, results from expert interviews and literature reviews complete the overview. The analysis comprises the results of all countries together; significant differences between countries are then mentioned separately.

3.1 (New) user groups

> "For me I would recover some of the lost time that I spend driving and commuting – every year there are lots of hours of wasted productivity time... You could have more time to enjoy life rather than commuting and paying attention to the technology of driving."
>
> *(Richard, 61 years old, USA)*

> "For us, we're getting to our silver age like myself... I know people who, because of their age and the difficulties... they have to call friends or somebody to do shopping for them or take them to some places. So self-driving cars would be great for us. It will continue to give me the mobility that I am enjoying now and the control – I can decide when to drive, and where to go to, so I am in control of my own time and when I go and when I come. And also, as I get older, I might lose my driving licence."
>
> *(Nabil, 74 years old, USA)*

Certain **user groups** might benefit from autonomous driving more than others, and for different reasons. Having the option of using AVs might significantly change the travel behaviour of these groups.

First, fully automated vehicles enable people who are currently unable to drive – or do not have permission to do so – to use an individual motorised means of transport. This user group includes **people with medical constraints**, e.g. disabled people, and **people with age-related constraints**, such as those who have developed visual or hearing impairments due to the advance of years, and **teenagers**. Having the option of riding in a car autonomously provides them with independence and flexibility in their mobility, enables easier access to essential services, and can reduce possible social isolation (Anderson et al., 2014).

Meanwhile, the socioeconomic status of these users evidences a distinct pattern: both the employment rates and the average income of those with disabilities are significantly lower than in the case of those without disabilities (WHO, 2011). One could reasonably assume that because of the lower spending power that elderly/retirees typically have, they are less likely to purchase new technologies than younger, employed individuals. This might, then, constitute a barrier preventing many of them from being among the first to use AVs.

Another user group that might have a particular interest in, or derive benefit from, autonomous techno-logy is **people who cover high annual mileages**, and in particular those who routinely make long trips, such as **long-distance commuters**. Since commuting to/from work is a major determinant of peak traffic, many commu-ters are regularly stuck in traffic jams, especially in urban/suburban areas. At the same time, employed people might be more sensitive to time spent travelling than unemployed as a result of a stronger sense of limitation of their time budgets. Furthermore, repetitive long-distance driving is often felt to be exhausting and tedious. The main benefits of autonomous driving for this user group therefore include the opportunity to make more efficient or more pleasant use of the time they spend in their cars. They might well benefit from lower levels of automation already, for instance a Highway Pilot (see section 1.1) that allows them to focus on alternative activities while riding on highways or highway-like streets. In addition, this group was identified as having a fairly high purchasing power, which makes it reasonable to assume that they could be among the first users of AVs.

> "I have motor and sensory deficits in my legs, so I decided not to try to get a driving licence. So if you have something like this [an autonomous vehicle], someone like me could be in a car."
>
> *(Gesine, 63 years old, USA)*

> "I would like to have it [an autonomous vehicle] for my everyday life. I said before that I actually enjoy driving – it is kind of relaxing for me. But there are days on which I don't want to drive, because I don't feel well, so I have to cancel an appointment although I really want to go to… [With an autonomous vehicle] I can get in the car and it can bring me wherever I want to. "
>
> *(Hartmut, 60 years old, Germany, Handicapped)*

Impact on mobility behaviour: How, then, would autonomous driving particularly change the travel behaviour of these user groups? As AVs might be a more attractive transport option than other modes of transport for **people with mobility constraints**, they might switch from using public transport to using this new kind of car, for example – at least those who can afford to do so. As AVs would facilitate the option of travelling independently as opposed to travelling as passengers, they might also display a tendency to travel more frequently. For instance, the techno-logy might give elderly people the opportunity to visit their relatives more often, or enable adolescents to travel more regularly after school to meet friends or to manage their after-school activities by themselves.

For **commuters** on the other hand, who would benefit from the opportunity, while driving to/from work, to undertake other activities or simply relax, autonomous driving could increase their willingness to commute longer distances.

In the following section, we will take a closer look at these two user groups in our three selected countries, focusing on their current travel behaviour as well as their travel needs, and examining possible future changes with regard to autonomous driving.

GERMANY

People with medical and age-related constraints in Germany

People with such constraints today are significantly less mobile than those without them (BMVBS, 2008). This group consists of disabled people, and a large proportion are elderly citizens (65+) who suffer from age-related health problems. Understanding their basic transport needs is becoming more relevant against the background of demographic change. According to current projections, the number of people over 65 in 2035 will amount to about 30% of the overall population, which represents an increase of almost 7 million upon today's numbers (Statistisches Bundesamt, 2009). But elderly people in Germany today are also fitter and more mobile than their counterparts in previous generations. Moreover, car usage among seniors has slightly increased. About half of today's seniors travel by car: 40% as driver, 10% as passenger (BMVBS, 2008). Many elderly people do not want to give up driving, because in some (mainly less densely populated) areas with little public transport infrastructure, it is difficult to reach essential services without a car. At the same time their driving skills are declining because of age-related health problems. Hence, AVs might enable them to maintain their lifestyle for longer, and also travel more safely.

Long-distance commuters in Germany

Commutes make up a third of all trips in Germany and determine the peak travel demand. Most of the commuting trips are short: 70% of them take less than 30 minutes. Commuting distances have remained the same for many years, whereas the time spent commuting has slightly increased. Today, 22% of the people in Germany spend 30 to 60 minutes a day getting to/from work. Of these trips, 66% are made by car, and in rural areas this proportion rises to 70% (Statistisches Bundesamt, 2014). AVs might recover some of the lost time spent commuting, particularly for those who travel longer distances or whose journey to work is prolonged because of daily congestion.

USA

People with medical and age-related constraints in the USA

The main challenges for this group are the poor public transport infrastructure and service found in many regions, and expensive para-transit services which for the most part also have very inflexible schedules.

Similarly to the situation in Germany, half of the people with disabilities are of age 65 years and above (U.S. Census Bureau, 2012). When older people stop driving altogether, they are usually in the 80+ bracket. The so-called baby-boomer generation (those born between 1946 and 1964 and thus presently in their fifties and sixties), who currently make up 23% of the US population, is characterised by significant purchasing power and an active lifestyle. Baby-boomers were the cohort most likely to purchase a new car in 2013, and they also have repeatedly been found to travel more than people in other age groups (Sivak, 2013; McGuckin & Lynott, 2012). In 2035, baby boomers will be between the age of 71 and 89, and more likely to have age-related health problems than other age groups, but are expected to still have a more active lifestyle than previous generations of elderly people. AVs could therefore become an attractive transport option for them, allowing them to keep up with their habitual mobility patterns.

Young transport users (under eighteen years old) in the USA

Another group of transport users with age-related constraints are adolescents, who are not permitted to drive because of their age. Autonomous driving will enable them to manage their after-school activities by themselves. Parents might consider letting their children travel alone in an AV. However, they would have to be of a certain minimum age. Parents might consider allowing their children to travel autonomously to school if their trips both begin and end at supervised places. Ride-sharing services for school children are available today in the USA – e.g. Boost by Benz, or HopSkipDrive[7] – and the trend is continuing. Also, private ride-sharing parents' communities have been sprung up. Hence, ride-sharing options with AVs might be another attractive use case for young transport users.

Long-distance commuters in the USA

Commutes in the USA make up less than 20% of all trips, but nevertheless play an important role in that they determine peak travel demand. The mean travel time to drive to work in the USA is 28 minutes (U.S. Census Bureau, 2014a). The majority of the trips (86%) are currently made by car, lorry or van (76% of the persons drive alone, 10% carpool), which results in congested roads in rush hours. Autonomous driving might recover some of the time lost in commuting. Also, there is a trend towards ride-sharing services, employer shuttle, and ride-sharing matching programmes, supported by employers and the government in order to reduce issues related to the ever growing use of the car.

CHINA

People with medical and age-related constraints in China

The main challenge for disabled people in China is to get access to public transport in the first place because the facilities in most terminals are poor, and not generally accessible to the disabled. Hence, autonomous vehicles could provide more mobility for those with disabilities, and facilitate their participation in social life.

Moreover, it is not uncommon in China for many older people to take care of their grandchildren (Ko & Hank, 2014) while the parents go to work. AVs could provide individual mobility to children without them having to rely on older people, who additionally suffer from age-related health problems.

Long-distance commuters in China

Although national statistics on commute distances for China do not as yet exist, travel data is available for the largest cities in China, that provides hints on travel distances in the country. Trip distances have in general increased (Ecola et al., 2015). Likewise, the time spent commuting has increased, not only because of the increase in home–work distances but also because of increasing traffic jams. In fact, a study found that commuters in China's main cities lose a large amount of time on congestion. For example, it is estimated (based on calculations of lost working time and average monthly wages) that commuters in Beijing lose US$127 per month on average because of traffic jams (China Daily, 2015).

[7] http://www.hopskipdrive.com/

3.2 Use cases and business models

> "I think that a lot of people wouldn´t fly or take a train if you can get into the car and don´t have to care and just go to sleep."
>
> *(Annette, 57 years old, USA)*

> "Once I trust the car, I would use it to send my kids to school."
>
> *(Fidel, 52 years old, USA)*

Use cases and business models of autonomous driving are strongly linked to the level of automation (OECS/ITF&CPB, 2015). AVs could, for example, make using a car more attractive even at a lower automation level than those we are discussing: parking assistants or pilots can ease the stress of parking, especially in urban areas (Fraedrich et al., 2016). Driving long distances or sitting in a traffic jam, which is usually a fatiguing and stressful task for users, is expected to be less unpleasant with a Highway Chauffeur (Fraedrich et al., 2016; Continental, 2013). Secondly, there are **new use cases** that arise from automation technologies, in particular from the highest level of automation. For example, fully autonomous vehicles (those able to make zero-occupant trips) might enable shared use of a car within households by employing a 'return-to-home' mode (Schoettle & Sivak, 2015). Another considerable use case includes empty-vehicle trips for picking up grocery shopping or fetching children.

Autonomous driving enables not only new use cases, but also, related to them, **business models**; that is to say, certain use cases of AVs become (more) profitable when meeting specific user demands. For example, vehicle-on-demand concepts might become more profitable for car-sharing or ride-sharing providers, since the cars have no need of a driver and can reposition themselves, which could enable companies to operate at lower costs owing to higher usage rates. At the same time, the reduced operation costs for such vehicles also lower the price paid by the users of the system, meaning that it becomes affordable for more people. Furthermore, fully automation technologies enable shared use of private vehicles, not only within single households, but also in the context of 'fractional ownership' use.

Impact on mobility behaviour: We suggest that **Level 3 automation**, where the driver still needs to pay attention to the traffic and intervene if required to, might be more of a convenience feature, and thus is highly unlikely to change the mobility behaviour of car users significantly. Possible changes could be expected at higher levels of automation.

With **Level 4 automation**, the vehicle is able to drive autonomously, but only in certain situations. A use case at this automation level is the Highway Pilot, which might be very attractive for long-distance commuters (see section 3.1, "(New) user groups") or generally for long-distance travel. As a result, people might prefer to ride in an autonomous car on longer family trips, rather than travelling by train or plane. Furthermore, people might also consider going on longer trips more often, for example to visit relatives, go on weekend trips, and so on.

In the following section, we discuss how attractive different use cases of autonomous driving are in each of the selected countries, and how they might influence the users' travel behaviour and mode choice decisions. First, we focus on current traffic issues in each country and how automation might solve them, looking also at what potential new use cases could arise from higher levels of automation. We then go on to discuss some business cases that arise from automation and their country-specific relevance.

GERMANY

The Highway Pilot might be an attractive functionality not only for long-distance commuting (see section 3.1, "(New) user groups"), but also for long-distance road trips more generally, such as holiday trips or visits to relatives. At the same time, if the car can drive in automated-only mode at a maximum speed of 130 km/h (which is under discussion for Highway Pilot), it is slower than what many drivers are used to today. This is because in Germany, unlike in most countries, there is no speed limit on some sections of motorway. However, the long-distance road trip was the use case perceived by German consumers as the most attractive application of autonomous driving, on the one hand because of the option of using the time spent travelling more pleasurably, and on the other because long highway drives were perceived as a very tedious task for drivers. Furthermore, many of the participants compared the experience of riding in an AV on long-distance road trips with travelling by train, but having the additional advantages peculiar to individual motorised transport, such as one's own private space and door-to-door mobility. Hence, some travellers might prefer using an AV to going by plane or train for the same journey.

The Parking Pilot might be a conceivable solution for parking problems in urban areas. However, we predict that when the Parking Pilot function first enters the market, this option will be permitted only on private land and at low speed (e.g. to park in one's own home garage, and also in shopping centre car parks). This will be more a convenience feature for users. If the Parking Pilot can also be used in public parking areas, i.e. on the streets, this might change the mode choice preferences of users for short trips in urban areas because of the reduction in access/egress time. It is not clear at this point whether the Parking Pilot might improve the traffic situation in cities or make it worse, but as a drop-off/pick-up function it can potentially save the access/egress time for its users (see section 3.3, "Value of time", for more on this).

The implementation of autonomous vehicles within car-sharing schemes might be a viable business model, particularly in rural areas, solving first-/last-mile issues. In urban areas, on the other hand, it has the potential to replace many trips which are currently made by car or public transport, since people who use it do not have to search for, or pay for, parking, and yet still have door-to-door mobility. Moreover, one of the disadvantages of current car-sharing systems, which potential users mentioned, is the limited areas where car-sharing providers operate. Autonomous vehicles, which can return to base by themselves, enable providers to extend the area where they operate, solving connectivity issues for people living in suburban areas.

