IMPACTS OF AUTONOMOUS VEHICLES ON TRAFFIC VOLUME:

SCENARIOS BASED ON SURVEY DATA FOR THE CITY OF KARLSRUHE

by

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ABSTRACT

IMPACTS OF AUTONOMOUS VEHICLES ON TRAFFIC VOLUME -

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Autonomous vehicles will become a significant influence in the field of traffic and transportation. To determine the possible impact of fully automated traffic, this thesis analyzes trip-pattern data for the City of Karlsruhe, Germany. Based on survey data from the year 2012, the traveled distances are calculated in a baseline scenario as well as two competitive scenarios: best-case and worst-case. The database is analyzed for the most emerging trip patterns in three areas of the City of Karlsruhe. Trip data, including trip distance and mode choice, are analyzed by trip purpose and individual groups (based on employment status). By modifying the average trip distance, mode choice and trip patterns based on literature reviewed information, the consequences of autonomous vehicles are estimated. The study shows, that autonomous vehicles have the potential to reduce traffic (best-case), but on the other hand, could approximately double the overall traveled vehicle distances (worst-case).

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1. INTRODUCTION

1.1 BACKGROUND

People all over the world have the vision of self-driving vehicles for decades. These autonomous vehicles (AVs) would allow travel without any human agency in terms of directional control. Today, engineers have been able to bring certain levels of automation to the market, but the level of full automation is not yet reached.

Nevertheless, the development is in progress and unstoppable; the only question is when full automation will enter the market and, moreover, how it will influence the field of traffic and transportation. The transition from manually controlled vehicles to AVs will include the challenge of mingled traffic of conventional and automated vehicles. This thesis briefly outlines some requirements to enable full automation vehicles, but does not discuss the transition phase between today and the era of full automation in detail. The focus is set on the consequences of a fully automated future on traffic volume.

It is uncertain how the population will react to the new form of transportation. These uncertainties include the questions about how mobility behaviour will be affected and to what extent people accept AVs. A survey by Fraedrich and Lenz (2014) shows that a common image of the autonomous vehicle does not exist. Consequently, every person has a different expectation and position towards AVs based on his or her own idea of AVs.

In public discussions, AVs are often praised as the solution for all traffic issues such as congestion, slow travel times through delay in dense areas et cetera. However, the disadvantages and side effects of AVs are often neglected. Many experts (Bagloee, Tavana, Asadi, & Oliver, 2016; Fagnant & Kockelman, 2015; Isaac, 2016) predict that the demand on mobility could quickly increase, as soon as the mobility supply develops in cheaper and easily accessible ways for all groups of people. With the development of AVs, a few questions arise, for example, whether the positive effects would reduce the traffic volume or mobility gains would lead to an exploding traffic volume (Friedrich & Hartl, 2016). The role of sharing services in the future traffic is another impact that has become a topic of research. To answer these questions, it is necessary to solve the problem how the impact on the mobility behaviour of people in a certain scope can be predicted. This leads to the issue of predicting and calculating characteristic values (e.g. traveled distance within the scope) for the resulting development of the traffic is in the focus.

1.2 OBJECTIVES AND SOLUTION APPROACH OF THE THESIS

As many institutions explore the potential change of mobility caused by implementing AVs, planners must "consider a range of potential outcomes, […] [that have] led to more questions than answers about the future impacts of self-driving cars" (Guerra, 2016, p. 216).

Therefore, to quantify the predicted impacts on traffic in a city, it is necessary to analyze data of actual trip patterns that would be affected by ubiquitous AV use. The City of Karlsruhe (Germany) presents an excellent test case, because the "omniphon" survey of 2012 contains relevant data to analyze the trip behaviour. Based on mobility data from the "omniphon" survey, which involved 3121 households with 7840 persons (with cities in vicinity) in the year of 2012 (Omniphon GmbH, 2012), this thesis elaborates future scenarios. Mobility behaviour and patterns for certain groups of persons can be subtracted from the survey results. Subsequently, these specific mobility data for Karlsruhe allows to make a future projection for the mobility behaviour for the collectivity of the City of Karlsruhe. The key performance indicator is the *traveled vehicle kilometers [km]* (of motorized individual transportation). This value does not represent the traveled distance for one vehicle, but resembles the overall traveled distance by all vehicles within the scope.

After a literature review focused on quantified trends of the impact on mobility and traffic caused by autonomous vehicles, two scenarios try to implement these trends using modifications on the actual survey data. The modifications of the data set will represent trends for the change of traveled distance per person depending on the trip purpose, the change of mobility patterns and new mode choices regarding three types of AVs. The scenarios are constructed as a worst-case and a best-case scenario. The objective of the scenario technique is to elaborate quantified prediction of unknown future development. Somewhere in between the worst-case and best-case path lies the most probable path of development.

After having quantified information about traffic increase or reduction, it is possible to draw inferences about urban and traffic planning: For instance, how the traffic can be managed if it increases, whether urban planning gains new space or whether less parking space is needed. Also, the results could point out which measures planners already able to anticipate in the development of AVs and which infrastructure will be needed.

Other repercussions of automated vehicles in terms of capacity and efficiency of infrastructure, road safety as well as environmental impacts are not in the focus of this analysis, but will be covered in the literature review section as "Risks and Chances" to connect them to the overall topic.

To summarize the objectives of the thesis, the research focuses on the:

- calculation of the traveled vehicle distance for the year of the conducted survey (2012),
- calculation of the traveled vehicle distance for the baseline, best-case and a worst-case scenario for the era of full automation,
- comparison of the results and illustrate consequences of AVs, and
- recommendations for measures to handle the upcoming challenges.

1.3 SCOPE OF THE RESEARCH

To define the scope of research, the thesis will use the example of Karlsruhe, which was covered by the omniphon survey 2012. Therefore, the reference date for any statistical data is set on 2012 to eliminate the probability of errors, due to false connection between different statistical data.

Location and Network Importance

The City of Karlsruhe is located south-west of Germany in the federal state of Baden-Württemberg near the French border. For the field of transportation, its location plays an important role in the German and European highway network. Due to its location on the Autobahn A5, Karlsruhe is well-connected to the national infrastructure network, especially the south-north axis. Daily traffic at the A5 in Karlsruhe is approximately 140,000 vehicles per day with heavy vehicles representing 15.2 % (Bundesanstalt für Straßenwesen, 2016). The A8 connects the axis of Munich, Stuttgart and Karlsruhe in east-west direction. Besides the relevance in the national highway network, the location of Karlsruhe also is significant in European context. In terms of the European road network, Karlsruhe is placed on a central spot in terms of connecting France, Italy and Switzerland to northern Europe (e.g. Sweden, Norway, Finland, Denmark). Also, for other modes of transportation as the rail traffic or shipping traffic on the Rhine, the location is significant in economical and connectivity regards. Especially for the rail network, the freight transverse rail traffic from Genoa to Rotterdam as well as the passenger transverse traffic from Paris to Bratislava are connected to Karlsruhe.

History of Karlsruhe

The specific city layout, which Karlsruhe is known for, started in 1715, when it was founded. The layout resembles a handheld fan; all streets in the old city center are pointing at the palace of Karl Wilhelm of Baden, the founder of Karlsruhe.

As the scope of research, the City of Karlsruhe has an inventive history in the field of mobility. For example, Karl Freiherr von Drais (engl. 'Karl baron of Drais') has invented the dandy horse (so called "draisine") in 1817, which can be seen as the forerunner of today's bicycles. The first train station and the railway to Heidelberg was completed in 1843; 70 years later, the main station, which still exists today was opened. In 2007, as a part of the European high-speed railway network between Paris and Budapest, the TGV railway Stuttgart-Karlsruhe-Paris was opened. In terms of public transit, Karlsruhe also have been developing an own specific way of the infrastructure from 1992 on (Stadt Karlsruhe - Amt für Stadtentwicklung - Statistikstelle, 2016). It connects the core of the City with the suburban and surrounding rural areas, without changing the trains. This model is called "Karlsruher Modell" and is based on the connection of train and tram tracks. The tram-train-system depends on vehicles, that can use both systems regarding the gauge, voltage as well as geometrical parameters (e.g. clearance gauge, height of station platforms, etc.), for instance. Since 2010, a tunnel for the tram has been constructed.

Regarding Karlsruhe's history of motorized individual traffic (MIT), the year of 1844 can be pointed out. It is the birth year of Carl Benz, who was a pioneer in the development of cars and who was born in Mühlburg, which is part of Karlsruhe. In 1885 he developed the first internal-combustion engine automotive (Stadt Karlsruhe - Amt für Stadtentwicklung - Statistikstelle, 2016).

Nowadays, Karlsruhe takes part in research of autonomous vehicles by conducting pilot projects and supporting different projects of the Karlsruhe Institute of Technology (KIT) and the University for applied sciences Karlsruhe (HsKA). As one of these projects, the “Testfeld Autonomes Fahren – Baden Württemberg” started in 2016 to implement a test field in the region of Karlsruhe. It is meant to test new technologies related to autonomous and connected vehicles under real traffic conditions by companies and research institutions.

Characteristics of the Research Area

The following map shows the three areas, which are defined as Karlsruhe I, Karlsruhe II and Karlsruhe III by omniphon. These can be seen as the urban core (Karlsruhe II), the suburban circle (Karlsruhe III) and rural area (Karlsruhe I). Within this scope, omniphon has collected the data of 3611 persons, of which 3545 are later used for the analysis. The exact attribution of the districts into the three areas is done in Table 4 on p.42.