USA

Results from the focus group discussions suggest that long road trips are one of the most attractive use cases of autonomous driving for US consumers. In fact, 90% of the long-distance trips in the USA are made by car, and these trips are on average longer than in Germany. Also, there is no passenger train service in the USA sufficiently extensive to rival the car. Hence, the Highway Pilot might be an alternative to planes worth considering. The main advantages from point of view of the user are the enhanced comfort, and the option of undertaking other activities while travelling – or being more attentive to their travel companions.

User demand for the Parking Pilot in the USA might be similar to the demand in Germany, since studies have estimated that 30% of the city traffic congestion comes from cars driving around looking for a parking space (Shoup, 2007). Moreover, the high parking prices are one of the reasons that people prefer alternative modes of transport for short trips, such as public transport or taxi providers/driving services (e.g. Uber and Lyft).

New use cases arise when AVs are allowed to make zero-occupant trips on public roads. For example, results from a recent study have estimated that AVs with a return-to-home option could reduce car ownership rates in the USA by up to 43%, but that this development could lead to a 75% increase in car usage because of the many zero-occupant trips undertaken (Schoettle & Sivak, 2015). The same trend can be expected if people use their AV to, for instance, run errands or fetch children (see section 3.1, "(New) user groups").

One attractive and viable business model for autonomous vehicles in the USA is a car-sharing system operating in rural areas. Many regions have a very poor or non-existent public transport system, so shared AVs could serve the unmet demand in such areas. At the same time, the use in urban areas of car-sharing or taxi services such as Uber and Lyft is continuing to grow. For instance, Uber has reduced the revenue of traditional taxis in San Francisco by 40% within a few years. The potential of AV car-sharing services might be even higher. Against this background, mobility providers have set up the first test fleets using AVs. For instance, Uber is testing a fleet of autonomous shared vehicles together with Volvo since September 2016 in Pittsburgh (Chafkin, 2016).

"My wife and I love to take long drives, so this would be perfect for a long drive because I don't have to pay attention to the road. We could be interacting, we can take pictures. I wouldn't have to worry about the traffic, the lorries. Doing long drives you always have to worry about the lorries, because they are slow, sometimes they pull out into the fast lane because they want to pass. If I go like this [autonomously] – this will be relaxing."
(Donald, 79 years old, USA)

CHINA

When it comes to China, use cases for autonomous driving are discussed mostly for urban areas. Urbanisation has been increasing in China, as many young people move to urban areas in search of better job opportunities. Additionally, the motorisation rate has increased substantially. As a result, the traffic situation in China, especially in urban areas, is characterised by congested roads, parking problems and crowded public transport. AVs might be a part of the solution for many of the current traffic issues. At the same time, their introduction into the transport system might be more open to challenge than in other countries. Conceivable use cases in urban areas that were discussed by experts include the use of AVs on separated AV-only dedicated lanes.

Long-distance trips and the Highway Pilot as an application of autonomous driving are each discussed as an attractive use case, the implementation of which might, however, encounter more challenges in China than in other countries. One of the reasons for this is the more complex situation on the roads.

Car-sharing systems using smaller vehicles, on the other hand, might solve first-/last-mile and other connectivity issues. Moreover, some big cities in China attempt to constrain overall vehicle ownership in order to mitigate traffic problems. Hence, car-sharing systems might become an attractive and also affordable alternative to car ownership. At the same time, there are also other alternative individual transport modes in urban areas, such as mopeds or electric bicycles.

"Well I would go to see my grandkids, because I can go on Friday night, get in the car and be there on Saturday morning. And be able to drive on Sunday and be back on Monday morning… I can sleep in the car."
(Annette, 57 years old, USA)

"I can imagine using it [autonomous driving] for long-distance trips so I can relax while travelling. I can imagine using it for an eight-hour trip."
(Birgit, 46 years old, Germany)

3.3 Generalised costs of travel and value of time

"It gains more time. You can use the time for other activities – this is a benefit, it is a kind of a luxury."
(Christiane, 46 years old, Germany)

"For me I think it [autonomous driving] would change my trips, because of the present situation in our area – the traffic jam in the morning and the evening. That [autonomous driving] would definitely change it – I wouldn't care."
(Richard, 61 years old, USA)

Autonomous driving could change the generalised costs of driving, **time costs** as well as **monetary costs**, and thus it might also change the mobility patterns of transport users. However, many of the more sizeable changes in this area are at this point subject to a degree of uncertainty.

The valuation of travel time has to be understood as a valuation of travel-time savings, and expresses the willingness to pay for travel-time reductions. It can differ from one situation to another. Time pressure when going to airport to catch a plane is higher than when driving to a lake at the weekend. Thus the savings in the value of travel time are lower in the second situation.

The valuation of travel time by transport users depends on the modes of transport, the trip purpose, and the travel conditions – for example congestion or comfort level. For instance, a framework developed by Litman (2009) for estimating the value of travel time suggests higher time values for car drivers than for car passengers, and also higher values for public transport passengers who are standing during the trip than for those who are sitting. Autonomous driving can significantly reduce the **value of travel time**, since the occupants can take their hands off the wheel and transfer their attention to other activities during the trip (Fraedrich et al., 2016). The time in the car might not be perceived as 'wasted' any more in concentrating on the driving task, and could be spent in a more 'meaningful' way. This is particularly relevant for people with a limited time budget (e.g. workers during the week) and those affected by poor travel conditions, such as traffic jams or bad weather. Furthermore, since users do not have to operate the vehicle (accelerate, steer and brake), they can enjoy a more comfortable ride. Hence, autonomous driving can change the individual's perception, i.e. valuation, of the time spent travelling, by enabling effective use of time and increasing levels of comfort.

Moreover, autonomous driving could also influence the **actual travel time**. The average speed might increase as a result of more efficient traffic flow and less congestion. However, significant changes in travel speed are only expected when AVs attain a substantial market share. At the same time, the access and egress time of the users might also decrease in the case where AVs pick their users, drop them off at their destination and park on their own.

There are some uncertainties about the impact of automation technologies on **monetary costs** of driving. Fixed costs, such as the purchase price of AVs, are expected to be higher at first owing to the more expensive components. For the same reason, maintenance costs will also rise. The increased safety might lower the insurance costs for AVs, but insurance companies still need to consider the higher repair costs in the event of an accident. Variable costs, such as fuel costs, might decrease because of optimised vehicle operation, AVs will drive in a more fuel-efficient way. At the same time, the shift from the traditional car ownership model to newer concepts of car-sharing changes the costs of car use for the customers of such mobility services.

Overall, regarding the generalised costs of driving, we assume that in the light of the effects described above, autonomous driving will mainly reduce the value of travel time.

Impact on mobility behaviour: As a result of the **reduction in value of time**, people might change their mobility behaviour by considering, for instance, travelling longer distances. Moreover, they might change their preferred mode of transport for certain trip purposes. For example, AVs might become a more attractive transport option than public transport, since people can undertake other activities while riding and at the same time benefit from the advantages that private motorised transport provides, such as private space and door-to-door mobility. In the following section, we discuss the effect of the generalised costs, and particularly of the value of time, on mobility behaviour, focusing on the user perspective and on country-specific issues.

"I imagine that it could be very relaxing [to drive autonomously], because it might be almost like travelling with public transport, but being by yourself – you can adjust your seat to sit as you wish to, you can hear music, you can even sleep while riding [autonomously]."
(Daniel, 22 years old, Germany)

"I think it [autonomous driving] is fantastic, it is a relief. I had felt I would probably have less pressure, less stress. I would feel like I would be more alert (?)with my kids if my kids were in the car [while driving autonomously]… It's just because when I'm driving I can't pay attention to whether they are being good back there or not."
(Alexcia, 35 years old, USA)

GERMANY

Value of travel time:

As mentioned above, the valuation of travel time depends on time pressure and the circumstances of the trip. For some German consumers with a limited time budget, such as workers on a working day, the option of riding autonomously and using the commuting time to get things done means more time for leisure activities in their non-working hours. Others, however, consider the idea of spending their travel time in a more productive way, e.g. by working, rather negatively – it would make them feel under pressure to work even more (Fraedrich et al., 2016). Moreover, some are concerned that riding autonomously could be just as mundane as, or even more boring than, driving on their own, when they at least have a task to focus on. Hence it can be seen that the value of time spent riding autonomously, and the willingness to use this function, depends also on how people would spend their travel time.

Other factors that influence the value of time are trip conditions and characteristics, such as the traffic situation or the trip length. German consumers stated that they actually enjoy driving overall, but that there are several situations where driving becomes rather a tedious task, e.g. extensive commuting, negotiating heavy traffic, or undertaking long motorway drives. In such cases, drivers do not mind handing over control to a driving system and enjoying a more comfortable and relaxing ride, or spending more quality time with their travel companions. Furthermore, users perceive the time spent riding autonomously in a similar way to travelling by train or plane, but with the additional advantages of a private car.

Costs: A recent study found that the stated willingness to pay for highly automated vehicles, which enable the occupants to undertake other activities, is higher than for automated systems that have to be supervised by the driver. Also, German consumers are willing to pay more for such services than US consumers (Dungs et al., 2016). At the same time, German consumers are often faced with several options when choosing a transport mode, with a dense public transport system and cycling infrastructure that is often of high quality. Hence, the costs for using a car for many of the trips are competing with the costs of public transport. Variable costs for using the car in urban areas, such as parking costs, also have to be considered. For instance, autonomous car- or ride-sharing services might be an attractive option in urban areas because of the lack of additional costs, such as parking.

"In my opinion, a great advantage [of autonomous driving] is that I don't need to drive. I ride as a passenger and I can get things done that I would usually do at home or at the office. So for me, my car would then be my small mobile office, where I don't need to focus on the traffic etc. I would then have more time – also more free time... which I can spend, for example, on the couch at home... I wouldn't use the travel time [in an autonomous vehicle] for relaxing – I would use it to get things done."

(Manuel, 36 years old, Germany)

USA

Value of travel time:
The reduced value of time that applies to riding autonomously is considered by the US consumer in a way that is similar to the German consumer, that is to say it is affected by the option of undertaking other activities while on the move, but even more importantly by the enhanced comfort. In contrast to German consumers, many US consumers complain about the lack of viable alternatives to the car, because of the poor quality of the public transport systems in some areas. Hence, the majority of the trips in the USA are made by car. Autonomous driving seems to be most attractive for the US consumers when taking long-distance trips, since they can travel more comfortably, enjoy entertainment functions (e.g. watch movies, use the Internet) or spend more quality time with their travel companions. Some of them can also imagine travelling overnight or taking longer road trips if they know that they can sleep in the car during the trip.

At the same time, autonomous driving might also improve the time spent on routine daily trips. Using the commuting time more effectively, i.e. for working, is perceived very positively by the US consumers, particularly if it can officially count as working time. From the commuters' perspective it would recover the lost productivity time taken up by commuting, and would free up leisure time in the hours outside work. The value of time on other routine trips, such as fetching children, might also change. For instance, parents stated that riding autonomously with their children would enable them to spend the travel time concentrating more on them, which would be one of the most important personal benefits.

Costs: Driving costs in the USA are lower than in Germany, mainly because of the low fuel prices. Although the average fuel consumption is higher than in Germany, the car seems to be perceived as a cheap transport option by many consumers. Furthermore, in many areas it is also the better option because of the poor service level of public transport. This suggests that the willingness to pay for privately owned AVs is comparatively high, making it attractive even in the lower-price small car segments. On the other hand, the willingness to use autonomous carpooling systems might also be high, as indicated also by the fast adoption of sharing services, such as Uber, in particular areas.

CHINA

Value of travel time:
Time pressure, caused by limited time budgets but also by heavy traffic on workdays, seems to have the most important influence on the value of time of working people in China. Hence, the time spent in driving to and from work is for the most part perceived as 'wasted' time. On the other hand, many commuters do not want to give up the comfort and the private space that a car provides, which contrasts with the crowded public transport of the peak hours. Moreover, the car seems to be a status symbol for many of them. As a result, those who can afford it have a personal driver, at least during the working week. This enables them to use the time they spend travelling more efficiently, e.g. for work-related activities, such as writing emails, making phone calls and preparing documents, or simply for having some time to relax after a busy day. Using the car as a kind of a mobile office or place to retreat after work is perceived by the groups of the people who currently have a personal driver as one of the most attractive use cases of autonomous driving. Additionally, some of them are convinced that the technology might be more reliable than a human driver by avoiding human error.

On the other hand, Chinese consumers can imagine using an autonomous driving function also for leisure trips, even if many of them stated that they enjoy driving themselves on the weekend. The main benefit of riding autonomously would be, similarly to the USA and German consumer, the option of spending more quality time with the family on holiday trips instead of driving.

Cost: Owing to the rapid economic growth seen in recent years, car ownership has become affordable for more of the Chinese, but in many cities there are additional costs for car ownership due to government restrictions. The willingness to pay to ride autonomously to/from work is expected to be higher than on leisure trips, because of the limited time budget and the heavy traffic on business days. This suggests also the fact mentioned above – that some working people prefer a personal driver for their commuting trips. However, Chinese consumers are more cost-sensitive than their US and German counterparts, suggesting that high costs of automation technologies to be borne when buying a car might represent a barrier for their market adoption. However, suitable business models, e.g. sharing models, might lower the costs and hence make autonomous driving an attractive option for certain groups of Chinese users.