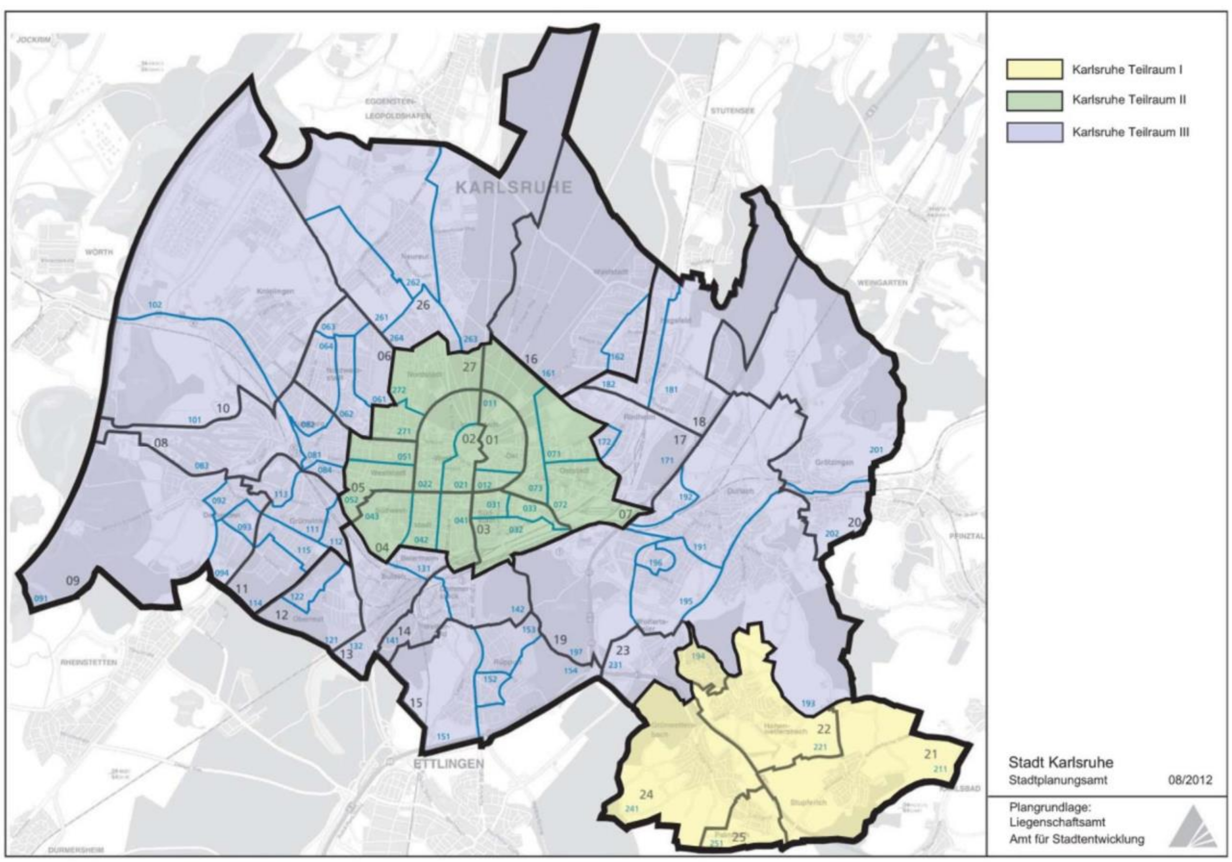


Figure 1: Map of the scope of Survey (Omniphon GmbH, 2012)

The population of the city is stated as 309,106 persons in June 2017; after a short peak in 2015 takes place (Stadt Karlsruhe - Amt für Stadtentwicklung - Statistikstelle, 2017a, p. 3). At the time of the omniphon survey, 2012, the population of Karlsruhe was 307,047 persons, distributed in the three researched areas Karlsruhe I (11,978 inhabitants), Karlsruhe II (110,558 inhabitants) and Karlsruhe III (184,511 inhabitants) (Stadt Karlsruhe, Amt für Stadtentwicklung - Statistikstelle, 2017b). Table 1 combines the population numbers with number of respondents within the areas.

Table 1: Population and Number of Respondents per Area

Area	**Population**	**Respondents for analysis**
Karlsruhe I	11,978	1,010
Karlsruhe II	110,558	878
Karlsruhe III	184,511	1,657
Total	307,047	3545

In terms of mobility, a common indicator is the number of licensed road vehicles for certain districts. Following from that, the calculation of the average vehicles per person ratio highlights differences in mobility behaviour in the areas. While in the urban core (Karlsruhe II) the average vehicle per person ratio is 41 %, in the rural area (Karlsruhe I) an average ratio of 65 % vehicles per person is given. The value of the suburban areas lies in between with 56 %. (See: Appendix 1 (Stadt Karlsruhe, Amt für Stadtentwicklung - Statistikstelle, 2017b)). These values represent a first tendency for the mode choices of the population.

Especially in terms of autonomous vehicles, the idea of Car Sharing should be taken into considerations. Therefore, the following figure shows the development of the number of Car Sharing users in the local service “Stadtmobil”. As seen in the figure, Car Sharing has shown growth in popularity. AVs could push this development further.

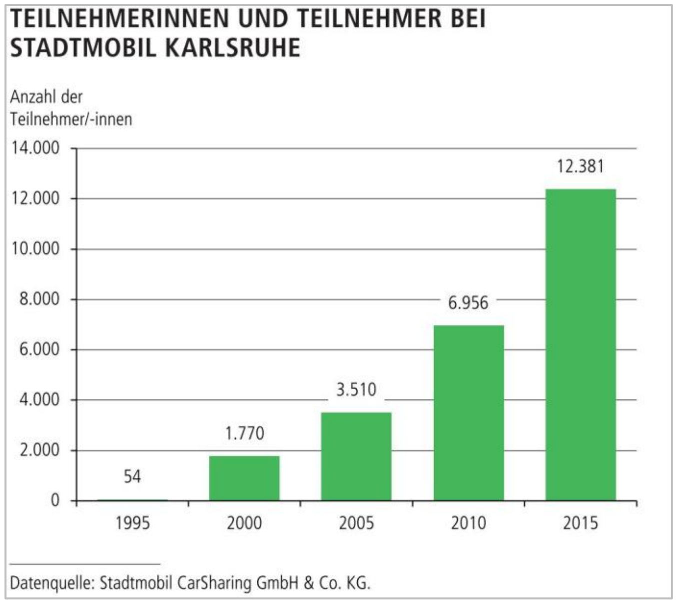


Figure 2: Car Sharing (Stadt Karlsruhe - Amt für Stadtentwicklung - Statistikstelle, 2016, p. 27)

Regarding the public transit, Karlsruhe has a well-developed network of tram and train ("Karlsruher Modell"), which is supported by a bus line system. During night, most of the trams are replaced by "nightline" buses. During day, the tram lines are traveling in frequencies of 5 to 20 minutes in the core, while in the suburban area the frequency is lower. In near future the subway, which is still under construction, will be part of the public transit network. That might have an effect on the mobility behaviour of inhabitants, but is not part of the thesis.

Besides public transit and motorized individual transportation, the City of Karlsruhe has been promoting the active transportation within the last two decades. Especially, the bicycle network has been supported by the "20-Punkte-Plan" (English: "20-article-policy") from 2005. The omniphon survey showed that the objective of this policy to reach a modal split of 23 % for cycling is already reality. Other objectives include reducing the number of severe crashes involving cyclists about 25 %, gaining the image of the "best City for cyclists" in southern Germany, regarding cycling as an equal participant in traffic in each construction measure and expanding the cycle network. The updated program plans to reach a modal split of 30 % in the year of 2020 (Herold, Ringler, & Wagner, 2013). Moreover, Karlsruhe has a bicycle share system called "Fächerrad" as well as a share system "call a bike" by the German railway company "Deutsche Bahn".

The omniphon report from 2012 provides the following figure for the modal split. This one differs to the modal split that results from the analysis later in the thesis. One explanation for that could be weighting factors that omniphon used for the survey. (See: Chapter 3.5)

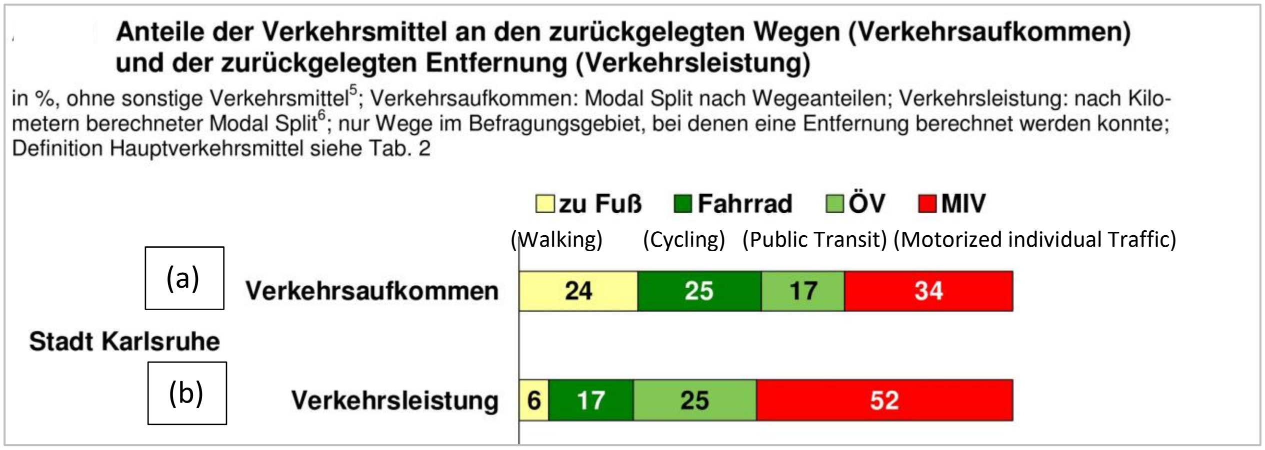


Figure 3: Modal Split depending on (a) trips and (b) person-related traveled distance (Omniphon GmbH, 2012)

The area of Karlsruhe is 17,346 hectare, of which 12.5 % are used as traffic area (Stadt Karlsruhe - Amt für Stadtentwicklung - Statistikstelle, 2016, p. 13). Excluding forest, bodies of water, agriculture and green areas, the traffic areas have the amount of 28.5 % of the constructed areas. Subsequently, the change of mobility in combination with traffic reduction carries the potential regarding land use and urban development.

2. LITERATURE REVIEW

This chapter begins with the definition of autonomous vehicles regarding the scale of automation. Next, the current technical state of AVs is reviewed in addition to current ongoing research to predict the impact on traffic and transportation. In order to give an overview of the research, some studies are reviewed and briefly listed. Besides the technical state of AVs, other different aspects of requirements are reviewed in literature. Following from that, expected development for the market entrance barriers for AVs are briefly mentioned.

The focus is set on the general occurrences and risks of AVs, the parameters that could shape the development of implementing AVs into daily traffic, the aspects that have to be regarded while observing the development and the positive developments that are connected to disadvantages.

2.1 LEVEL OF AUTOMATION

Different institutions define the automation of vehicles in various ways. To specify the level of full automation, which is fundamental for the researched topic, it is necessary to regard the common used definitions. The American (NHTSA) and German (BASt) authorities have defined five levels of automation. The higher the level, the more actions are performed by the vehicle itself.

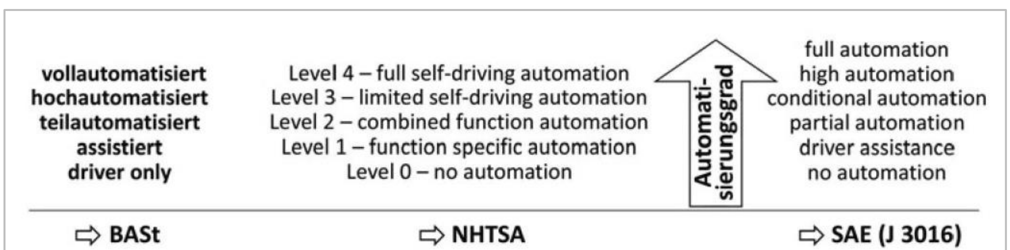


Abb. 17.1 Kategorien der Automatisierung nach BASt / NHTSA / SAE

Figure 4: Level Automation - Comparison BASt NHTSA SAE (Thomas Winkle, 2015, p. 354)

In comparison, the Society of Automotive Engineers (SAE International) categorizes six levels (from 0 to 5). Regarding the following figure, the difference of high and full automation, which is not defined by the BASt or the NHTSA, is illustrated.