"To me it is flexibility [to drive autonomously]. To me it would be a luxury just to be able to sit there and let the car do the driving while I do something else – work, pleasure, watch a movie or maybe I am on the way to the opera and I can fix my earring – something like that. "

"I think at the same time a lot of people right now who are taking public transport [are doing that] because they don't want to drive. Because when they drive, they can't do other things. But if this self-driving car is available – they will stop using public transport and they will go for a self-driving car, because now they'll do more things."

(Nabil, 74 years old, USA)

Chapter Four
Scenarios for Autonomous Driving
for the year 2035

In this chapter, we introduce three different scenarios for the year 2035, for each of the three countries. The first scenario, "Evolutionary automation", envisages a possible future based on a more evolutionary development of automation systems and subsequently of the share of AVs in the overall vehicle fleet. Its implications for future behaviour, as well as its influences on the use of other transport modes and overall traffic, will be discussed. The second scenario, "Technology break-through", assumes a more progressive development of the AV fleet. What these two types of scenarios have in common is that they still require humans to sit inside the vehicle while riding – although the vehicle is fully automated, meaning that it can drive itself, be that in specific use cases only (Level 4) or in every situation (Level 5). This presupposition unfolds a major impact insofar as AVs are still used in a fairly conventional way, comparable to today's use of cars. The third scenario, "Rethinking (auto)mobility", deals with AVs as part of new – and on-demand – mobility concepts. That means that vehicles are allowed to move without humans inside.

Demographic, economic, and traffic factors all have an impact on mobility in a general sense, but they also influence individual motorised traffic specifically. The future projections, summarised in Table 4.1, are derived from ifmo's scenarios developed for Germany, the USA, and China (Phleps, Feige & Zapp, 2015; Zmud et al., 2013; Ecola et al., 2015). They were also applied for the reference scenario ("base case, AV fleetshare = 0%).

Certainly, significant differences appear between the three countries, depending on whether more or fewer AVs are introduced into the transport system and on the way in which they are used in the future. However, to provide comparability, we also assume that certain aspects remain the same (or similar) within these scenarios, at least including demographic and spatial developments as well as cohort effects in driving licence possession, for example.

For reasons of lack of data, the scenarios for China have not been modelled and therefore follow a more qualitative approach, reflecting the results from focus groups and expert workshops that have been carried out with Chinese partners.

In the following, all changes presented - an increase in vehicle-kilometres travelled (VKT), for example - refer to the base case (AV fleetshare = 0%).

Table 4.1: Summary of current and future trends in Germany, USA, and China

	Germany		USA		China	
	2015	2035	2015	2035	2015	2035
Total Population	82 million	75 million	321 million	370 million	1.35 billion	1.40 billion
Urbanisation	75% urban population[8]	increasing	82% urban population[8]	increasing	56% urban population[8,12]	strongly increasing
Car ownership rate	588 per 1,000 inhabitants[9] 1,02 vehicles per household	dependent on scenario	809 per 1,000 inhabitants[10] 1,89 vehicles per household	dependent on scenario	ca. 92 million passenger vehicles[11]; rapid growth over recent years[12]	Continues to grow, decelerated due to government restrictions

[8] United Nations, Department of Economic and Social Affairs, Population Division (2015)

[9] MiD 2008 (BMVBS, 2008)

[10] NHTS 2009 (USDOT, 2011)

[11] China statistical yearbook 2014 (National Bureau of Statistics of China, 2016)

[12] Note that there are currently marginal differences in the number of employed persons in urban as against rural areas, but there are extremely high differences in the income: there is an income gap, in that income per capita is much higher in urban areas than in rural areas (China statistical yearbook 2014, National Bureau of Statistics of China, 2016)

GERMANY

2035: Overall shrinking population, but more active elderly people

Overall, the population in Germany has grown older and shrunk – on the one hand, advances in medicine have increased life expectancy while, on the other hand, birth rates have decreased and thus led to a thinning of younger cohorts. In particular, the ageing of rural areas, and the share of single and two-person households, has further increased in recent years. Single-person households now account for 41% of all households – an increase of around 5% compared with the early 2000s. More people have moved to the urban agglomerations – a trend that is still continuing. Cohort effects have led to an increase in elderly female car users while, in general, older people maintain an active lifestyle and have therefore become more mobile. Owing to spatially diversified family and social relationships, there has been a rise in leisure trips to visit family and friends.

USA

2035: Trend of 'greying and browning' has been continuing

Overall, the population in the USA has further grown slightly because of ongoing immigration, as well as fertility rates sitting at or near replacement level. It has also grown older and – particularly in the younger cohorts – become more ethnically diverse as a result of migration movements that have been going on continually throughout the last twenty years. The average size of households has stabilised at 2.6 persons, with more elderly people living alone and more (immigrant) families living in larger households of over two children. More than ever, US Americans live in urban agglomerations with the boundaries of cities moving ever outwards – and it is, most notably, the elderly who have started to move from the suburbs to the city centres to benefit from a variety of cultural and social provision. This has affected mobility in a way that has put solutions to deal with automobile-related traffic congestion at the centre of attention even more than before. As for the distribution of the population in different areas (urban, suburban, rural), the shares have essentially remained constant throughout the last three decades.

CHINA

2035: Slightly increased population, but heavily increased urbanisation

China's population growth has slowed down significantly over the last ten years (2025–2035). By today, it is only increasing slightly, stabilising at a level of around 1.4 billion. The share of older people has increased dramatically, due to advances in medicine – almost twice as many Chinese are aged 65 years or older than was the case in the decade beginning in 2010. Urbanisation trends have continued significantly, with about 75% of the population now living in metropolitan areas. Some cities have therefore continued to apply strict policies to deal with car-related parking and congestion problems, while simultaneously promoting and supporting innovations which address challenges in urban transport and mobility. In tandem with more and more young people having moved to metropolitan areas, long-distance travel has increased: in a manner similar to many of the Western countries, family and other social relationships have become more diverse and spatially distributed. While in the early 2000s almost all Chinese lived in some sort of family household, this share has decreased significantly during recent years in favour of a rise in single-person households.

4.1 "Evolutionary automation"

GERMANY

Regulation and market development

Legal and political regulation has led to the deployment of AVs into the transport system. In the segment of luxury cars (see Appendix, section A.1, for a discussion of the segments), highly automated vehicles (Level 4) have been on the market in appreciable numbers since 2025; medium- and compact-sized vehicles followed in 2027 and 2028 respectively, and from 2030 on AVs have been available in the small-car segment. 2030 also marked the year in which fully automated (Level 5) systems were first introduced, subsequently replacing Level 4 systems in new cars of the luxury class. These two classes of vehicles are capable of executing navigation as well as longitudinal and lateral control of a vehicle without human intervention in defined use cases (Level 4), or for all use cases in every situation (Level 5). However, even if it was technically feasible, these AVs are not allowed to drive on most public streets without a human inside the vehicle. They can, however, park themselves outside and into garages or in dedicated (parking) spaces. Legislation was furthermore altered in terms of regu-lating the access to AVs: what used to be a 'driving licence' became a 'rider's licence', and transport users who are not able to own a 'conventional driving licence' (because of age or other constraints) are now allowed to use a Level 5 AV provided they are at least fourteen years old.

AVs have largely entered the fleet as company cars and proceeded to the private car market after two to three years. In 2035, Level 4 and 5 AVs have reached a market share of 39% (for new car registrations) and account for 17% of the total private vehicle fleet (see Figure 4.1.1). The costs for an AV are still higher than for a conven-tional car in terms of the purchasing price. However, insurance companies have accredited the safety benefits offered by these vehicles, and therefore set lower insurance costs for them. This effect has not yet compensated for the higher purchase cost.

Use and user groups

According to their users, AVs are considered beneficial. They allow for a variety of activities while driving (using mobile Internet devices, working, relaxing, watching movies, etc.) that are not possible when driving in a conventional car. Particularly when travelling on longer trips, users of autonomous cars appreciate the possibilities of the technology – AVs therefore have become popular most notably for specific leisure trips such as weekend escapes or overnight trips to visit family and friends living far away. The initial idea, however, of people being able to spend their time productively at last, has not come to fruition so far, for various reasons: the share of people being able to work in their cars while travelling, because their jobs offer them this option, is rather low. Moreover, on average, car users require approximately twenty minutes for work-related trips – a time period often too short to conduct work activities. Still, the use of an AV for working while travelling has become a popular habit, particularly for those who commute longer distances.

Overall, time spent in congested traffic – especially in urban areas while on the way to the shops, workplace, etc. – is perceived less negatively with the advent of AVs, since users no longer have to focus on the actual driving. The share of people who suffer from mobility impairments – e.g. visual or walking disabilities – has increased as the share of elderly people has risen. With the availability of AVs, requirements for retaining one's driving licence for a conventional, human-driven car have become stricter, especially for elderly people. A considerable number of them 'switched' to a 'rider's licence' for an AV instead, so that they can stay personally mobile into old age. Mobility-impaired transport users seem to benefit from cars that drive themselves, as these can compensate for physical limitations. With the introduction of Level 5 vehicles into the transport system, this specific group is now legally permitted to ride in an AV. Nonetheless, highly subsidised public transport infrastructure has further improved its reputation and is a popular means of transport, and therefore in serious competition with the automobile.

Adolescents living in rural areas or areas remote from public transport use AVs also, owing to changes in legislation, for example for leisure trips, which leads to an increase in car usage from 5% to 8% for this specific group (see Figure 4.1.3).

Mobility

AVs have been stated to increase traffic efficiency because they are able to drive at closer proximity to other vehicles running ahead of them and/or contribute to a stable traffic flow. However, AVs in the year 2035 only account for 17% (see Figure 4.1.1) of the total vehicle fleet. Therefore, they are part of a mixed traffic situation with a great variety of different types of vehicles (from human-driven, to partially or highly automated, to fully automated) – hence, the potential efficiency gains of AVs have not yet materialised. In addition, as a result of changes in regulating the access to AVs as well as the perceived attractiveness of the new cars, a slight increase in overall traffic volume is observed: more transport users use individual motorised transport as a means of fulfilling their daily needs, leading to about 2.4% more vehicle-kilometres travelled (see Figure 4.1.2). Overall, these effects (mixed traffic and an increase in traffic volume) have, so far, compensated for the increase in traffic efficiency. In general, it seems that the use of privately owned vehicles has continued to gain momentum, even though it initially appeared in the decade beginning in 2010 that the car would slowly but eventually lose its predominant status. In particular, the share of AV users among commuters has increased noticeably, and has added to the trend of people using privately owned automobiles to get to work, a trend that has been going on for decades.

USA

Regulation and market development

Several states initiated regulatory and legislative processes to address AVs in the mid-2010s. By now, all states have passed bills that generally permit autonomous driving on public streets if a human is present in the vehicle. However, some differences exist from one state to another, for example concerning age limits: most of the states permit children of fourteen years and older to use an AV with their parents' consent, while a few others determined boundaries of use for all those teenagers sixteen years and younger. Using an AV for the mobility-impaired or children who are not able to obtain a conventional driving licence has become legal in general with the advent of Level 5 vehicles, since these are able to function in all defined situations without any driver necessary.

There have been discussions on permitting AVs on high-occupancy vehicle (HOV) lanes, too – an essential argument here is the verifiable increase in safety attributable to the technology. However, the public debates in several states lead to no agreement on this issue, and AVs are not permitted to drive on HOV lanes in most of them.

The introduction of AVs into the country's vehicle fleet has got off to a slow start in the 2020s: by 2035, about 11% of all passenger cars are autonomous vehicles (see Figure 4.1.1). The national fleet in general is still rather old, making it harder for new vehicle technologies to break through. Another aspect is the lower share of luxury vehicles, which tend to be the bearers of new technologies into the rest of the market. For new car registrations the share is significantly higher, with about 25% within the medium segment and more than 80% within the segment of large vehicles now being AVs.

Use and user groups

When AVs first got introduced into the American automobile market in the mid-2020s, it was particularly the generation of baby-boomers who were among the 'early adopters' of the technology: it gave them the ability to stay personally mobile into old age, and enabled them to keep up with their usual active travel behaviour. For this user group, which consists mainly of retired people, AVs have become a popular means of transport for long trips to visit faraway family and friends while, at the same time, they are also increasingly valued by employed transport users for commuting trips: using the time productively or to relax is considered a unique benefit for the consumers. A total of about 13% of the population has access to an AV (see Figure 4.1.4). Another user group that has seemed to embrace the benefits of autonomous driving is the mobility-impaired. Although improvements have been made throughout recent years to specifically address the mobility needs of the elderly and the impaired people, infrastructure in many regions throughout the country is still poor. AVs compensate for these lacks, and have therefore become a highly popular means of transport among this user group. Smaller communities in some states also provide a fleet of AVs for the use of their elderly and/or impaired residents, to make their places of residence more attractive.

Mobility

As people who use AVs can conduct several activities while riding, spending time in traffic has become less of an issue for its users, specifically for commuters, who still form the majority of car traffic in peak hours. Being physically 'stuck in traffic' is perceived differently from the individual point of view of AV users – but from a macro perspective, traffic volume has continued to increase, and AVs are more and more becoming a part of this development – although by 2035, their share in this development is still low.

While younger people, as well as the elderly, tend to live in cities, families with children have continued to dwell in the suburbs of urban agglomerations. There, the trend towards owning two or more vehicles per household has continued due to the continued inadequacy of public transport supply.

These developments have led to an increase in vehicle-kilometres travelled of about 3.4% (see Figure 4.1.2), mainly because of a higher number of leisure and shopping trips. The already low share of public transport trips has further decreased, by roughly 5.0%. These effects are most distinct for very short and very long-distance trips (see Figure 4.1.5).

As for traffic efficiency, the effects are comparable to Germany, where in the aggregate no changes have occurred so far because of the low share of AVs in the vehicle fleet.

CHINA

Regulation and market development

While the Chinese government has started to get involved in the topic of autonomous driving later than Western countries, in the early 2020s they became ever more heavily engaged with AVs. To deal with increasingly pressing issues related to traffic safety, and to specifically address the mobility needs of the elderly as well as the mobility-impaired, autonomous driving has been seen as a powerful technology in this regard.

Autonomous vehicles have been available on the Chinese market from the mid-2020s on – however, the vehicles entered the market mainly as luxury cars, and thus did not address the high cost-sensitivity prevalent among consumers and, as a result, have only diffused very slowly into the market so far. In addition, the government has continued to apply strict regulations in relation to car use and ownership, especially in urban agglomerations, to deal with an ever-increasing traffic volume on Chinese streets. A few model regions and test beds have tried to incorporate AVs in an integrated transport system, with a strong focus on supporting intermodal travel behaviour. Here, the self-driving cars serve to get to and from metro stations as a last-mile service, significantly increasing accessibility to fast public transport.

Use and user groups

By 2035, around 50% of the Chinese possess a driving licence, and using and owning an automobile has become a widely adopted behaviour. With the introduction of AVs into the transport system, however, the former rapid growth in driving licence holding has recently slowed down significantly, and the possibility of using an automobile without having to get a driving licence seems to be an attractive possibility.
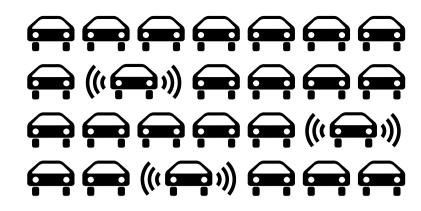
AVs have become a popular means of transport, particularly for trips to and from work and other business-related trips. As congestion problems in the cities have not yet been solved, many working citizens are spending more than 1.5 hours in traffic every day. With AVs, this time is often used as working time, and accredited as such by the employer. In addition, AVs have become a favoured privacy retreat in cities that are often known as crowded, noisy, polluted, and stressful. However, AVs are still expensive, and therefore only common in the higher-income groups, as company cars in larger enterprises, or as part of car-sharing fleets.

Children are carried to and from school by shared AVs, a task that was formerly often accomplished by their grandparents. However, owing to more diverse family relationships, Chinese families have converged with many of the Western countries, where generations live apart from each other far more often than they live under the same roof. AVs have, at least in higher-income families, proved beneficial in compensating for the loss of older generations who often were in charge of 'fetch' and 'bring' services.

Mobility

A common practice is the provision of dedicated lanes for AVs – in this way they can better display their benefits for traffic efficiency, thus specifically addressing congestion challenges in urban areas. These dedicated lanes are first and foremost provided on motorways and similar dual-carriageway roads. In addition, AVs can be seen as a supplement to the metro and railway stations in many inner-urban areas to adress the first-/last-mile problem, and to offer door-to-door service. As such, AVs are often part of a (semi-)public vehicle fleet – which is in part also due to the strict registration regulations of new cars for private purposes that are still in place in many Chinese metropolitan areas.
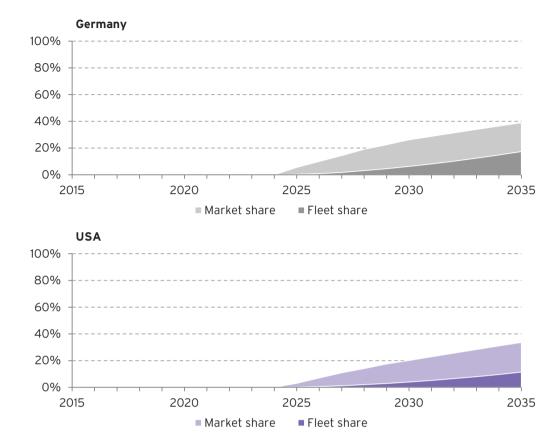
2025

RIDERS LICENCE

Germany

USA

Figure 4.1.1: Penetration rate of vehicles with Level 4 & 5 automation systems under scenario "Evolutionary automation"
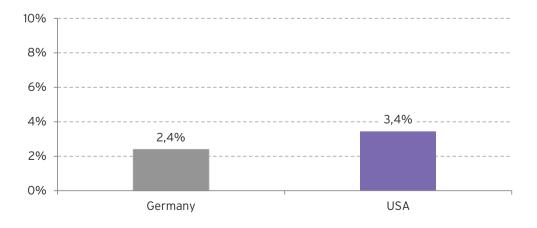

Figure 4.1.2: Impact of the introduction of autonomous driving on vehicle-kilometres travelled (VKT) under scenario "Evolutionary automation" compared to the base case scenario
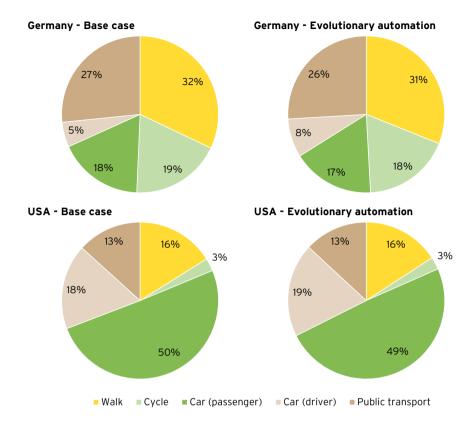
Germany - Base case

Germany - Evolutionary automation

USA - Base case

USA - Evolutionary automation

■ Walk   ■ Cycle   ■ Car (passenger)   ■ Car (driver)   ■ Public transport

Figure 4.1.3: Comparison of modal shares of teenagers (10-17 years): Base case (AV fleetshare = 0%) vs. scenario "Evolutionary automation"

Germany

USA

■ Car availability (AV)
■ Car availabilty (conventional)
■ No car availability

■ Car availability (AV)
■ Car availabilty (conventional)
■ No car availability
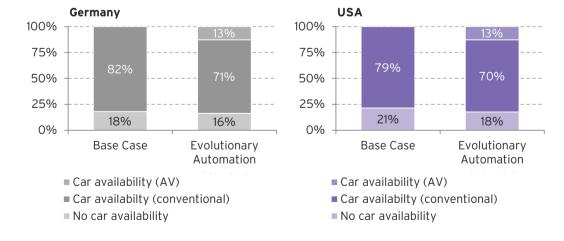
Figure 4.1.4: Sizes of user groups differentiated by car availability classification under scenario "Evolutionary automation"
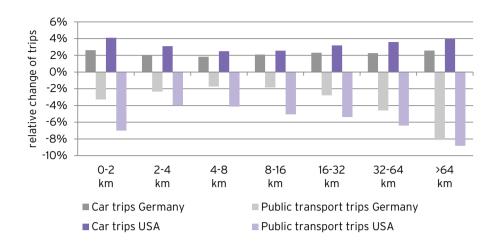
Figure 4.1.5: Relative change of public transport and car trip numbers for different distance bands under scenario "Evolutionary automation" compared to the base case scenario

4.2 "Technology breakthrough"

In the following section, we will describe a scenario where autonomous technologies are introduced to the market earlier than in the scenario "Evolutionary automation", in combination with faster adoption of such systems. Within the scenario "Technology breakthrough", technology has proven to be safe and beneficial, and the regulatory barriers – as well as liability issues – that autonomous systems face today have been overcome faster. Additionally, specific political and legal measures introduced in the 2020s to push the adoption of the technology have led to significantly higher shares of AVs in the year 2035.

Apart from the significantly larger fleet of AVs within the overall fleet of the examined countries, the only other parameter that has been altered is the age of persons able to 'drive', which has been reduced for modelling purposes. Therefore the effects of autonomous driving on the transport system described in the scenario "Evolutionary automation" can also be applied to the scenario "Technology breakthrough". The descriptions of the scenario below will focus on the differences between the two.

GERMANY

Regulation and market development

As a result of efforts made primarily by industry players, a public debate that started in the years leading up to 2020 strongly addressed safety benefits of AVs, as well as safeguarding the competitiveness of Germany's automobile industry. As a result, statutory rules pushed the proven technology strongly. Consequently, Level 4 vehicles had entered the market already by 2022 in the luxury class, and this was followed by a fast adoption down to the small-vehicle segment through to 2025, due to a government subsidy programme. The year 2025 also marked the introduction of Level 5 technologies into the premium vehicles segment. This led to a widespread introduction of AVs into the transport system, with a share of more than 40% in the overall fleet by 2035 (see Figure 4.2.1). The share of AVs on new car sales amounts to almost 80%, making purchasing a conventional vehicle the exception.

Use and user groups

Regulation also permits the use of what is perceived to be the safest means of transport from an early age on – children of ten years and older are therefore able to use AVs, and their parents have been getting used to sending them to school or to leisure activities in the self-driving vehicles. There is also a new user group which has started to embrace AV technology, one that was not able to drive a car before the implementation of the technology: mobility-impaired transport users (see scenario "Evolutionary automation"). Within this scenario a share of about 46% of the population has access to an AV (see Figure 4.2.4).

Mobility

Even though considerable benefits have been discussed, and indeed expected, with regard to traffic efficiency, these aspirations have not come to fruition as yet. As AVs have become widely owned and used, the trend of stagnation and saturation of the individually owned and used automobile (known under the keyword 'peak car') that was promoted in the early 2000s developed in the reverse direction. As a result, using AVs on short trips, normally of walking distance, and on longer trips led to an overall increase of vehicle-kilometres travelled of about 9% (see Figure 4.2.2). Primarily responsible for this is a significant increase in shopping and leisure trips by car (+10%). With the rising appeal of AVs, the use of public transport significantly declined in like manner for short distances and longer distances, with an overall reduction in trips of about 10% (see Figure 4.2.5).

USA

Regulation and market development

Similarly to the development in Germany, the introduction of AVs has been pushed by the US government from an early stage. However, the diffusion of the technology within the fleet has taken place at a slower pace, mainly because vehicles in the USA are driven for a longer period of time before being replaced, which leads to a slower renewal of the vehicle fleet. In 2035, AVs account for 32% of the fleet, and 75% of new car registrations are AVs (see Figure 4.2.1).

Use and user groups

Some years before fully automated vehicles entered the market, highly automated vehicles were available and have been seen to be beneficial for many consumers: particularly in heavy traffic – the typical commuting situation for many Americans living in urban agglomerations by 2035 – highly automated vehicles have given users the ability to get their eyes off the traffic and, at least temporarily, focus on other things.

Comparably to the situation in Germany, it is younger transport users (see Figure 4.2.3), as well as the mobility-impaired, who have started to make widespread use of AVs. The technology compensates for a sometimes poorly developed (and in case of para-transit options for the mobility-impaired, often expensive) public transport infrastructure, especially in rural and suburban areas.

Mobility

The effects of such a large fleet of AVs on vehicle-kilometres travelled in the USA are similar to those seen in Germany: vehicle-kilometres travelled increased by about 9%, mainly because of a reduction in public transport trips of about 16% (especially trips at the shorter and longer ends of the spectrum) and the generally increasing number of persons having access to a car (see Figures 4.2.2, 4.2.4, 4.2.5). Hoped-for gains in traffic efficiency could not be realised owing to the growing share of car trips.

CHINA

Regulation and market development

As a consequence of increasing car use and ownership, China is facing gridlocks in many of its urban agglomerations. What started in the early 2000s, when the Chinese middle class began to rely increasingly on the car to be on the move, has continued throughout the succeeding years and has caused many traffic-related problems, to the extent that the situation is now even worse than that in Western countries. One of the problems has been the dramatic rise of traffic accidents, which induced the government to authorise AVs early in the 2020s, on the assumption that they were a safer means of transport. Furthermore, the Chinese government pushed the adoption of AVs with financial programmes, making it more attractive to buy such vehicles than conventional vehicles.

Against this background, the Chinese tech-industry has adopted many foreign technologies very rapidly, and has started to offer their own solutions. Thus, smaller, and cheaper autonomous cars have become available on the market early on.
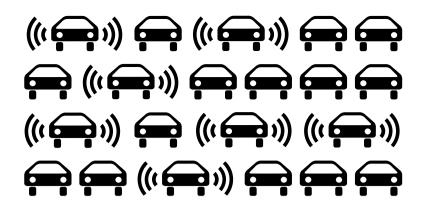
Use and user groups

Particularly in the large and crowded urban agglomerations with their restricted and small living spaces, the car has become the so-called 'third space' in many residents' lives, alongside the home and work locations. For many urban dwellers, this small cocoon is one of the only places that they can have all to themselves without having to share it with anyone else – in contrast to their working and living spaces. AVs have been perceived as of great benefit, even enhancing this private and solitary 'quality time', since users are able to carry out a multitude of activities without having to concentrate on the outside environment.