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

Figure 5: SAE International J3016 (SAE International, 2014)

Most of today's research is based on the SAE levels. The following paragraph briefly describes the key features of the SAE levels. Level 0 has no intervention of the vehicles in the driving task. The driver controls the longitudinal and lateral movements. In Level 1, the driver can give one of these tasks to the driver assistance system, while fulfilling the remaining task. Level 2 allows the vehicle to take control of both tasks for a certain case (e.g. parking). The driver has to constantly observe the environment and the actions of the vehicle. In between Level 2 and 3 the task of constantly observing the environment switches to the vehicle system. Level 3 enables drivers to concentrate on other things within certain road situations. This requires a system, that requests the driver early enough to take over the control, as soon as the manageable situation ends. For Level 4, the driver has no interaction with the vehicle in most cases. The vehicle can perform on its own. Level 5 in comparison, does not even need a driver. Every situation is handled by the vehicle on its own. Some car manufacturers, differentiate the Level 4 and 5 in terms of the interior design. So, Level

5 often is design without a specific driver seat, steering wheel and gas pedal. The vehicle is not meant to be directly controlled by the operator.

The Levels 4 and 5 are totally independent of the control of a driver. Therefore, when speaking of autonomous vehicles in this thesis, the high and full automation (SAE levels of 4 or 5) are meant.

2.2 CURRENT STATE OF AUTOMATION

As one big player in AVs, Tesla entered the market with the Model S and Model X in 2014. The Model S and Model X can be classified as “Level 2” or “Level 3” AVs, due to the requirement of a driver, who touches the steering wheel frequently. Different versions of the autopilot include certain driving assistant systems, examples include: cruise control, autosteer on divided highways and on certain local roads up to 35 mph. While the software of the autopilot gets new features with new updates, the hardware is distinguished in two sets. The new version (Hardware 2), which is standard equipment of the vehicles build since October 2016, is promised to be able to serve the needs of a “Level 5” AV (Tsantilas, 2016). The software, to identify every detail and classify everything of the surroundings as one example, is not developed enough. In a TED talk at a conference in Vancouver, Elon Musk, the CEO of Tesla, predicted to have the technical requirements to let the driver sleep (“Level 5”) while the AV drives within the next two years, so until 2019 (Kesteloo, 2017). Since the market entrance a few incidents happened, in which Tesla vehicles were involved, including one fatal accident.

Earlier than Tesla, Google started in 2009 to test AVs on the roads. They began to examine simpler traffic situations such as highways and freeways. In 2012, they set focus to the more complex environment of urban cities. After testing the technology in 2015, Google built their own prototype of the so-called autonomous “Firefly”, a self-driving vehicle. In 2017, they switched back to retro-equip conventional cars, as they did already in the beginning of the project. Until now, tests have been exceeding five million kilometers on public roads without any severe crashes. Nowadays, Google’s self-driving project founded a new unit, which is called “Waymo”. First test drives, which are mostly located in Phoenix, are conducted without a person in the driver’s seat; in near future, those test drives are announced to be open for the public within an “early rider program”. Waymo itself declares the level of automation in these vehicles as “Level 4”. Regarding the definition of the SAE, it is closer to “Level 5” than to “Level 4”. In an interview with the "FAZ" ("Frankfurter Allgemeine Zeitung"), an expert also classified the test drives of Waymo as "Level 5" due to the fact, that no driver is required (Lindner, Armbruster, & Preuß, 2017).

As German representative, Bosch, that already provided a lot of technical equipment for Google's Firefly, works close with Mercedes-Benz on the development of autonomous vehicles. The goal is to have autonomous vehicles ready for series production in the early decade of the 2020's. As an advancement of the Car2Go service, they plan to implement their AV fleet as a mobility-on-demand service (Lindner et al., 2017).

On the one hand, the current technical state of automation can be defined in the development of in between of "Level 4" and "Level 5" AVs in certain pilot areas as the Waymo test drives demonstrates. The challenge for the near future is to expand areas, where AVs can act on the same safety standards independent of environmental specification, different weather conditions and availability of high-definition digital maps.

On the other hand, new cars available on the market to purchase are on the technical state in between "Level 2" and "Level 3" (Sieg, 2017). Also, Golokow et al. define today's technical state as Level 2 (Golowko, Zimmermann, Zimmer, 2017, p. 30). The same source expects the market entrance of Level 3 to Level 5 until the year of 2025.

2.3 CURRENT RESEARCH TO PREDICT THE TRAFFIC IMPACT OF AVS

In the booming development of autonomous vehicles, traffic and transportation planners all over the world research the impacts of the implementation of AVs. Different approaches are used to find out about the trends and developments in the future.

The most common method of determining the answers for the posed questions in the introduction is to use traffic models and simulations, as for example the Karlsruhe Institute of Technology did, by elaborating the case study of the City of Stuttgart. They set up a travel demand model of 100 % of AVs in a scenario without privately owned cars. The AVs acting as an autonomous mobility on demand (AMOD) service including Ride Share, if the trip has the same origin and destination (Heilig, Hilgert, Mallig, Kagerbauer, & Vortisch, 2017). Similar studies are conducted by the "TU Braunschweig", which simulated the impact of different sizes of autonomous Car Sharing fleets on the mobility behaviour in the City of Cottbus. In this study, they used a software called MatSim and modified a taxi-fleet-based simulation to represent an autonomous Car Sharing fleet (Bienzeisler, 2017).

The Boston Consulting Group, in comparison, developed four scenarios to research the impact of self-driving vehicles. The four scenarios are distinguished as follows: the self-driving car as a premium vehicle, the AV as the common transportation mode of motorized individual transportation, the implementation of "robo-taxis" as an on-demand Car Sharing service and as fourth scenario, the "Ride Share Revolution" (Lang et al., 2016).

The OECD study examined "the changes that might result from the large-scale uptake of a shared and self-driving fleet of vehicles in a mid-sized European city" (OECD - International Transport Forum, 2015). As autonomous shared on-demand services, they defined two modes: the "TaxiBot", which resembles the idea of an autonomous Ride Share fleet and the "AutoVot", that acts like a Car share service. The key findings include, that around 10-12.5% of the shared AVs could serve the same mobility demand as today, the overall volume of MIT travel is likely to increase, and therefore parking space can be reduced.

Inspired by that study, Friedrich and Hartl expanded the simulation and applied it for the City of Stuttgart. The terminology for the three modes of autonomous vehicles within the study is used for this thesis (Friedrich & Hartl, 2016). Its results are compared in section 5.6 with the calculated values.

Compared to the simulation-based studies, the survey data-based calculation, which this thesis elaborates, uses the analysis of mobility behaviour and trip patterns in addition to the implementation of trends, which are concluded from the simulations.

2.4 REQUIREMENTS FOR FURTHER IMPLEMENTATION OF AVS

2.4.1 Ethics, Laws and Regulations

Two of the main challenges for implementing autonomous vehicles in current traffic conditions are to adjustment laws and resolve ethical questions. As one of the first countries, the German federal government adopted new guidelines for the ethics of AVs on August 23rd, 2017. It should serve as a foundation for further legal guidelines. Compared to Germany, the U.S. do not have any national guidelines, which leads to different drafts of regulations in each state. To prevent developments like this, one point in the German guideline is to support international standards to allow transnational functionality of AVs. The core statements of the guidelines include:

- The priority of human life over damage to property or animals.
- Each human life is equal. In fact, the decision on life or death in a dilemma situation can not be programmed dependent on age, gender, race, disability or any other recognizable features. The vision is, to hit the person, who has the lowest chance of fatality caused by an unavoidable incident.
- The ethic of connected and autonomous driving is given, if the systems causing fewer incidents than human drivers.
- In every situation it has to be defined, whether the driver or the car is in charge of control.
- The person who drives, has to be documented in terms of questions of liability.
  (Bundesministerium für Verkehr und digitale Infrastruktur, 2017)

To implement the guidelines into binding regulations, the German road traffic law needs to be adjusted to the technological progress. In addition to that, the legal framework for the ethic guidelines has to be developed further (Presse- und Informationsamt der Bundesregierung, 2017). Moreover, it seems necessary to work on laws and regulations in an European context to allow transnational trips within the same standards. This process will probably take longer than the technical development itself.

In terms of liability for incidents, the laws have to be modified. The question, who is accountable for the crash must be answered. Is the passenger, who does not interact or steer the vehicle, responsible or the company that built the AV? Regarding the issues of liability, a lot more detailed questions arise, but will not be elaborated more in depth within this thesis. Furthermore, privacy issues and virtual security will play an important role in the future of AVs and its legislation process. These issues will be covered in chapter 2.5.2.

2.4.2 Market Development & Purchase Costs

According to Fagnant & Kockelman, who collected statements from Google, Volvo and Tesla, the mass market entrance of autonomous vehicles could be in 2022 or 2025 (Fagnant & Kockelman, 2015, p. 168).

A similar view on the market development is shown in the following figure. Isaac expects in her guide that the market penetration of AVs will reach 100% until 2040 and thus replace the typical public transit. That rapid implementation of AVs seems debatable, but in her scenarios the governmental and local authorities will regulate traffic strictly towards automation.

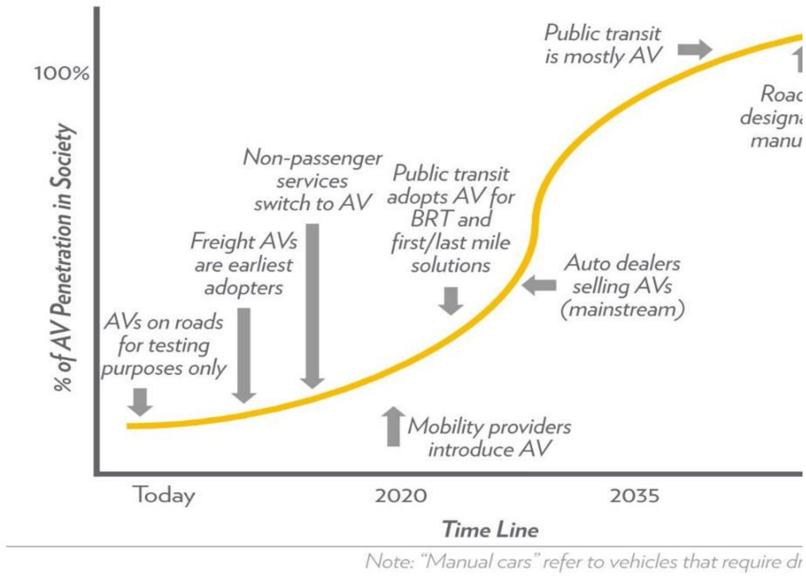


Figure 6: Implementation of AVs in society based on (Isaac, 2016)

She further expects primarily freight and non-passenger services to fulfill requirements for AVs to be implemented. Also, according to other sources, it seems most likely, that the implementation of AVs will start in the sector of public transit or sharing services for person transportation services. These interact in limited areas, which are easier to manage. In limited areas, it is possible to build necessary infrastructure, develop high-precision maps and achieve other requirements for the implementation of AVs. In further implementation process of AVs, it is predicted that AVs will enter as premium vehicles. The automation features as the peak of high-tech equipment let the purchase cost increase to status of luxurious business cars.

Following from that, the development of the market penetration of AVs will be slowed due to the purchase cost. This is caused by the use of high-tech equipment, such as sensors, LIDAR, RADAR, cameras, other hardware as well as the computing software. In their study, Fagnant & Kockelman elaborate the costs of AVs and their required technical equipment. By researching other sources, they conclude that the price could fall to a feasible price 20-22 years after the introduction of

AVs. Therefore, the attainment of 100% fully-automated traffic is expected slower than in Figure 6. They further cite a study of J.D. Power and Associates (2012), that states, that "37% of persons would 'definitely' or 'probably' purchase a vehicle equipped with autonomous driving capabilities in their next vehicle, though the share dropped to 20% after being asked to assume an additional $3000 purchase price" (Fagnant & Kockelman, 2015, p. 176). Further details to cost related aspects of AVs are not conducted within the frame of this thesis.

2.4.3 Infrastructure and Reliable Technology

The requirements for the new infrastructure can be seen as a multidisciplinary task. Various fields of engineers and planners have to be coordinated. The keywords for the required technology are "connected vehicles" and "big data" (Bagloee et al., 2016). The connection between vehicles allows interactions such as pooling, lower reaction time and gap requirements as well as information transfer. The "big data" results from various sources, especially from the vehicle communication with other vehicles (V2V), infrastructure (V2I) or other possible participants (V2X).

In terms of the "connected vehicles" idea, the cellular network has to develop up to 5G standard and needs to be comprehensive (Bagloee et al., 2016). The AVs need strong data connection for all its information systems. To build up a gapless cellular network infrastructure, the rural areas will take longer compared to the already well-connected urban areas.

Regarding the connection V2I, the infrastructure has to be equipped with sensors, measuring and monitoring technique, communication facilities (Wi-Fi or cellular network) as well as orientation points for AVs (specifically during the phase of development). For example, traffic lights could either communicate with approaching AVs or identify them via sensors or video techniques. The gained data has to be collected in a modern high-tech traffic operation center, which is able to filter and process the "big data" in a way, that the traffic information is processed and imparted to the "connected vehicles" in real-time. Therefore, high computing power, purchase costs and maintenance costs for all the high-tech facilities, sensors and redundant communication panels are required.

If autonomous vehicles are powered by electricity within cities (most likely for Ride Share and Car Share vehicles), the infrastructure has to provide enough charging stations. Some opinions are dubious, concerning the electrical network will reach its limit, if AVs turn large amount of traffic into electrified traffic.

2.4.4 User Acceptance

Even if the previous points have been achieved, it is unclear how fast and in what way the users accept and trust the AVs. Especially in Germany, as a country of car manufacturers, people see driving as personal freedom. For many of them, driving is more than changing the location from A to B. Besides that, people's trust in the new technology depends on different factors. Most of them are related to aspects of safety. The proof of safety over a certain amount of time could neglect this trust issue. Besides the safety, the purchase and operational cost could make it unfeasible for users to travel with AVs and lead to low acceptance of the technology.

2.5 RISKS AND CHANCES OF AVS

The policymakers and studies regard the topic of automated traffic with focus on "sustainable mobility" (Klumpp, 2016, p. 14). This term includes different aspects: The automated mobility is seen as more efficient, which makes traffic and congestion management more sustainable by managing the whole communicating mass of individual vehicles. Consequently, traffic conditions are expected to be optimized and safer. Moreover, automation is often attached to Car Sharing and similar systems, which increase the occupancy rates of a vehicle. Higher occupancy in vehicles, reduces the required space on infrastructure. Also, sustainability in terms of environmental aspects are regarded, which is elaborated in 2.5.6.

As the Boston Consulting Group illustrates in the following figure, policymakers expect AVs to have these positive impacts.

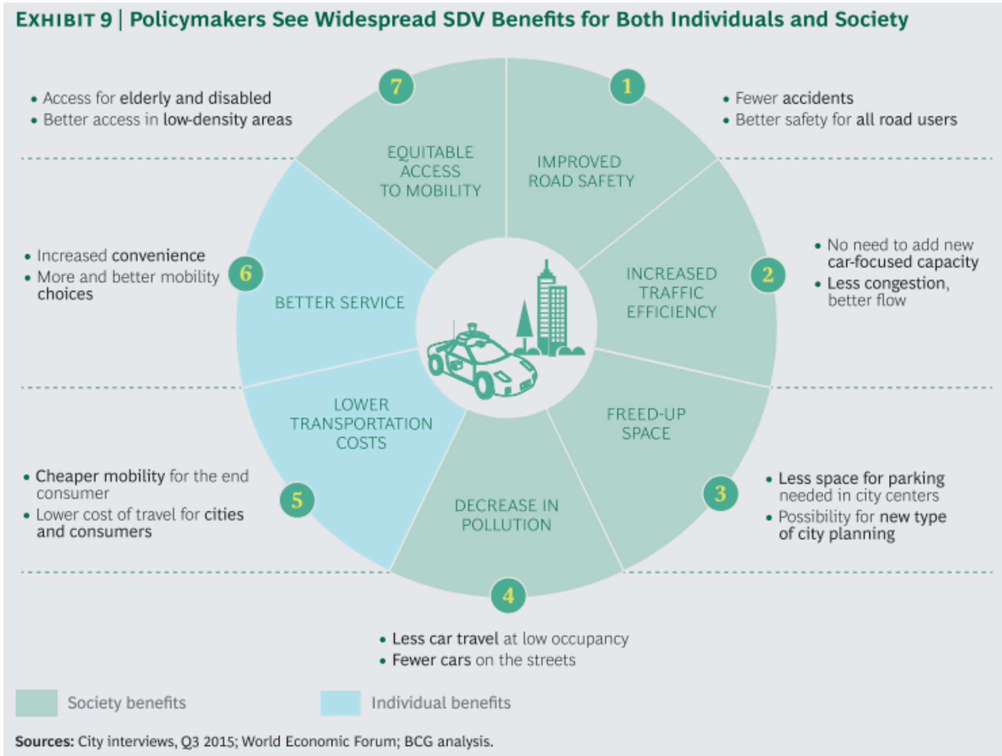


Figure 7: Expected Benefits of AVs (Lang et al., 2016)

In the following, different aspects are elaborated in further detail to show, which risks are related to the benefits and chances, that AVs carry. As the next sections show, it is difficult to separate the different aspects, due to the strong interconnection between them. Factors of travel time, travel distance, modal choice, mobility behaviour, safety, capacity, parking and infrastructure are highly interdependent. This section should call attention on the interdependence instead of giving a complete detailed overview of each aspect.

2.5.1 Safety

- Chances: Different studies show, that nowadays human mistakes are the main reasons for crashes. For instance, the US Department for Transportation states, that human drivers are the cause of incidents in 94 % of the cases. Following from that, they distinguished the reasons for the human mistakes. Given the percentage of the total number of accidents, the main human errors occur in recognition (41 %), decision (33 %), performance (11 %) non-performance (e.g. sleep) (7 %) errors (National Highway Traffic Safety Administration and U.S. Department of Transportation, 2015). Illustrated by these numbers, the potential safety gain by neglecting human mistakes through AVs is perceptible. For instance, the first tests of the

Google car confirm, that safety can be increased. On current tests, most of the incidents are caused by cars driven manually (Dolgov, 2016).

Experts, as for example Hayes, expect that fatality rates (per person-mile traveled) could be reduced close to 1% of today's rates in motorized vehicles (Fagnant & Kockelman, 2015, pp. 169–170). As an assumption for Germany, resulting from analyzing data of the "German In-Depth Accident Study" (GIDAS), the AVs are able to reduce incidents up to 50 % until 2050 and almost complete avoidance of incidents, caused by the AVs, in 2070. In terms of incidents, caused by conventional vehicles, AVs can avoid some of them, but not all. These cases are not within the stated percentages (Thomas Winkle, 2015, p. 367).

- Risks: The development of guaranteed safety of AVs is still a challenge. Sensors and the driving operator has to be specified on different conditions that could occur. Poor weather such as heavy rain, fog, snow and reflective road surfaces in terms of vision-related issues as well as high snow or icy road surfaces, which have different driving characteristics can increase risk. This leads to many questions such as how AVs react to high snow levels and whether they will classify the snow as an obstacle; or whether the AV detect icy roads and slows down. Given these issues, it explains, that computer vision has problems identifying, whether an obstacle is harmless or not (Fagnant & Kockelman, 2015, pp. 169–170). Backup systems and combinations of different systems could solve these issues.

  Another risk is, that the attention to other traffic participants gets reduced. As persons do not have to observe the environment while traveling with the Level 4 or Level 5 AV, the ability to observe the environment while riding a bike or a conventional car could decrease. Similar development can be seen in driver assistance systems or other automated processes. If people get used to automation, they lose the ability to concentrate on a certain task.

  Another issue in urban areas could appear from people knowing, that AVs avoid incidents as highest priority. Pedestrians could walk on the street, jay walk or even stand on the street knowing, that AVs yield or stop for them. Consequently, the AV is blocked by other traffic participants, who do not comply with regulations. Imagine the situation of a busy shopping street (e.g. 5th Av. in New York, Queen Street in Toronto), where many people are willing to cross traffic lanes often to visit different shops and stores; the vehicles on the street are fully-automated. Pedestrians, who know that AVs will avoid crashes, will most likely cross the street wherever they want, instead of walking a detour to find a signalized crossing. Same issue could appear to cyclists and other manually controlled modes of transportation. "In short, pedestrians and other humans could actively exploit the predictable and safe behaviour of autonomous vehicles" (Millard-Ball, 2016).

2.5.2 Data Analysis and Privacy Issues

- Chances: The analysis of the travel data enables transportation planners to optimize future traffic planning, improve signalized intersections and manage congestion development. This could lead to more efficient route choice and trip quality for individual travelers. The capacity of the traffic network can be used more efficient by optimizing the whole system (system optimum) by implementing an autonomous and communicating infrastructure, instead of the intention of each individual optimizing travel time and trip quality of its own trip (user optimum).