Mobility

The availability of small and inexpensive AVs led to a rapid uptake, especially in the metropolitan areas. Citizens enjoyed the freedom that the new kind of car gave them in heavy traffic during the rush hour. In combination with the constantly growing car fleet, traffic volumes increased further, and therefore the efficiency gains seemingly promised by autonomous technologies could not unleash their potential. A small consolation was that the smaller size of the vehicles at least compensated somewhat for the increase in overall traffic volumes.
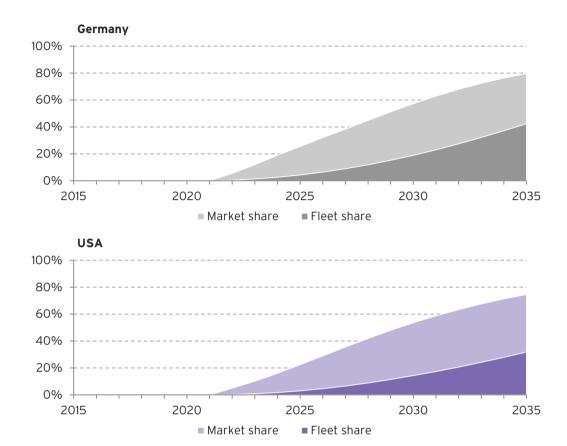
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Technology Breakthrough

RIDERS
LICENCE

Germany

USA

Figure 4.2.1: Penetration rate of vehicles with Level 4 & 5 automation systems under scenario "Technology breakthrough"
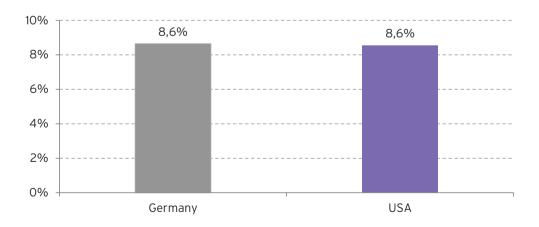

Figure 4.2.2: Impact of the introduction of autonomous driving on vehicle-kilometres travelled (VKT) under scenario "Technology breakthrough" compared to the base case scenario
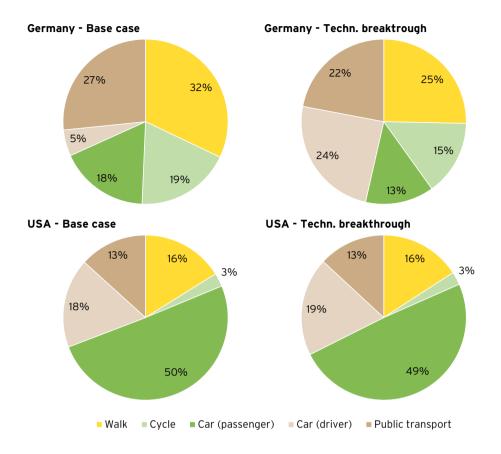
Germany - Base case
Germany - Techn. breaktrough
USA - Base case
USA - Techn. breakthrough

■ Walk ■ Cycle ■ Car (passenger) ■ Car (driver) ■ Public transport

Figure 4.2.3: Comparison of modal shares of teenagers (10-17 years): Base case (AV fleetshare = 0%) vs. scenario "Technology breakthrough"

Germany
USA

■ Car availability (AV)   ■ Car availability (AV)
■ Car availabilty (conventional)   ■ Car availabilty (conventional)
■ No car availability   ■ No car availability
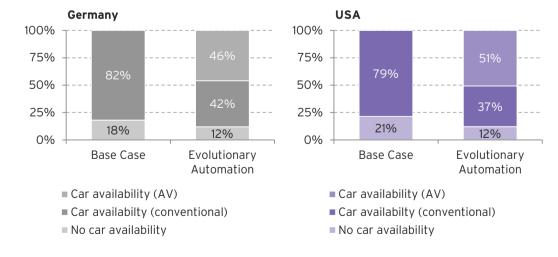
Figure 4.2.4: Sizes of user groups differentiated by car availability classification under scenario "Technology breakthrough"
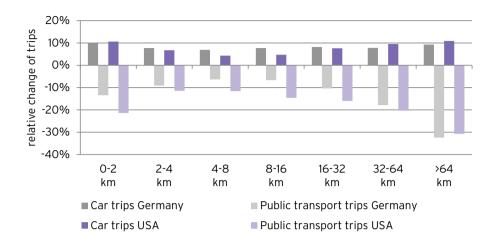
Figure 4.2.5: Relative change of public transport and car trip numbers for different distance bands under scenario "Technology breakthrough" compared to the base case scenario

4.3 "Rethinking (auto)mobility"

Autonomous vehicles on demand

In this scenario, it is assumed that autonomous systems will not only be a technology used for privately owned automobiles, but that it will also become part of public transport systems and/or passenger transport systems. The operation of AVs that do not require any human inside the vehicle[13] could have a significant impact on mobility as "they would be able to autonomously reposition themselves to more efficiently and effectively meet a wider array of customers and their needs, they could refuel or charge themselves, and they could travel for cleaning and maintenance" (Shaheen & Galczynski, 2014). Specifically, these systems could redefine relatively 'new' mobility concepts such as car-sharing, and also older ones like public transport, in the sense that they become more flexible and highly individualised, eventually even transforming the systems of individual and public transport in a fundamental way.

Up until today, little is known about the potential, benefits, costs, profitability, impacts, and challenges of autonomous vehicle-on-demand (AVoD) systems. In this scenario, car manufacturers will compete with new mobility service providers (such as Uber, Lyft or Didi), and will themselves become mobility providers investing in new business models. AVoD will become an emerging market.

Against this background, the goal of the following investigations is to model the effects of autonomous car-sharing (ACS)[14] or autonomous pooling (AP) systems on the mobility market in two different sub-scenarios. "Rethinking (auto)mobility" focuses on the German case only, and is otherwise based largely on the assumptions of the "Technology breakthrough" scenario, the results being compared to that scenario as if it were the base case. The following paragraphs now present how the new travel alternatives, ACS or AP, are introduced into the transport model, and what effects different possible price and service levels of the ACS or AP system will have on – amongst other indicators – operator profit, modal split, and vehicle-kilometres travelled.

Regulation and market development

The legality of empty rides by ACS or AP vehicles – so-called 'ghost trips' – has fundamentally improved the concept of mobility-on-demand. A handful of actors operate their fleets almost all over the country – in a variety of environments, not merely in densely populated urban areas – with differentiation by fleet density and user prices in different areas. Most people have access to vehicles from these operators, and use digital devices for on-demand bookings.

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[13] In the previous chapters, in contrast, we considered only Level 4 & 5 vehicles (as defined by SAE standards) that always require a human inside the vehicle, at least on public roads.

[14] Autonomous car-sharing (ACS) allows at most one party in the same car at all times (one party means one person on their own or a self-organised group). Autonomous pooling (AP) allows more than one party in the same car at the same time, but passengers have to expect detours picking up and dropping off others. Both ACS and AP are defined as Autonomous Vehicle-on-demand (AVoD) systems.

The high density of ACS or AP vehicles, in urban areas in particular, means that the access time amounts to a matter of minutes. In rural areas longer access times are observed from time to time. Because of the high utilisation rates of ACS vehicles – the vehicles are on the move for up to 50% of the day – combined with the ability of the vehicles to reposition themselves, relatively low user prices[15] of €0.30–€0.35/km[16] can be realised. Owing to ride- and cost-sharing in densely populated urban areas, prices for AP rides are even cheaper, around €0.10/km. AP systems therefore hit similar price ranges as public mass transport systems. In rural areas it is more challenging to operate AP systems; this is due to lower population densities and thus reduced opportunities for finding sufficient demand to fill a pooling vehicle. Moreover, the higher percentage of ghost trips needed to pick up different passengers increases the operator cost in these areas. Hence, AP is less attractive for passengers in the countryside than an ACS system.

Use and user groups

The ACS system is widely used across the population, but usage by non-motorised individuals and those living in households with few cars is higher, since ACS vehicles are available for all trips without the necessity of intra-household arrangements. On the one hand, the easy access and short waiting times associated with the ACS system increase the demand for this travel mode. But on the other hand, user prices per kilometre are still almost three times as high as for conventional public transport – ACS therefore tends to be used for short trips. AP, since its prices are in the range of public mass transit systems, tends to be a substitute mode for longer trips.

Mobility

The introduction of ACS or AP systems, with the above-mentioned end-user prices and service levels, yields changes in the modal shares between the different modes.

Figure 4.3.1 shows that the ACS system reaches an overall market share of 10% of all trips in Germany – slightly less in rural and suburban areas, slightly more in urban areas. Furthermore, it can be observed that the ACS system attracts trips from all other modes in comparison to the scenario "Technology breakthrough" (which is being used as a base against which to compare): in total numbers, the most trips are coming from car, followed by walking, cycling and public transport. Figure 4.3.1 exhibits that – relative to the initial number of trips in each mode – the reduction in trips is most pronounced in public transport, followed by cycling, walking and car. That is, in terms of the proportion by which it reduces patronage of any given mode, the ACS system competes mostly with public transport and environmentally friendly modes.

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[15] Assuming that AVoD operators set prices that are close to their break-even points.

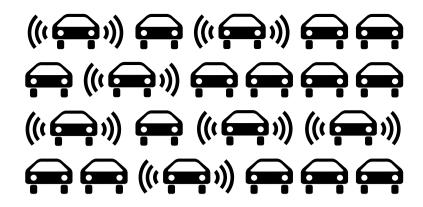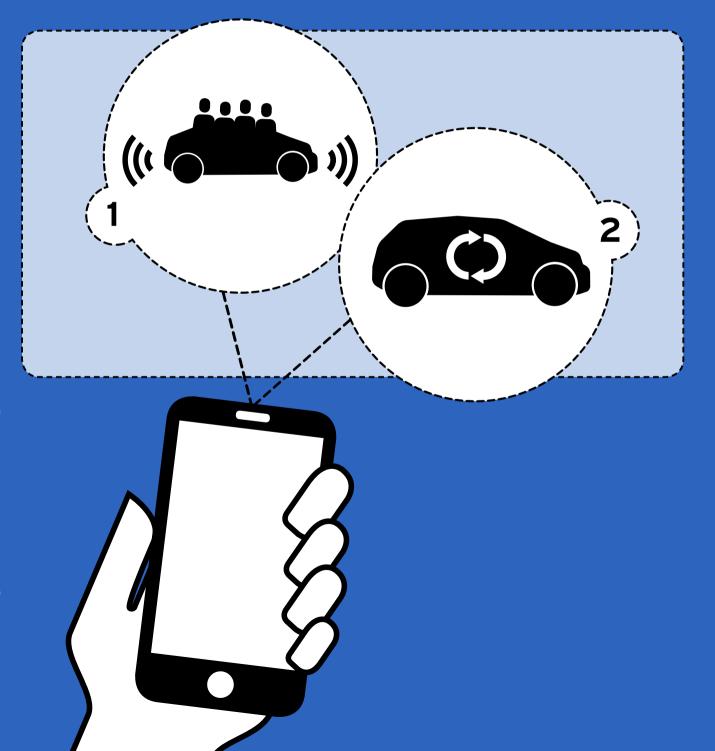[16] 2016 prices.

Figure 4.3.2 shows that the AP system reaches an overall market share of 8% of all trips in Germany, but with much more spatial heterogeneity than in the case of the ACS system. Owing to the greater likelihood of sharing rides with other passengers, and the lower user prices, the market share of the new system is substantially higher in urban areas than in rural and suburban areas. Figure 4.3.2 reveals that the AP system also attracts trips from all other modes, when this scenario is compared with "Technology breakthrough", but shows that the decrease in use of public transport is even more pronounced – and the decrease in cycling, walking and car less pronounced – than in the case of the ACS system.

When looking at changes in transport performance resulting from the introduction of the ACS service, Figure 4.3.3 shows that the total vehicle-kilometres travelled on the road increases by roughly 4% compared to the scenario "Technology breakthrough". This effect is more pronounced in urban areas, i.e. in regions where congestion levels are already high. Decomposing this overall effect shows that the vehicle-kilometres travelled by private cars are reduced, which is, however, overcompensated by the increase in ACS-kilometres travelled. The results also show that empty ACS-kilometres are more-than-proportionally high in rural areas, where ACS vehicles often need to relocate without a passenger in the car.

The introduction of the AP system increases vehicle-kilometres travelled on the road by only about 1% compared to the scenario "Technology breakthrough" (see Figure 4.3.4). This effect results from the performance of the transport system in rural and suburban areas on the one hand, and a decrease in urban areas on the other. The latter effect, resulting from a high level of trip-bundling opportunities, and fewer vehicle-kilometres travelled by private cars, almost compensates for the increase in demand in rural and suburban areas.