  Moreover, the collection of crash data could reduce technical errors as well as help to clarify the causes or the responsible vehicle of an incident. This could lead to new gains in knowledge of technical issues or difficult situations in traffic, that have to be solved. Furthermore, data for researches in mobility behaviour, peak hours, etc. could be collected more easily.
- Risks: Besides the road safety aspects themselves, the privacy and digital issues play an important role. Private user data has to be protected from misuse in a world of digitalism. Data like positioning data or other traveling information could allow draw conclusion about the user. Personal data could include the location of the person's home, working place as well as the current location, but moreover the religious or political view (e.g. if the trip destination is a mosque or church, political institution) or shopping behaviour etc. Concluding, AVs as "smart vehicles" carry similar privacy issues as smart phones. The personal data collected by the AVs could be valuable for companies in different fields as well as for misuse in other cases. Furthermore, the driving systems have to be secured from hacking or foreign influence, that could manipulate the systems. Especially in times, in which trucks are used as weapon for terror attacks, as for example, in Nice (France) or Berlin (Germany), the AVs have to be developed with a high standard of virtual safety.

2.5.3 Parking & Land use

- Chances: The advantage of AVs in terms of parking is mainly dependent on the so-called valet-parking. This means, the AV drops-off the user, at the door of the destination and searches a parking lot alone.

  First, the valet-parking could lead to less parked cars in city centers by concentrating parking facilities. Each user can be dropped-off directly at the destination, and the valet-parking of AVs enables concentrated parking facilities to provide parking space for a higher number of vehicles, instead of using wide-spread on-street parking lots. The valet parking enables the concentration by cutting the dependency of the parking location to the user's destination. On the other hand, the parking facilities could be outsourced from the city centers. As the model of Correia and van Arem shows, it can lead to a reduction of land use for parking space in dense urban areas, though external parking facilities might be less attractive in terms of utility (e.g. waiting time) and additional trip distances (Correia & van Arem, 2016, p. 87).

  Second, due to the automation of the parking process, space use can be optimized. Gaps between cars can be reduced, if the car drops off the person(s) before getting in the parking lot doors do not have to be opened in the parking lot then. Furthermore, if a parkade is at its capacity, it would be possible to park even on driving lanes. The vehicle-to-vehicle communication (V2V) could arrange that the blocked vehicle is able to leave its parking lot by demanding the other car to move.

  Third, if a vehicle communicates to infrastructure (V2I) and gets the information, where parking space is available, the traffic caused by the search for parking lot can be reduced. Of course, this requires high-tech infrastructure with, for example, sensors that detect whether parking lots are empty or occupied. In addition to that, parking facilities have to be close to the parking demand (e.g. city center), otherwise the AVs will cause additional vehicle-kilometers to the parking lot. The system has to "block" the requested parking lot for other vehicles, as soon as it gave the information to one AV to avoid, that two vehicles are on the way to the same parking lot.

- Risks: As mentioned in the previous third point, additional traffic could be generated due to "external" parking facilities. Of course, the outsourcing of parking facilities in areas outside the city, where the land property is cheaper, has advantages for the city center, but trip numbers and distances will increase, while the utility for users decreases. If users of AVs have to wait a certain time before the AV is ready for a trip, because it was parked autonomously outside the city centre, the utility of the mode of transport decreases, because the acceptance of the people to wait decreases with the increase of waiting time. While trip numbers and distances increase, the traffic in the city center grows, induced by saving parking space.

  Another point could be the number of owned vehicles in cities. Nowadays, the lack of available parking space in urban areas plays a role preventing to buy a second or third vehicle. If parking facilities get shifted in suburban areas, people in the city center do not have to struggle with the parking pressure. Consequently, new vehicle ownerships could be induced by the autonomous parking process in another area.

2.5.4 Additional Mobility for Certain Groups of Persons

This section is specific to Level 5 AVs. Only Level 5 vehicles can provide full, new mobility for groups of persons, who are unable to drive a vehicle on their own. Level 4 vehicles are still dependent on selecting a driving mode, which is defined as “a type of driving scenario with characteristic dynamic driving task requirements (e.g., expressway merging, high speed cruising, low speed traffic jam, closed-campus operations, etc.)” (SAE International, 2014). Followed by that, the user has to have at least a competence in selecting the driving mode, which makes Level 4 critical for mentally unfit (e.g. children of young age) persons.

- Chances: One of the most mentioned objective of automated traffic is to provide a new transport mode to people, who can not benefit from the advantages of driving a car. Speaking of people, who are disabled, inebriated due to alcohol, drugs or medication, weak vision, physical and mental handicaps, no matter if it is temporary or permanent as well as persons, who are not allowed to drive a car because of their age, they will have a chance to gain new mobility (Friedrich, 2015, p. 332).

Children are often dependent on their parents in terms of trips, that are out of range for public transit, cycling or walking. Children can be separated into a group, who are in need of duty of supervision, and a group, that are old enough to take daily trips independently. At what age to draw that line might be difficult, but the younger children, who need supervision, are causing additional trips for parents. Compared to them, older children can make a certain amount of their trips independently (e.g. to the local football training, to the local school, to the friend in the neighbourhood). The chance of giving the children an independent and safe mode of choice could reduce the number of trips. The driving age (in Germany: 18 years, to drive alone with a car) plays an important role for the mobility behaviour of children.

The issues with elderly persons often caused by disabilities, less concentration ability, larger reaction and action times (Kocherscheid et al., 2007). Elderly persons often have a lack of physical mobility, which exacerbate walking or cycling as well as unsettle them in driving a car on their own. Having weak vision and impaired hearing are also often evolved with increasing age. In fact, AVs could regain their mobility and consequently, a quality of life, because mobility enables to take part in society and the personal environment.

Another example for driving issues are inebriated situations. As Kocheschied et al. cited Lyrer & Müller-Span, studies indicate faintly, that 5 to 10% of all car trips are executed under the influence of medication (Kocherscheid et al., 2007, p. 25). Roughly one out of five medications leads to losing the fitness to drive (Westhoff, 2014). Medication is often increasing with the age of a person, so tight related to the elderly generation. Besides medication as tranquilizer or antidepressants, alcohol or synthetic drugs are more common in younger generations, and often the cause of incidents. At the era of full automation, the alcohol limitation for driving does not play a role except the policy authorities regulate, that passengers have to be sober in any worst-case of system failure.

To sum up, safety in these cases of unfit driver conditions could be increased, as well as the mobility for especially under-aged, elderly and disabled people can be improved.

- Risks: By providing new mobility to certain groups of persons, their demand on trips and owning vehicles could rise. Knowing about the availability of a more attractive mode of transportation additional trips and higher travel distances could be generated by new groups of persons. If the supply of AVs is large and cheaper than conventional modes of transportation, the demand will follow.

> *Given the example of two 16-year-old girls, who want to go shopping in the afternoon; why should they stay in their small hometown with unattractive shops, if the AV offers a cheap and uncomplicated opportunity to go to the next bigger city with a more attractive shopping mall? Without AVs, they would have to take the public transit or asked their parents to drive them there. So, there exists a certain barrier to go to further destination.*

Regarding the example, a lot of different cases could appear, in which people, that are not able to drive conventional cars, would cause additional traffic on the roads with AVs. Not even in unordinary trips, also in their daily mobility behaviour and mode choice, these groups could shift to the autonomous vehicles instead of their current modes.

2.5.5 Travel Time

Chances: First, the travel time can be seen as a user-specific factor. In that case, the factor of travel time has impact on the decision how far one travels, and which mode of transportation is used. The obstacle is, that the travel time for drivers of conventional cars, decreases for users of AVs because the travel time is not "lost" anymore. If the travel time is large, a lot of persons are concerned about concentration issues and being tired of driving. Therefore, for large travel times, persons take into consideration to take the train instead of car, to gain their travel time as time they can use. Compared to conventional cars, the time spent in AVs can be used more efficiently, for instance as working time, relaxing time or communication time. Different approaches of how to spend the time in autonomous vehicles can be deduced from the interior design of developers. Some designs appear like a mobile office, other concepts are more like a social place, where people face each other, and some are designed as a place of relaxation, providing enough space to almost lay.

Second, regarding travel time in the whole transportation system, the travel times of users can be reduced by optimizing the system. Due the communication between the vehicles themselves and the infrastructure, traffic management could reduce travel time by easing congestion and coordinating route choices, as mentioned before. Congestion on freeways could be solved by eliminating human behaviour of having different safety distances, different reaction times in breaking and so on. AVs could travel as one constant platooning traffic stream with certain velocity and certain safety distances. As a result, the platooning and communication ability of AVs lead to a more stable traffic stream, which is less likely to collapse into congestion (Friedrich, 2015, p. 344). Higher capacities of freeways and highways could be possible. Mathematical models show, that compared to the current capacity of 2200 vehicles per hour per lane could increase to a capacity of 3900 vehicles per hour and lane of full-automated vehicles (Friedrich, 2015, p. 341). Similar models, also, regard the impact of the percentages of heavy vehicles as well as different ratios of conventional and full-automated traffic. In the words of Bagloee et al., "AVs further reduce the opportunity cost of travel in terms of the saved value of time pertaining to off-wheel activities" (Bagloee et al., 2016, p. 290).

- Risks: If travel time loses importance to users of AVs, the travel distance could consequently increase. In other words, as the quality of transportation rises, the attractiveness to travel rises, too. This could lead to more and longer trips. The range of an acceptable travel time towards certain destinations may rise. The other way around, popular destinations probably gain more attraction. The travel in terms of changing the location gains attractiveness while at the same time the distance and the travel time are less seen as a restraint.

2.5.6 Environmental Aspects & e-Mobility

Chances: As in the introduction of that chapter mentioned, the AVs are regarded as a new chance of sustainable traffic. Regarding environmental aspects, the combination of e-Mobility and autonomous mobility seems obvious to improve environmental sustainability. The development of AVs and electrified vehicles are both booming, due to policies, that should prevent climate change. Especially in shared vehicle concepts, e-Mobility can find application. "In this context, one can find natural and organic synergy between shared AV fleets and EV technology: a fleet of AVs can resolve the practical limitations of EVs including travel range anxiety, access to charging infrastructure, and charging time management" (Bagloee et al., 2016, p. 289). In further analysis, Bagloee expects the operational costs for shared vehicles to be equal to privately owned vehicles. "[T]he combined cost of charging infrastructure, vehicle capital and maintenance, electricity, insurance, and registration for a fleet of AVs […] can be offered at the equivalent per-mile cost of private vehicle ownership for low-mileage households" (Bagloee et al., 2016, p. 289).

Within e-Mobility, battery technologies could act as new power source. As one advantage of the battery technology, visions of electric vehicles (EVs) as temporary energy storage for local power stations and the electric network are arising. Especially, renewable energies are producing energy unsteady, therefore EVs could cut the peaks, while they are connected to the network, and also can deliver the energy back to the network, if they are not scheduled to be used within the next time.

Another advantage of electrified AVs is that they could drive to the next free charging station on their own. So, the restraint for the user to park at certain spots, where charging facilities exists, disappears. The communicating AV, can get the information of the next free charging facility and park there autonomously.