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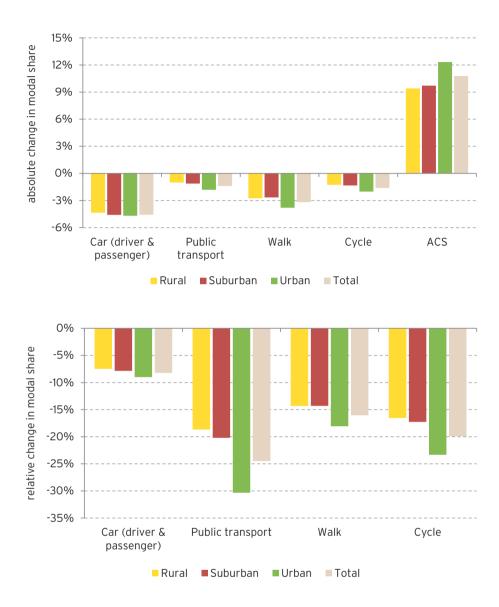
2

Rethinking (Auto)mobility

Figure 4.3.1: Absolute and relative change in modal share per day resulting from the introduction of an ACS system with user prices in the range €0.30-€0.35/km and a vehicle fleet of 3.0 to 4.5 ACS vehicles per 1,000 inhabitants (dependent on type of area) compared to scenario "Technology breakthrough"
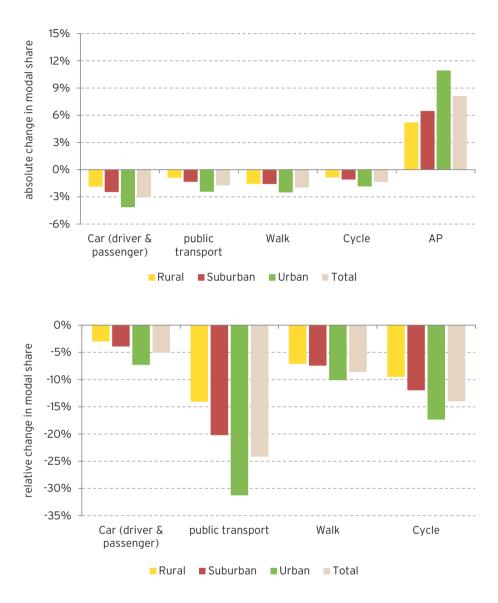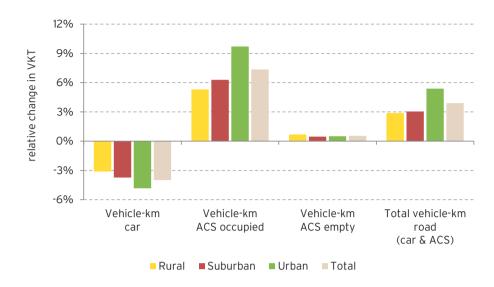
Figure 4.3.2: Absolute and relative change in modal share per day resulting from the introduction of an AP system with user prices in the range €0.11 - €0.38/km and a vehicle fleet of 2.5 to 4.0 ACS vehicles per 1,000 inhabitants (dependent on type of area)

Figure 4.3.3. Change in vehicle-kilometres travelled (VKT) per day resulting from the introduction of an ACS system in Germany by type of area (relative to total VKT without the ACS system) compared to scenario "Technology breakthrough"
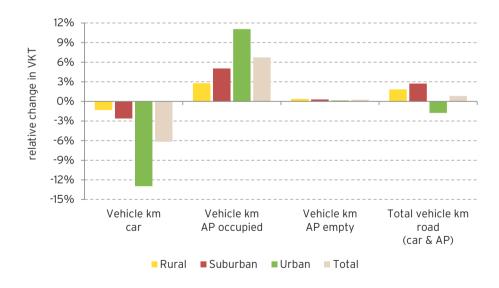
Figure 4.3.4. Change in vehicle-kilometres travelled (VKT) per day resulting from the introduction of an AP system in Germany by type of area (relative to total VKT without the AP system) compared to scenario „Technology breakthrough"

This study has investigated possible changes in travel behaviour and mode choice that are expected to occur when autonomous vehicles become available as private vehicles, and/or as part of a car-sharing fleet. For this purpose, it looks at Germany, the USA and China. Since the introduction of autonomous vehicles into the transport system is expected to have a wide range of impacts on the mobility behaviour of the population, we have developed three different scenarios and used a transport model to quantify these impacts.[17] The key findings are the following:

By 2035, we expect to see about 17% AVs in the private car fleet in Germany, and 11% in the US. Depending on the assumptions that underlie these figures, these shares could be higher, but 42% and 32% (in Germany and the US respectively) are the realistic upper limits for the proportion of AVs in the fleets by 2035.

The rate at which AVs will enter into the market, and the speed with which they will then diffuse throughout it, are both still subject to high levels of uncertainty, and are particularly dependent on overcoming technological, regulatory and legal issues, with societal acceptance of automation technology also playing an important part. Analysing the legal and regulatory framework in different countries, we found that regulatory bodies are currently addressing the topic of autonomous driving, and are working on adjusting the legal framework to pave the way for this innovation.

By 2035, we expect to see a moderate increase in vehicle-kilometres travelled by private cars – about 3% – as a result of the introduction of AVs. Assuming the maximum share of AVs in the private car fleet that is realistic, the upper bound of this increase is estimated at 9%.

While we found a small increase in vehicle-kilometres travelled owing to a decrease in the (perceived) cost of travel, the main driver behind the overall increase in distance travelled consists of new groups of users who have not had access to a car before. This includes, but is not limited to, disabled individuals, elderly people and teenagers – and even children. Furthermore, people who had formerly been regular car passengers now more often 'drive' themselves. As a result of the effects above, the increase in vehicle-kilometres travelled is expected to be 3–9% (depending on scenario and country) compared to a case without any automatisation in the private car fleet.

[17] As a consequence of inadequate availability of data, the modelling of impact was not possible for China. The quantification of ACS and AP effects has been carried out only for Germany.

This resulting increase comes at the cost of a reduction in public transport usage, particularly in very short- and very long-distance trips.

Between now and 2035, autonomous car fleets have great potential for increasing the market share of mobility-on-demand systems, taking them up to perhaps 8–10% of all trips in Germany.

Autonomous car-sharing (ACS) and autonomous pooling (AP) each have a great potential for bringing car-sharing systems from a niche to a mainstream market. This is especially true in urban environments, where they can operate very efficiently. Our analysis reveals that under the defined input assumptions, ACS could be profitably operated at €0.30–€0.35/km. It is even possible that AP systems could be cheaper still in urban areas, reaching price ranges of around €0.10/km, i.e. similar to public mass transport systems. In particular, AP could in this way act as an attractive public transport service to supplement existing ones. It is estimated that total ACS trips might reach a modal share of approximately 10% of all trips in Germany by 2035. Looking at the AP option, the potential market share of trips in Germany is estimated at around 8%, but AP's benefit over ACS systems vanishes in rural areas. Both ACS and AP are expected to attract trips from all other transport modes.

Appendix A: Methodology

Several models were developed to quantify different impacts of the introduction of autonomous vehicles (AVs). The first one – a vehicle technology diffusion model – addresses the calculation of diffusion rates of AVs into the private car fleet. The second one is a travel demand model to analyse mode-and-distance-choice decisions. In the following, all models are presented in more detail. The results from the diffusion model are used as input for the travel demand model. The travel demand model is described in two parts, starting with a general description of the model, followed by a presentation of the adjustments for modelling AVs, autonomous car-sharing (ACS) systems, and a potential dispensing with private cars. Figure A.1. gives an overview of the model parameters used in the different scenarious.

	Base case Scenario 2035	"Evolutionary automation" "Technology breakthrough" 2035	"Rethinking (auto)mobility" 2035
Demographic Change and Urbanisation	✳	✳	✳
Cohort effect of driver´s licence holding rate	✳	✳	✳
Diffusion of AV (level 4/5)		✳ (differentiated)	✳ (adjusted)
Mobilisation (mobility-impaired persons, teenagers)		✳ (differentiated)	✳
Reduction of access and egress times when using AV		✳	✳
Reduction of value-of-travel-time -25% when using AV		✳	✳ (adjusted)
Availability of an autonomous-car-sharing (ACS) system			✳

Figure A.1: Overview of model parameters

The following descriptions of the models are mostly taken from Kröger et al. (2016).

A.1 Vehicle technology diffusion model

The diffusion of AV technologies is modelled by an S-shaped market take-up. It is differentiated for car segments, with consideration given to the national car market. Four segments are distinguished for each country. In Germany the segmentation results in the classifications: small vehicles, compact class, medium-sized vehicles and large vehicles. In the USA, small vehicles, pick-up class, medium-sized vehicles and large vehicles are differentiated. The pick-up class is handled separately because of its large share despite the diversity of vehicles in the pick-up class. The German segmentation is an adapted version of the KBA classification (KBA, 2016). The US classification is an adapted version of the vehicle-type definition used in the NHTS (USDOT, 2011: A–8).

Differences in the diffusion rates of different car segments arise from differing years of introduction, initial diffusion rates, and parameters for the increase of the curve. The number of newly registered AVs P_t in year t is calculated as follows:

$$P_t = P_\infty * a^{b^t} \qquad \textbf{1}$$

with

P_∞ : maximal number of newly registered AVs (with the assumption of a maximum 95% rate of AVs);
a : quotient of the initial rate of newly registered AVs in the year of introduction;
b : factor of growth;
t : number of years since introduction.

The differences between the transport modes are set by considering historical developments of vehicle technologies, for example for driving assistance. The forecast of years of introduction follows published road maps, e.g. those of suppliers of automation technologies from the European Road Transport Research Advisory Council (ERTRAC, 2015).

The vehicle technology diffusion model distinguishes between Level 4 and Level 5 automation technologies. Level five can be seen as referring to fully autonomous vehicles (SAE, 2014). There is no overlapping of Level 4 and Level 5 diffusion. An integrated curve with a change from Level 4 to Level 5 diffusion is used for simplification. The diffusion of automation technologies follows a top-down approach. Automation technologies will be introduced first in the luxury segment and later in the smaller vehicle segments. The delay, as well as the initial diffusion rate and market growth within the different segments, is adapted from the observed market take-up of automated cruise control (ACC) systems. Since there is no publicly available data, Internet automotive classifieds such as cars.com (for the USA car market) and mobile.de (for the German market) have been analysed for the share of vehicles equipped with ACC systems for each vehicle segment and model year within the last fifteen years. It was observed that the share of vehicles equipped with ACC systems in the USA is significantly lower than in Germany mainly because of the lower share of luxury-segment vehicles, and longer vehicle lifetimes resulting in a slower diffusion of such systems.

A.2 Aspatial travel demand model

The travel demand model used for simulations is a highly aggregated macroscopic one. Transport models can be differentiated by the level of detail in their representation of transport demand and traffic flow (Abdulhai et al., 2011). Interactions between vehicles or flows by capacity restraint functions or queuing models are not considered in the aspatial model. Following the classification of Tarko & Anastasopoulos (2011), the model is a transport demand model for demand generation, based on a sequential four-step process:

> (1) trip generation;
> (2) trip distribution;
> (3) modal split; and
> (4) trip assignment.

The aspatial travel demand model consists only of the first three steps. With respect to trip distribution, a distance choice model is used, combined with a mode choice model. There is no final traffic assignment.

Input data

Sociodemographic forecasts, travel survey data and travel cost data are the main exogenous data inputs for the travel demand model. Sociodemographic forecasts for the scenario year 2035 are used with population data differentiated by age, gender and spatial area. The national population projections for Germany (Statistisches Bundesamt, 2009) and for the USA (U.S. Census Bureau, 2014b) for the coming decades are used. Moreover, forecasts of driving-licence-holding rates by age cohorts are assumed. In Germany, and particularly in the USA, the rates – reported in the national household travel survey data set – are saturated and the future development is foreseeable.

National household travel surveys are used for trip generation and for calibration of the distance choice and mode choice in the travel demand model. National household travel surveys are conducted in many countries in a comparative but partly dissimilar way to get an idea of how and why people travel (Kunert, Kloas & Kuhfeld, 2002). To compare impacts in Germany and the USA, data sets of the MiD 2008 (BMVBS, 2008) for Germany and the NHTS 2009 (USDOT, 2011) for the USA are used. These surveys are comparable to a great extent. Both surveys consist of various data sets, namely a household data set, a person data set, a trip data set and a vehicle data set. Weights are given for each data point.

Owing to the different minimum age limits in MiD and NHTS (zero years in MiD 2008; five years in NHTS 2009) and because the minimum age for using an AV in the scenarios is at least ten years, only the data from persons of ten years and older is used. For the USA data, the reported proxy variable 'being a driver' is used instead of holding a driving licence because of a lack of information. Main users of vehicles are reported in the vehicle data set and determined heuristically if missing. If respective main users are not completely known, main users are identified on the basis of actual behaviour of the household members.

Some missing values in the data set make a data cleaning exercise necessary. This concerns persons without a stated age value. The final step of data preparation is the calibration of the data set weights to meet benchmark values. We assume that an additional weight for correctly assigned person and trip data is better than the consideration of randomly aged persons. In other cases of missing data that are more substantial, strategies of data imputation are used (e.g. for non-reported vehicle-kilometres).

Besides assumptions of out-of-pocket costs such as fuel costs and fares, the use of generalised costs for mode-and-distance-choice modelling requires a monetised value-of-travel-time-savings (VTTS).[18] Beside the comparability of the travel survey data, the comparability of the VTTSs is necessary. Due to country-specific particularities, these values differ. For Germany the time-valuation study of Axhausen et al. (2014) is used, which describes a logarithmic curve of VTTSs over distance. The USDOT Departmental Guidance on Valuation of Travel Time (USDOT, 2014) is used for US values, with an adjustment to a logarithmic curve.

Modelling approach

The aspatial travel demand model consists of a trip generation submodel and a combined mode and distance choice submodel. Besides the reweighting for trip generation, the assumptions of the distribution of activity locations in space, and the idea of generalised costs (see Figure A.2.1) as input for the logit mode choice model, are the central elements of the developed aspatial travel demand model.
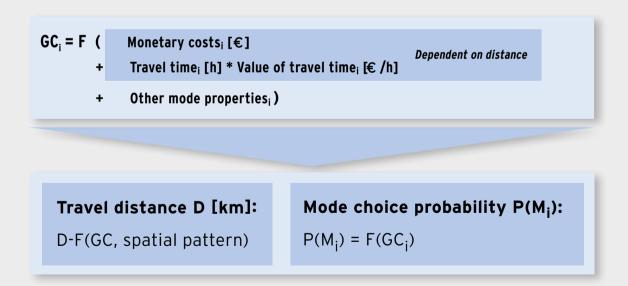
$GC_i = F ($ Monetary costs$_i$ [€]
+ Travel time$_i$ [h] * Value of travel time$_i$ [€ /h]   *Dependent on distance*
+ Other mode properties$_i$)

Travel distance D [km]:
D-F(GC, spatial pattern)

Mode choice probability P(M$_i$):
$P(M_i) = F(GC_i)$

Figure A.2.1: The concept of generalised costs

[18] Note that in this report „value of time" or „value of travel time" are both used as a synonym for „value-of-travel-time-savings (VTTS)

The model distinguishes two trip purposes, namely education and work trips on the one hand (mandatory trips), and all other trips on the other hand (non-mandatory trips). Trip purpose differentiation is important for the VTTS and the heterogeneity of trip length distribution.

The reweighting of the person and trip data aims at fulfilling the benchmark values by groups of persons (differentiated by age, gender, spatial area and driving licence holding). Reweighting in this context means that the weights of reported trips made by a growing group of persons, with respect to share of total population (e.g. older people), increase, and the weights of those made by other groups of persons decrease. Clustering the trips by trip purpose and car availability category leads to a trip table of the summarised trip weights. The total sum of the person weights is the total number of persons in the person data. The total number of trips is the total number of trips per day based on the travel survey. The day has to be seen as an average day, as all trip data from the survey is considered. A differentiation of weekday and weekend travel would imply the need for an adjusted reweighting after splitting the data set, but has not been implemented here.

Reweighting with regard to forecasting of driving licence-holding rate follows the shares of groups differentiated by gender and five-year groups. Current shares are forecasted into the future by adding the age difference. The most important shift results from the increasing prevalence of driving licence among older women in Germany. Driving licence information is essential to classify car availability, as we assume availability if the person holds a driving licence and the affiliated household owns at least one vehicle.

Generalised costs involve variable monetary costs of a trip such as fuel costs, fares and monetised travel-time costs. Constant fuel costs per kilometre, based on average consumption per 100 kilometres and a price per litre, and almost constant public transport ticket costs per kilometre are set: only fares for very short public transport trips are higher, using an asymptotic function. The generalised costs as the explanatory variable are difficult to handle for mode choice decisions of a car passenger. The fuel price elasticity is positive for the car passenger mode in contrast to the car driver mode (Litman, 2004). In the model, the share of car passengers is fixed for all distance bands for each of the trip-purpose/car-availability categories. Therefore a smoothed function is used, because the share for many distance bands would be zero or one owing to the discontinuity of values.

Owing to the lack of reported travel mode alternatives and related data, in particular travel time, mode choice is calibrated by an assumed choice set of alternatives consisting of the attributes of the reported alternative, and generated attributes of the other alternatives. Travel modes are walk, cycle, car driver and public transport; the car passenger mode is handled with fixed shares per distance band per trip-purpose/car-availability category, as described above. Travel times consist of a fixed access/egress time plus a calculated in-vehicle time resulting from speed functions. The reported value for the chosen alternative already comprises the total travel time; this is true for MiD and NHTS data. Speed functions for the different travel modes are developed for both countries to calculate travel times for the generated mode alternatives. These speed curves are logarithmic over distance, but not differentiated by trip purposes. The speed curves are derived from used travel survey data sets. The missing differentiation between access/egress times and vehicle-use times (in-vehicle travel times) in the MiD and NHTS complicates the estimation of the speed curves. A differentiation of travel speeds considering the travel distance for generated mode alternatives improves the mode choice model (Agarwal & Kickhöfer, 2015) and is therefore regarded as necessary for analysing the data.

The total travel times $tt_{total,i}$ of the alternatives i are calculated by:

$$
tt_{total,i} \begin{cases} tt_{reported,i} & \text{, if } i \text{ is the repoerted mode alternative} \\ tt_{(access/egress, i)} + \dfrac{d}{v(d,i)} & \text{, if } i \text{ is not the reported mode alternative} \end{cases}
$$

2

with

$tt_{(access/egress, i)}$: mode-specific constant access/egress time values;
$tt_{reported,i}$: reported travel time in the travel survey for the chosen mode alternative;
d : travel distance which is constant for all travel modes;
$v(d,i)$: distance- and mode-dependent travel speed.

The mode-specific constant access/egress time value is determined by an incremental regression analysis of the total travel times. The access/egress time values used in the model are set for Germany and the USA in Table A.1.1.

Table A.2.1: Overview of access/egress times of different modes used in the model for Germany and the USA

	Germany	USA
$tt_{access/egress, walk}$ [min]	5	
$tt_{access/egress, bike}$ [min]	5	
$tt_{access/egress, driver}$ [min]	5	4
$tt_{access/egress, publik\ transport}$ [min]	15	

One problem in estimating general speed functions for different travel modes based on reported mode choice alternatives is the lack of non-reported mode alternatives. Considering the minimum public transport modal share in the USA, and the qualitative differences in public transport supply between big cities and the countryside, the 40th percentile has been taken as average speed. Different maximum distances between the German and the US model result from the distributions of the lengths of intranational trips (those starting and ending within the same country) modelled here. The maximum value in the German model is set to 512 km, and the maximum value in the US model is set to 1,024 km.

A multinomial logit-based mode choice is used. The probability, P_i , of choosing a mode alternative i from a set of alternatives J = {walk; cycle; car (driver); public transport} is calculated by:

$$P_i = \frac{e^{U_i}}{\sum_{j=1,...4} e^{U_j}}$$

3

with

U_i : utility of a mode alternative i .

The utility U_i is calculated as:

$$U_i = \beta_i + \beta_{gc} * gc_i$$

4

with

β_i : mode-specific constant;

gc_i : mode-specific generalised costs.

Table A.2.2 gives an overview of the mode-specific constants. The mode-specific generalised costs are a sum of travel costs as out-of-pocket costs for car and public transport trips only, and the monetised travel time which depends on access/egress times, distances, speeds and the VTTS.

Table A.2.2: Model parameters of the mode choice model

GERMANY

	Trip purpose work/education		Other trip purposes	
	No car availability	Car availability	No car availability	Car availability
Mode specific constants				
β_{walk} (reference mode)	0	0	0	0
β_{bike}	-1.117	-0.894	-1.263	-1.686
$\beta_{car\,(driver)}$	-4.469	+0.246	-3.318	-0.155
β_{PT}	+0.423	-0.319	-1.327	-2.470
β_{gc}	-0.705	-0.589	-0.284	-0.346

USA

	Trip purpose work/education		Other trip purposes	
	No car availability	Car availability	No car availability	Car availability
Mode specific constants				
β_{walk} (reference mode)	0	0	0	0
β_{bike}	-3.280	-3.143	-2.436	-3.755
$\beta_{car\,(driver)}$	-5.926	+0.835	-3.593	+0.222
β_{PT}	-0.424	-2.232	-1.757	-4.053
β_{gc}	-0.587	-0.386	-0.339	-0.522

The model step of trip distribution is replaced by a distance choice approach concerning different heterogeneities of activity locations for different trip purposes. Distance bands of one kilometre are distinguished. Analysing travel survey data, the trip length distribution of different trip purposes differ, and this also results in different average trip lengths. Among others, influencing factors for this include the density of activity locations and the heterogeneity of activity locations for different trip purposes. To give an example, for shopping a supermarket at a certain distance probably does not differ significantly from others that are closer, but a workplace may be

much more specialised than the others which are at a closer distance. Choosing trip length and travel mode for a trip depends on costs and benefits. To estimate a distance-based benefit, parameters for activity location density and heterogeneity are chosen for each trip-purpose/car-availability category to calculate a benefit value for each distance band. Combined with generalised travel costs (weighted by modal shares), a distance band probability can be calculated. Mode choice for each distance band is independent from the benefit.

The output from the combined mode and distance choice model is a table with probabilities of choosing a travel mode and a distance band for a trip classified by trip purpose and car availability. Multiplying the probabilities by the appropriate trip sum from the trip table leads to modal shares over all trips. Multiplying the numbers by distances leads to vehicle- and person-kilometres for car mode and the alternatives.

The total modal share P_i for travel mode i for all trips is:

$$P_i = \sum_{tpccat} \left(n_{tpccat} * \sum P_{dist,i,tpccat} \right) \qquad 5$$

with

$tpccat$: trip-purpose/car-availability-category;

n_{tpccat} : total number of trips from trip table for each $tpccat$;

$P_{dist,i,tpccat}$: probability of choosing travel mode i and a distance band $dist$ dependent on $tpccat$.

The total trip lengths L_i for travel mode i over all trips is thus:

$$L_i = \sum_{tpccat} \left(n_{tpccat} * \sum P_{dist,i,tpccat} * dist) \right) \qquad 6$$

The resulting table from the combined mode-and-distance-choice model characterise different travel behaviours of persons in different car availability categories. An expected value of kilometres per person per mode can be calculated in the way that the total trip length is calculated.

A.3 Adjustments of the travel demand model for modelling AVs

As a first step, the technology diffusion model and the travel demand model are used jointly to estimate the impact of introducing AVs into the private car fleet: the output of the vehicle technology diffusion model is used for reweighting the data sets and setting up different scenarios in the travel demand model. Figure A.3.1 gives an overview of the combined model scheme. As a second step, the aspatial travel demand model is adjusted in order to model the impacts of the introduction of autonomous vehicle-on-demand (AVoD) systems.

A.3.1 Autonomous private vehicles

The vehicle technology diffusion model and the aspatial travel demand model are linked by allocating AVs in the travel demand model according to the extent calculated in the vehicle technology diffusion model.
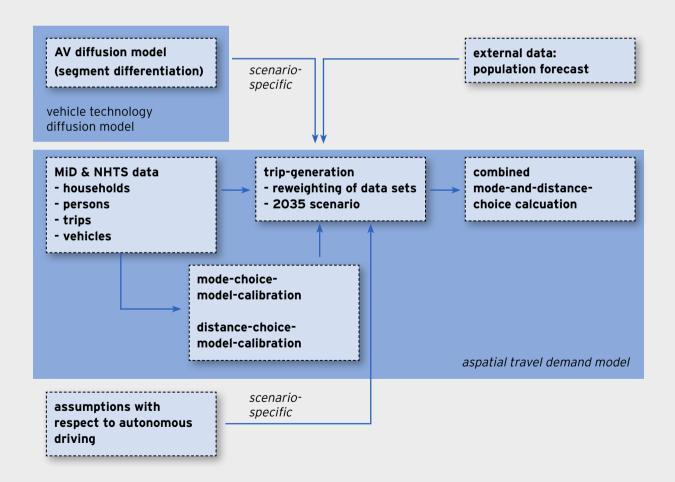
Figure A.3.1: Model scheme of the combined model approach for AV application

AVs are assigned to households ranked by kilometres covered annually. The vehicles are ranked in twelve groups of vehicle segment and vehicle age differentiation. Vehicle age groups are 0–4 years, 5–8 years and >8 years. The shares result from the vehicle technology diffusion model. The car segment groups are those from the diffusion model, and differ between Germany and the USA. A similar vehicle age distribution of vehicles compared to present age values in the vehicle data set is assumed. Therefore the vehicle age in the vehicle data set in the base year is the determining age for classification. Reweighting factors result from person and household reweighting.

In the aspatial travel demand model, different assumptions for modelling autonomous cars are made. One of these assumptions is the activation of new user groups, in particular the mobility-impaired people and teenagers. The rate of car availability of mobility-impaired people is raised to the level of non-impaired people by reweighting person and trip data weights. The higher mobility impairment rate of older people reinforces the stronger need to mobilize them. This results in a higher probability for older people to obtain an AV in order to match the level of car availability of non-impaired people. For older people, no additional mobilisation is assumed. The cohort effects of additional mobilisation resulting from a higher driving-licence-holding rate, especially for women, exist for the base case and for both AV scenarios. Another assumption relates to the main driver: while that user of an autonomous car within a household can use it for all of his/her trips, usage by any other household member is limited to non-mandatory trips only. The macroscopic model presented here does not facilitate the use of car diaries – this would be necessary to consider real trip-based car availability. To avoid an overuse of the AVs, and owing to the lack of intra-household empty rides, this constraint is set. Furthermore, the VTTS is reduced in both scenarios by 25% from the eleventh minute of driving onwards, assuming a make-ready time. The relative reduction applies to all car trips made by persons with availability of an AV for that trip. As car diaries are not available for the macroscopic simulation, actual, real-time car availability is unknown. The estimated parameters are based on this assumption. There is a differentiation between the main user of a vehicle and other household members: main users can access the AVs at any time, whereas any other household member can use them for non-work and non-education trips only. By this mechanism, all identified main users have AV availability for all trips. With respect to access/egress times to AVs, a reduction is assumed. In Germany the access/egress time is reduced from five to three minutes, and in the USA from four to three minutes. In Germany the initial value is higher because of infrastructure conditions, e.g. reduced parking areas. Adjustments of both access/egress times and VTTS are considered by adapting the mode choice data. The diffusion model differentiates between Level 4 and Level 5 automation. To model the impacts on travel demand, only Level 5 vehicles with fully autonomous driving technology are considered, by using only the Level 5 diffusion rates.