Even if the electrification will not be the main engine, technologies like hydrogen storage systems and fuel cells could be supported by autonomous sharing concepts. New technologies are often more expensive and have certain restrictions (travel range, certain charging facilities, etc.). In areas, where fleets of shared vehicles are implemented, these restrictions could be provided easier than for one private vehicle, that operates in an unlimited area. In terms of costs, the utilization of a shared vehicle is higher than of a private car, therefore, the utilization-cost ratio for a shared vehicle could result in being more feasible.

Moreover, AVs are predicted to use less fuel than today's manual cars. Higher technological standards and further development over the next years are expected to increase the energy efficiency. In addition to that, AVs are expected to use less energy due to a different way of driving, that is more far-sighted and constant than human drivers.

The AVs could also carry one specific advantage with them, as Bagloee describes as the following: "From a completely different perspective, the increased level of safety of AVs may lead to lightweight vehicles from car manufacturers. In fact, safety efforts are being directed towards accident avoidance and away from old-fashioned crashworthiness cars. Therefore, light vehicles are promising by-products of AV technology which in turn greatly contributes to less fuel consumption. For conventional vehicles, up to 20% of the weight is attributed to safety-related features. As an engineering rule-of-thumb, a 10-percent reduction in weight can lead to a 6- to 7-percent reduction in fuel consumption" (Bagloee et al., 2016, p. 290).

- Risks: If autonomous vehicles induce additional traffic, the environmental consequences could tighten. Even if the engine technology develops positive, the energy (fuel, electricity, etc.) is still required and has negative environmental results. More traffic could lead to busier streets, shorter life-cycle duration of roads as well as noise and air pollution, depending on the used engine technology.

2.5.7 Modes of Autonomous Transportation

Private (Not-Shared) AVs

The first type of AVs is the privately owned autonomous vehicle by one person or household. Due to this feature, the mode of transportation is called "Private AV" or "AV-NS" as Friedrich & Hartl defined it. "NS" stands for "No-Sharing". This type of vehicles is only used by this limited number of people in the household and is not shared with other people. Unlike Friedrich & Hartl, who assumed in their study, that these vehicles will not take unoccupied (u.o.) vehicle relocations, in this thesis unoccupied vehicle trips are taken into considerations due to the following ideas:

First, if the vehicle is owned by a household of more than one person, it is possible, that each user has different destinations. In terms of serving each person's demand, the vehicle needs to relocate unoccupied back to the origin of the other household members trip.

For example (A), a vehicle is used by one family with two children. The father has to get to work with the private AV in the north of the city while the children have to get to school in the south of *the city one hour later. The AV brings him to his workplace, moves back to the home of the family unoccupied, picks up the children and drop them off at school.*

Second, the drop off location of the user by an AV will be different from the parking location (valet parking). Therefore, the AV will relocate unoccupied. The advantage for the user is the reduction of travel time for searching a free parking lot as well as a closer drop off location to the destination. Some opinions fear, that some people will let their AV drive within a certain range instead of letting their AV park somewhere (and probably pay for parking), while they short errands.

The second example (B), is the availability of parking space in dense urban area. Assuming the car owner wants to drop off in the city center, where only few parking lots are available and expensive. It seems more likely, that the AV finds a cheaper or better parking option within a reasonable range.

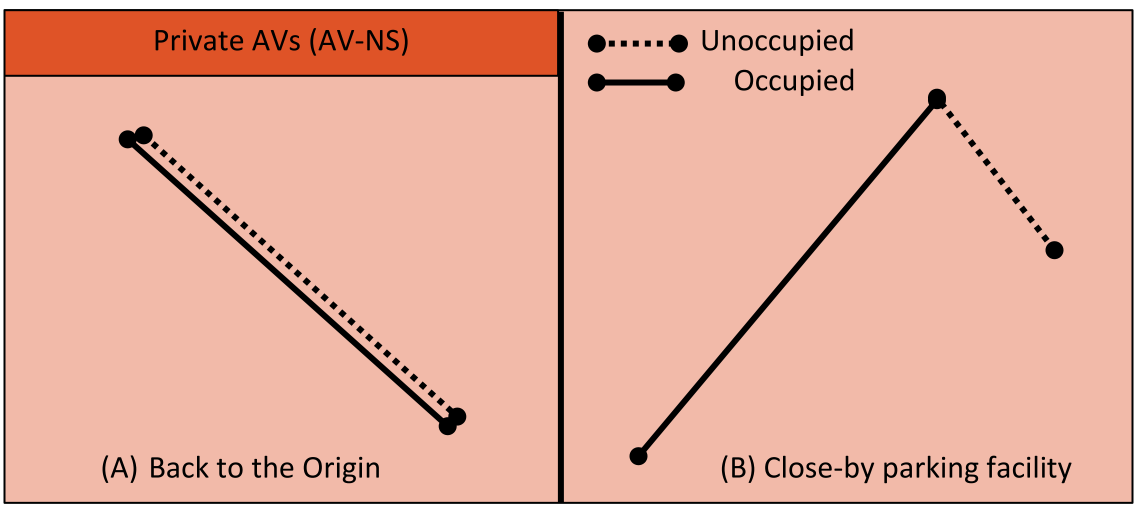


Figure 8: Illustration – Trip Occupancy of Private AVs

In the calculation of the scenarios, these effects of unoccupied vehicle relocations will be represented by a certain increasing factor p_{unocc}. In case (A) the traveled distance would double, while in case (B) the increase depends on various number of factors, which could include number of available parking lots within a certain range, parking fees, trip lengths, urban density and vehicle intern algorithms, which search for parking space and evaluate reasonable options.

- Chances: Obviously these AV-NS will increase the comfort of traveling, the use of travel time, as already mentioned, and all the other chances that were mentioned in this section.
- Risks: The AV-NS will likely be a driving force to increase traffic on the road by enabling more persons to use this form of mobility and by increasing the comfort it leads to lower obstacles to choose this mode of transportation.

Car Sharing with AVs

The second type of autonomous vehicles are autonomous Car Sharing vehicles (AV-CS). Friedrich & Hartl characterize them as “public AVs in a mode of private use” (Friedrich & Hartl, 2016). These vehicles are part of a Car Sharing fleet and can serve different users in sequence. In comparison to the private AVs, the Car Sharing vehicles are normally owned by a Car Sharing company and not owned by one private person (except the following example of the GETAWAY idea). Car Share services are already available with conventional cars. Besides the commercial CS services like StadtMobil, Car2Go, DriveNow or Flinkster, a few new Start-ups like GETAWAY are pushing the trend of shared mobility. GETAWAY for example, offers car owners to rent out their car in times they do not use. By implementing technical equipment (cost: €199, www.get-a-way.com) to open the car for other users as well as some safety and tracking features, the car is ready to be shared. Similar to conventional vehicles, AVs could more likely act as a shared vehicle, either by private car owners or by commercial Car Sharing services.

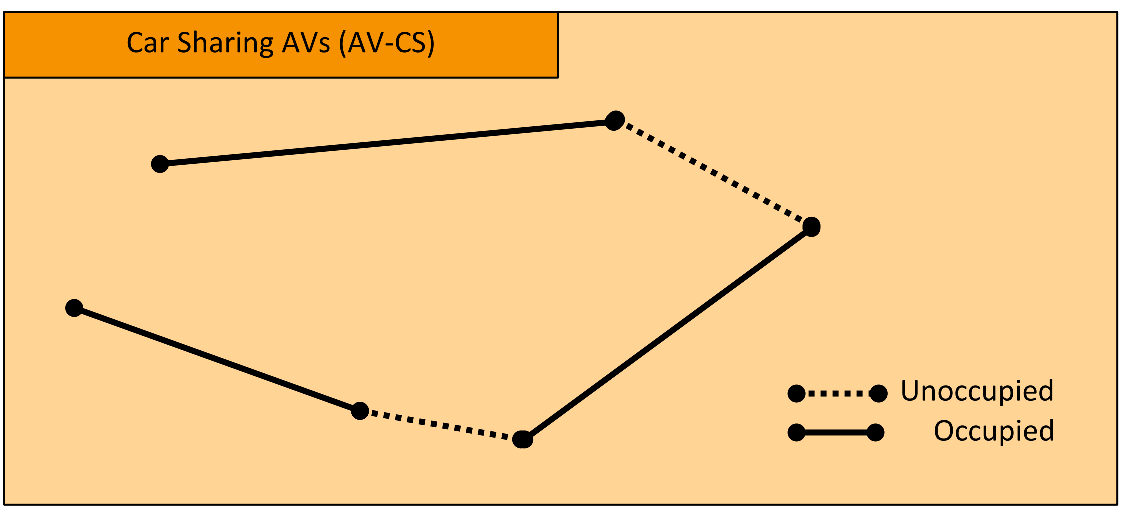


Figure 9: Illustration – Trip Occupancy of Car Share AVs

- Chances: The number of Car Sharing users in Germany increased rapidly. The registration number at the beginning of 2017 hit the number of 1.715 million. In comparison, in 2012 only 262,000 persons were registered. The development of AVs could boost this mobility form of Car Sharing. By sharing a vehicle, one AV-CS could replace a certain number of private vehicles. Various replacement ratios are mentioned in studies. A report of the City of Bremen, Germany, found a replacement rate of eleven private cars (Freie Hansestadt Bremen, 2012). In a study in Cologne, a replacement ratio of up to 18 private cars by one shared vehicle (Berger, 2016). This ratio carries enormous potential for new land use of parking space.
- Risks: The AV-CS has similar to the AV-NS a certain amount of unoccupied vehicle relocation, which is most likely depending on the demand of users, the location of the demanding user and the number of vehicles in the Car Sharing fleet as well as their location. In the best case, the location of the AV-CS is close to the next demanding user, to keep the unoccupied trip distance short. In the worst case, the Car Sharing fleet is not used a lot, AV-CS will probably cause additional trip distance and park often. A negative case could also be caused within the rush hour in one direction, which leads to the effect, that the AV-CS have to travel back unoccupied to the origin of the traffic, to serve more users. In the scope of a city, that effect might be neglectable but maybe noticeable in events like a football game or a concert. The demand on one hotspot could bring the system out of balance and increase the unoccupied traveled distance. Furthermore, the efficiency regarding the occupancy rate of Car Sharing vehicles, does not get improved compared to the AV-NS. It serves one user after the other.

Ride Sharing with AVs

The third type of AVs, are the so called autonomous Ride Share vehicles (AV-RS). Similar to the AV-CS, the AV-RS is normally owned by a Ride Share service (analog to Car Share service), but instead of serving users in sequence, the AV-RS serves multiple users within one trip. The principle is, to collect users, who want to travel in the same direction, and drop them off at their individual destination. So, autonomous RS vehicles are open to share on each trip for the whole community.