A.3.2 Autonomous car-sharing (ACS) and autonomous pooling (AP)

In order to calculate the impact of an ACS or AP system on travel demand, the mode choice and distance choice models are enhanced. It is hereby assumed that all private vehicles have reached some level of automation, represented by an average VTTS reduction of 20% for private car travel. The VTTS for the ACS or AP system (operated by Level 5 vehicles only) is reduced by 25% compared to the initial value to reflect the fact that people can perform all sorts of other activities while travelling. Offering the ACS or AP travel alternative to the individuals in the simulation additionally requires an approximation of travel times, waiting times and monetary costs, as well as a definition of how people perceive – other things being equal – the new travel mode in comparison to alternative modes (modelled by the mode-specific constant). Travel times and distances of ACS are set equal

to those of private cars. Travel times and distances of AP additionally include a detour factor to take into account the sharing of trips between different parties. Monetary costs are systematically varied by simulating different user prices per kilometre. Waiting times depend on the quality of supply, which is also varied systematically by introducing different fleet sizes for the ACS or AP system. The operator costs of the ACS or AP system consist of fixed costs for maintenance, insurance and tax, and of variable costs per vehicle-kilometre for depreciation and energy costs.

The simulation is performed for three types of areas in Germany, namely rural, suburban and urban areas. These are differentiated by population size and density. Results are calculated for 20 x 9 reasonable user price/fleet size combinations, which we call the 'grid-search approach'. This allows for a comprehensive analysis of all potential business cases.

Modelling the ACS and AP operation

Before a new transport mode can be introduced, there are several questions that need to be answered. Potential operators might ask under which conditions the service turns out to be profitable. Public authorities might wonder what impacts the new mode will have on the usage of the other transport modes (in terms of shift in modal split and vehicle-kilometres travelled), how to avoid the emergence of a monopolistic provider, and whether to subsidise the new service in certain areas in order to provide a cost-efficient travel alternative to the private car or expensive conventional public transport. In the first instance, it is therefore important to identify the user prices and the numbers of necessary vehicles (the fleet size) where (i) travellers use the system and (ii) the operator can run the business profitably.

Figure A.3.2 and Figure A.3.3 show the operator profit as a function of user price (in €/km) and fleet size (in vehicles per 1,000 residents) for the ACS and the AP system respectively. The lower the user price, the higher the demand for the AVoD mode, but the lower also the operator revenue per kilometre. The more vehicles are offered in the system, the higher will be the demand, but the higher the operator costs for maintaining the system.

The figures show that there is a positive ACS business case even for rural areas for user prices above €0.30/km and levels of provision between one and eight ACS vehicles per 1,000 inhabitants (the profitable area is represented by green shading). In suburban and urban areas, this profit area is larger, presumably because of higher demand and better utilisation of capacities. Additionally, the absolute level of profit is higher in these more densely populated areas. There is a positive AP business case for all areas as well, in urban areas indicating even very low prices, down to roughly €0.10/km. The profit area covers slightly lower levels of provision for rural and suburban areas. An AP fleet density of eight vehicles per 1,000 inhabitants in the profit area is reached in urban areas only at a very low price level.

In order to limit the analysis to operationally feasible supply settings for ACS or AP, the combinations of user price and fleet size which lead to a capacity utilisation of above 0.5 (the car is on the move for more than 12 hours per day) are depicted in white in Figure A.3.2 and Figure A.3.3. It is assumed that ACS or AP supply, respectively, is only operational at lower rates of capacity utilisation. One can observe a high capacity utilisation towards low user prices and small ACS fleets (see the lower left of the figures). To enable further analysis of the effects of AVoD systems on mobility behaviour in this report, three user price/fleet size combinations are identified for the three area types (rural, suburban and urban), where:

      a. the operator is breaking even;
      b. the capacity utilisation of the vehicles is under 0.5; and
      c. the user price is lowest (emulating competition in the market).

Considering these user price/fleet size combinations (ACS: approximately €0.30–€0.35/km and 3.0–4.5 ACS vehicles per 1,000 residents; AP: approximately €0.11–€0.38/km and 2.5–4.0 ACS vehicles per 1,000 residents), the total ACS fleet in Germany amounts to roughly 300,000 vehicles, and the total AP fleet in Germany amounts to roughly 250,000 vehicles.

a) Rural

b) Suburban

c) Urban
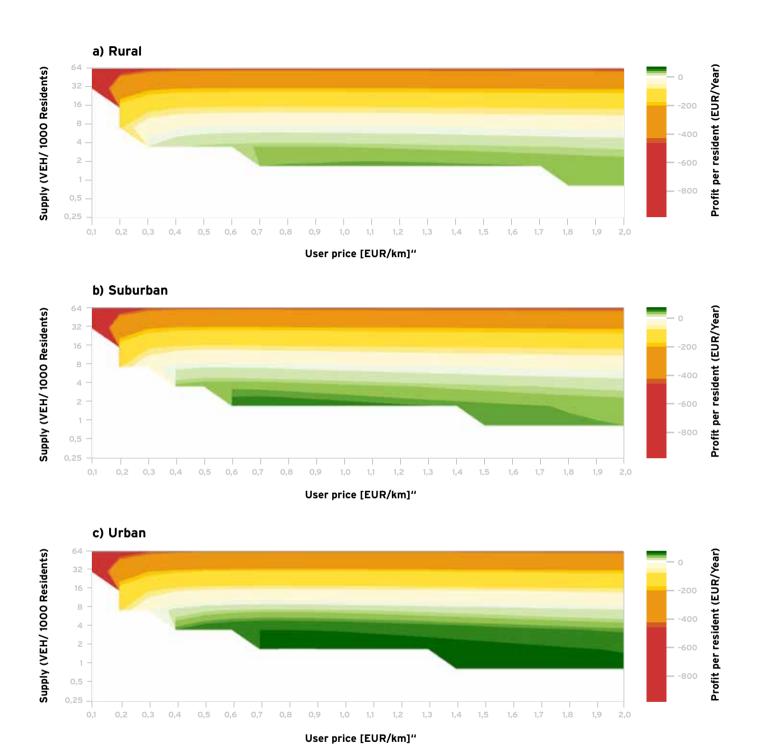
Figure A.3.2: ACS-Operator profit per inhabitant and year as a function of user price (€/km) and level of provision (ACS vehicles/1,000 residents) for different types of areas in Germany
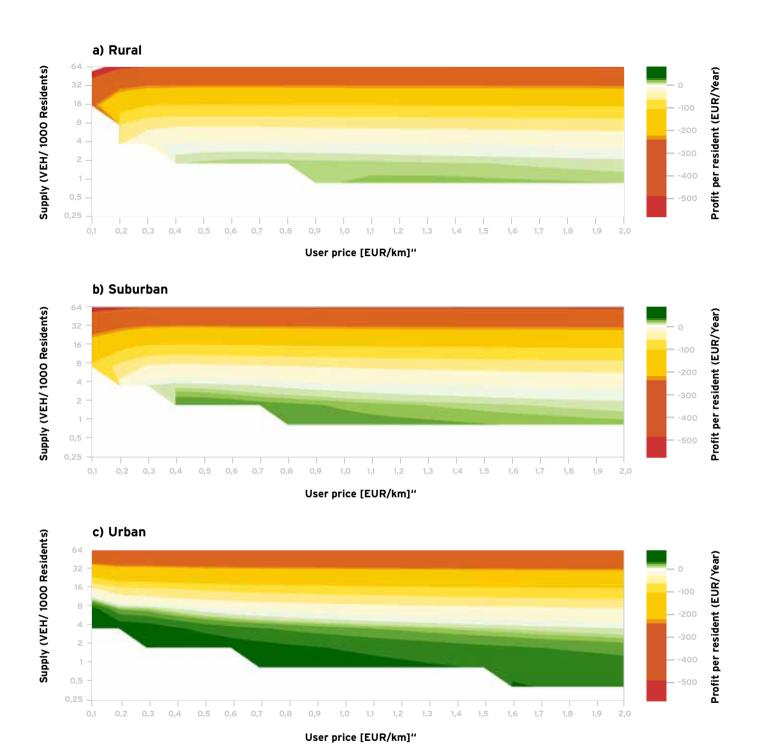
Figure A.3.3: AP-Operator profit per inhabitant and year as a function of user price (€/km) and level of provision (AP vehicles/1,000 residents) for different types of areas in Germany

Appendix B: List of Experts

GERMANY	
Siegfried Brockmann	Head of Department, Unfallforschung der Versicherer, Gesamtverband der Deutschen Versicherungswirtschaft e.V.
Christhard Gelau	Federal Ministry of Transportation and Digital Infrastructure (Bundesministerium für Verkehr und digitale Infrastruktur)
Rico Gast	Head of the Department Business Development, Berliner Verkehrsbetriebe (BVG)
Daniel Göhring	Junior Professor, Mobile Robotics and Autonomous Vehicles, Freie Universität Berlin
Marko Gustke	Senior Consultant, Koordinationsstelle Vernetztes/ Automatisiertes Fahren, Verband der Automobilindustrie e.V. (VDA)
Meike Jipp	Head of Human Factors Department, Institute of Transportation Systems, German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt e.V.)
Florian Krummheuer	Project Manager, DB Regio AG
Katrin Lippoldt	Operational Business Development, DriveNow GmbH & Co. KG
Wilko Manz	Director of Innovaplan GmbH
Dietrich Manstetten	Adjunct Professor, Robert Bosch GmbH
Michael Ortgiese	Professor, Fachhochschule Potsdam
Peter Wagner	Research Associate, Institute of Transportation Systems, German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt e.V.), Professor, Technische Universität Berlin
Ronald Winkler	Allgemeiner Deutscher Automobil-Club e.V. (ADAC)

USA	
Stephan Dolezalek	Managing Director, VantagePoint Venture Partners
J. Christian Gerdes	Director, Center for Automotive Research at Stanford, Revs Program at Stanford
Andrea Goldsmith	Professor, Electrical Engineering Stanford University
Stefan Heck	Consulting Professor, Precourt Institute for Energy at Stanford University
Jerry Kaplan	Fellow at the Center for Legal Informatics, Stanford University
Tim Kentley-Klay	Founder and CEO, Zoox
Shad Laws	Innovation Projects Manager, Renault Innovation Silicon Valley
Key Lee	Human Factors Researcher, Robert Bosch LLC
Bakhtiar Litkouhi	Manager, Automated Driving Systems, General Motors
David Lyons	Co-Founder & Chief Innovation Officer, Peloton Technology
Grant Mahler	Research Fellow, BMW
David Miller	PhD Candidate, Stanford University
Marco Pavone	Assistant Professor, Aero/Astro Stanford University
Mark Platshon	Senior Investments Advisor, BMW i-Ventures, Birchmere Ventures, Icebreaker Ventures
Caroline Rodier	Associate Director of the Urban Land Use and Transportation Center (ULTRANS), University of California
Silvio Savarese	Assistant Professor, Computer Science Stanford University
Susan Shaheen	Adjunct Professor, Civil and Environmental Engineering, UC Berkeley

CHINA	
Haixiao Pan	Professor, Director of Land Use/Transport Study, Department of Urban Planning, Tongji University
Lun Zhang	Professor, Department Transport Engineering School, Tongji University
Haiyun Jian	Ph.D Candidate, Research Associate, Tongji University
Yi Cui	Ph.D Candidate, Research Associate, Tongji University
Xiaorong Lin	Ph.D Candidate, Research Associate, Tongji University
Hui Chen	Professor, Department Automobile, Tongji University
Yishun Lang	Director of Urban Transport Department, Shanghai Urban Planning Institute
Chen He	Deputy Director, Shanghai Transport Information Center
Liyu Qin	Senior Engineer, Shanghai Traffic Police Bureau
Ximing Lu	Former Director, Shanghai Comprehensive Urban Transport Institute
Prof. Zhutin Zhang	Professional Training School of Ministry of Transportation of China
Yichen Shen	Deputy Director of Planning Dept. in the Commission of Transportation of Shanghai
Yifeng Cai	Director of Urban Transport, Shanghai Municipal Engineering Institute
Bizhuang Chen	Deputy Director, Shanghai Shanghai Comprehensive Urban Transport Institute
Renbiao Zhang	Professor, College of Law, Tongji University
Zhaojun Chen	Director, Huicong Automobile Service.
Hui Chen	Professional Training School of Ministry of Transportation of China

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Figures and Tables

Abbreviations

ACS	Autonomous car-sharing
AP	Autonomous Pooling
AV	Autonomous Vehicle
AVoD	Autonomous Vehicle-on-Demand
ERTRAC	European Road Transport Research Advisory Council
HOV	high occupancy vehicle
ICT	information and communication technology
LiDAR	Light detection and ranging
MiD	„Mobilität in Deutschland", the name of the national household travel survey in Germany
NHTSA	National Highway Traffic Safety Administration
OEM	original equipment manufacturer
PKT	Person-kilometres travelled (if used)
USDOT	U.S. Department of Transportation
VC	Vienna Convention on Road Traffic
VDA	Verband der Automobilindustrie e.V.
VKT	Vehicle-kilometres travelled
VTTS	Value of Travel Time Savings
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-X