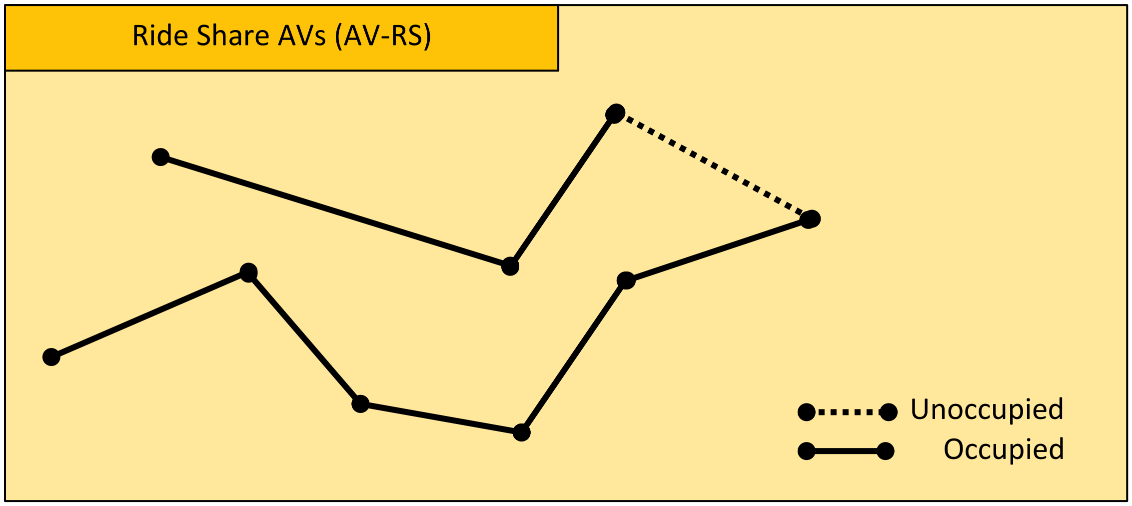


Figure 10: Illustration – Trip Occupancy of Ride Share AVs

Today, occupancy rates of current vehicles are often low. Consequently, the efficiency of one person per vehicle is low. In Canada, for instance, authorities tried measures as high-occupancy lanes or peak-period pricing to support Car Pooling and Ride Sharing. Different services already are available today to share rides, in Germany for example BlablaCar, or Websites such as www.mitfahrgelegenheiten.de, which are mostly used for long distance trips. A start-up called CleverShuttle builds up a Ride Share community in a few German cities like Berlin, Munich, Hamburg (beta test) and Dresden, for example. They state, that they can provide a trip per person for half the price of a conventional taxi. At the moment, the service is only available during certain service times, mostly afternoon until night. In Canada, the most popular one is probably UberPool, which is much more flexible than German services.

- Chances: The AVs could change that issue, by supporting Ride Sharing in a different way. The willingness of doing Ride Share though depends on persons individual behaviour. A survey of the Boston Consulting Group shows, that male respondents (37%) are more likely to do Ride Share than female ones (33%). Moreover, the generation under 30 are more open (45%) to use Ride Share than the generation over 50 years old (22%). Another point, that affects the behaviour in terms of Ride Share is the price. The survey shows significant increase of Ride Share, as soon as the price gets cheaper than a conventional Taxi ride (Lang et al., 2016).

Due to the pick-up of different users along the route during the collection process, the trip distance of each person might increase, but compared to not shared vehicles the vehicle trip distance can be reduced because only one vehicle serves the demand of a few persons.

The occupancy rate of autonomous Ride Share vehicles is more likely to be higher than conventional vehicles, which makes the mode of transportation more efficient. As Friedrich & Hartl suggest, these autonomous Ride Share vehicles could be specified to the needs of the user demand. That could lead to more seats, more space for more privacy in the vehicle while sharing it with strangers and adding more space for luggage. Continuing this process of development, the AV-RS act as public transportation service.

- Risks: Low demand on Ride Share services could increase the number of unoccupied trips as well as larger trip distances. If fewer people demand an AV-RS, the pick-up locations are more likely to be farther away from each other, so the resulting route to collect users gets longer. Also, unoccupied trips are more likely to get longer due to the higher distribution of users. Finally, the average occupancy rate of the vehicles decreases compared to high-demanded RS. The demand on RS depends on the willingness to share a ride, subjective safety, reduction of independence and privacy during the ride. The risk of RS are these factors, that are uncertain to predict.
  Furthermore, the attractiveness of Ride Share could cause decreases of public transit and active transportation. That would lead to higher traffic on the roads, caused by a travel demand, that is nowadays handled more efficient.

2.5.8 Public Transit

- Chances: Private or shared AVs could lead to extend the availability of the public transit. The AVs are able to fill the gaps in the network of public transit and connect low dense areas with important hot spots, where it is not feasible to implement an additional bus line. Public transit services could optimize their network in low dense areas by providing autonomous buses, which act like an on-demand service (and act like a Ride Share service). These bus routes are more likely dynamic, flexible and optimized on user demand. The user demand can be served 24 hours and include door-to-door connections.

Sieg concludes, that automated “collecting and feeder vehicles” could be part of the public transit services (Sieg, 2017), and therefore extend the available area of public transit. This idea is often called the “last mile” or “first mile” principle. It means, that the “last mile” (or “first mile”) of a trip taken by public transit often has the issue, that the destination can not be reached directly with public transit. Therefore, the last mile has to be fulfilled with another mode of transportation. AVs could solve that last mile issue. Especially in dense areas, the high-performance bus, subway or streetcar lines could gain attraction, if the change of the feeder vehicle to the high-performance network is optimized. These intermodal changes must be no obstacle for users, otherwise it leads to a loss of attraction. Another chance of AVs in the field of public transit is to support the necessarily conversion of the public transit fleet to electrified buses and vehicles to handle the noise and emission issues in cities. Besides that, the cost of a driver can be reduced if “Level 5” is reached (Sieg, 2017). In the European average, driver personal costs in public transit in regular service are around 56 % of the total costs (Ieperen & Braun in (Sieg, 2017)).

- Risks: The AVs could, instead of being a supplement to public transit, be an adversary. A research, based on the simulation of the implementing autonomous car sharing vehicles, shows that the use of public transit could be reduced drastically while the general traveled distance increases (Bienzeisler, 2017, p. 70). Moreover, the financial support for public transit could be not feasible anymore; maintenance and operations costs exceed utility. Consequently, tickets for public transit has to get more expensive or public authorities have to invest more into sustain public transit. In addition to that, the competition on public mobility will have new players involved as for example new Ride Share and Car Share services, development companies and the car manufactures (Sieg, 2017), which probably change their concept from “production to sale” to “production and share” as for example Mercedes & Bosch with their idea of an enhancement of Car2Go. The multi-modal (combination of different transport modes within one trip) travel behaviour, which is typical for public transit, will evolve into a single modal choice – the AV. Public transit could be more uncomfortable, due to the change of buses or trains, and more expensive than an on-demand autonomous car/ride sharing fleet.

The changing of trains or intermodal change from bus to streetcar, for instance, is causing additional waiting time and reduction of comfort. Due to that fact, trips with public transit, that require a change of trains or a change to other public transit vehicles reduce percentages of the modal share (Friedrich & Hartl, 2016). By analyzing the omniphon data, around 8.8 % of the trips, taken by public transit, require more than one change of vehicle. Exactly one change is required in 32.4% of the cases. These trips could in the future be more likely to switch towards automated vehicles, if the public transit does not include Ride Share services.

As a result, the role of the public transit has to be thought over and renewed.

To sum up, all these risks and chances of AVs will affect travel behaviour as well as travel demand. Consequently, the change will challenge the fields of traffic planning and operations. This leads to the question, how is it possible to predict potential outcomes? The following chapter elaborates the methodology used in this thesis to explore the impacts of autonomous vehicles.

3. METHODOLOGY AND DATABASE

3.1 SCENARIO TECHNIQUE

In different fields of research, the scenario technique is a sophisticated option to quantify outcomes of uncertain developments in the future. Due to expected wide range changes in mobility behaviour of individuals by implementing autonomous vehicles in our current infrastructure, the scenario technique is a tool to research impacts on future traffic.

Different from former attempts to model specific and precise future prediction, the aim today is more focused on plausible pathways for future developments with their key influencing parameters. Besides the key parameters, the interdependencies of them are often explored and topic of research within the field of future prediction. The plausible pathways, that describe a complex future development influenced by different parameters are called "scenarios". Because of the definition, a scenario is plausible to happen, but it is not necessarily going to happen. Today's state-of-the-art in future research follows the idea of generating plausible scenarios instead of trying to find one precise prediction (Gausemeier, Fink & Schlake, 1995 qtd. in (Trommer et al., 2016, p. 5)).

A common method to illustrate the scenario technique is the "Cone of Plausibility". Charles W. Taylor, who researched strategic vision in military application, stated, that "the Cone offers a logical way to trace the consequences of dynamic trends and events through the passage of time enabling the future leaders to create strategic visions or planning scenarios" (Taylor, 1990).

The Foresight Horizon Scanning Centre defined four principles for using the scenario technique. First of all, the scenarios have to be based on data analysis. In the case of this thesis, the survey data of omniphon serves as foundation. Second, scenarios have to be plausible. Third, scenarios must be internally consistent, which will be considered in this thesis by having the same calculation process in each scenario. Fourth, scenarios are engaging and compelling (Foresight Horizon Scanning Centre, Government Office for Science, 2009).

"The 'cone of plausibility' method offers a more deterministic model of the way in which drivers lead to outcomes, by explicitly listing assumptions and how these might change. […] This approach is most suitable for shorter-term time horizons (e.g. a few months to 2-3 years), but can be used to explore longer-term time horizons. It also suits contexts with a limited number of important drivers" (Foresight Horizon Scanning Centre, Government Office for Science, 2009). Followed from that statement, the methodology to develop long-term scenarios for the impact of AVs on traffic is possible. The "listed assumptions" and their changes, caused by AVs, will be elaborated in chapter 4.

The idea of the "Cone of plausibility" is illustrated in the following figure.

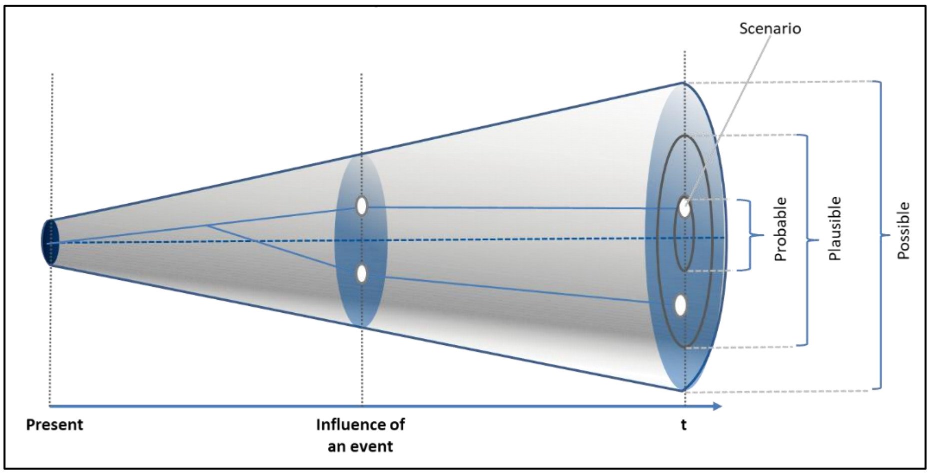


Figure 11: Cone of plausibility - Illustration based on (Kromkamp, 2009)

Based on the data analysis, the current state and trends can be determined at the point of "present". If no trend changes, the baseline scenario, which is often projection forward of the current situation, will result in a "probable" area. This means, that the outcome of this scenario is likely to happen. An alternative scenario, which might be affected by upcoming trends or new developments (e.g. new technologies), could result in the "plausible" area. A future scenario in this area could happen based on the knowledge of the present. The area of possible outcomes, can not exactly be foresight at current knowledge. These outcomes depend basically on future knowledge. For example, an unpredictable event changes the whole situation, based on that event, new parameters influence the pathways and possibly lead to other new unpredictable events. So possible outcomes "might" happen, based on future knowledge.

In this thesis, three scenarios for the impact on traffic by autonomous vehicles will be developed: A baseline scenario, an ideal (best-case) scenario and a worst-case scenario.

3.2 OMNIPHON SURVEY 2012

As already mentioned, the omniphon survey is a household-based survey focusing on the mobility behaviour of inhabitants of the City of Karlsruhe and surrounding area. The City of Karlsruhe commissioned the “omniphon GmbH” to conduct the survey in 2012.

The survey exists of four parts: household related questions, person related questions, additional questions and trip related questions. In the framework of the thesis, the person and trip related information carries the key information for further calculations.

The first part, collects data about the number of persons in the household, number of cars, Car Sharing memberships, location of the household, parking facilities and public transit stations close-by as well as the income of the household.

The second part, gathers personal information such as gender, age, education, employment status, ownership of a driver license, frequency of car use as driver or fellow passenger as well as bicycle and public transit use, parking situations and personal disabilities.

The third part, mostly focuses on area specific questions due to new mobility services, as for instance E-bike services, on-demand-ride-share taxis, or general changes in the mobility behaviour.

In the fourth part, information of each trip is ascertained. Information about the reasons, why a person did not leave the house, the number of trips on the observed day, the time of the trip’s start and end, the used modes of transportation for the trip as well as related information to the specific mode of transportation, the trip purpose, the origin and destination of the trip are collected.

The following sections describe the methodology, that is used to analyze the data of the questionnaire.

3.3 DEFINITION OF TRIP CHARACTERISTICS

The subjects of the analysis are trip patterns. In order to construct trip patterns, each of the single trips has to be analyzed. Therefore, it is necessary to define a trip with all its characteristics.

A trip is defined by its origin and its destination, and further by its distance between origin and destination. In the omniphon survey, the distance is provided, calculated by a route choice software. In cases of round trips, in which the destination is also the origin, the trip distance is not possible to determine. Furthermore, these trips were not asked for within the survey. Examples for round trips could be walking the dog, going to run, or sport cycling.

For the further procedure, the origin and destination are classified in purposes, which allows to specify the trip. For each origin-destination pair (depending on the purposes), an average distance can be analyzed. This average distance is calculated dependent on the group of persons and the area as well as the mode of transportation. Similar, for each origin-destination-pair, an average modal split is analyzed depending on the group of persons and the area. The modal split shows the distribution of the defined modes of transportation for that specific trip purpose pair.

The concatenation of several trips (origin-destination-pairs) for one specific person results in a trip pattern (see also in section 3.5.5). The survey is collecting trip data of a few specific chosen days. Therefore, a trip pattern of a person is representing the mobility of one respondent on one specific day.

In section 3.5, the characteristics of the trip data is further categorized regarding the preparation of the data set for calculating the scenarios.

3.4 PROCEDURE OF PREPARATION AND ANALYSIS

First of all, the survey data has to be prepared before analyzing it further. Therefore, the areas in the scope have to be filtered, trip purposes have to be defined, trip patterns of each person during the day are shaped, the primary transportation mode of each trip needs to be elaborated and person features have to be categorized into certain groups of persons.

The second part is to analyze the data in the scope. The number of respondents of each area, percentages of respondents in the groups of persons and modal splits in the different areas are reviewed.

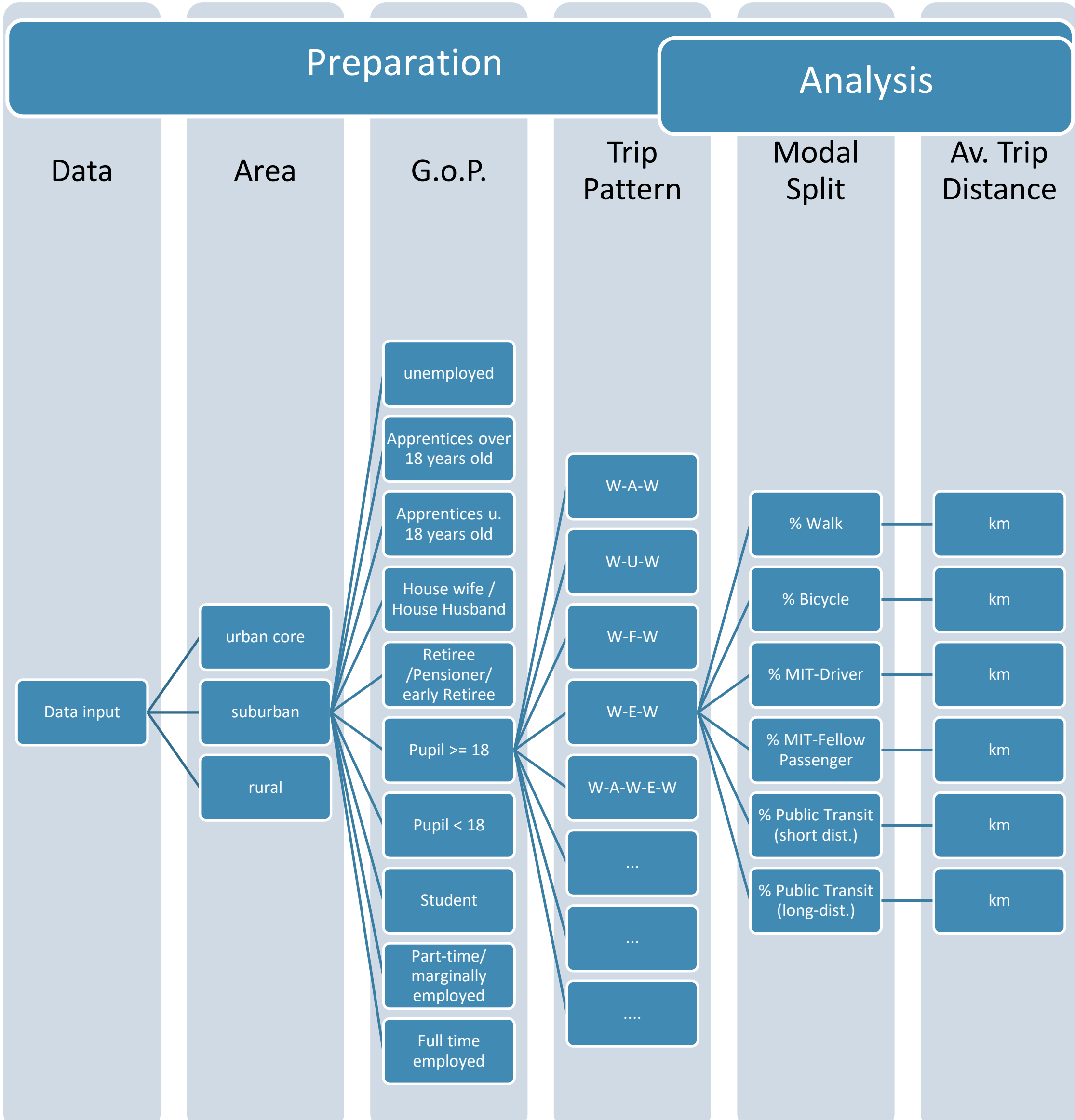


Figure 12: Methodology – Preparation and Analysis Process for Baseline Scenario

As shown in Figure 12, for each group of persons (Column 3) and each area (Column 2), the most common trip patterns (max. 10, Column 4) are collected. Each trip pattern gets separated in its single trips again. The modal split (Column 5) as well as the average trip distances (Column 6) for each mode of transportation are obtained from the survey data as the average trip data for the specific trip purpose of the group of persons in this area. The longest of the common trip patterns in the scenario development is a pattern of nine single trips. Based on the structure of the maximum ten most common trip patterns, the scenarios are calculated and modified as shown in section 3.7.

3.5 PREPARATION OF THE SURVEY DATA

The chosen tool to analyze the data is Microsoft Excel. Most tasks are solved with VBA (Visual Basic for Applications) coding in combination with pivot tables. The algorithms are not described in detail.

3.5.1 Types of Trip Purposes

First of all, the purposes of trips are categorized. Different optional answers of the survey are taken together. For example, "Recreational" includes trips to sport facilities, special events like concerts or similar things, cultural activities, private visits, restaurants, rest & relaxation and others. "Education" involves trips to primary schools, secondary schools and other educational facilities.

The following table shows the categories of the trip purposes, which are used in this thesis.

Table 2: Definition of Trip Purposes

Purpose of the trip	**Short form**	**German term**
Home	W	Wohnen
Employment/Work	A	Arbeiten
Education	U	Bildung / Ausbildung
Shopping	E	Einkaufen
Recreational	F	Freizeit
Pick up/ Drop off	H	Holen / Bringen
Private errands	P	Private Erledigungen

3.5.2 Categories of Modes of Transportation

The survey offers ten different options for the mode of transportation and allows the respondent to combine different modes for each trip. To analyze the mode choice, the ten options can be categorized in groups and the combinations have to be simplified to one primary transport mode.

To declare one mode of transportation as the primary one, the highest rank mode is used. So, in other words, if a respondent used a combination of transportation modes, the highest ranked mode is chosen as primary mode.

Because the real proportion of each mode on the trip is unknown, the mode that normally has the larger travel distance or travel time is considered as a higher rank mode.

For instance, it is unlikely, that in a combination of walking, public transit and car as a fellow passenger, walking is the primary mode of transport. In that case, the public transit is the highest rank mode, so, that would be the chosen primary mode. In real conditions, the drive with the car might be a larger proportion of the trip and consequently would be the primary mode, but due to the lack of that knowledge, the mode choice has to be declared after a certain pattern.

The following table shows the declaration of the categories as well as the ranking (the last category has the highest ranking, the first the lowest ranking):

Table 3: Declaration of the Primary Mode of Transportation (Omniphon GmbH, 2012)

Choice of transport mode on the trip	**Category (Primary mode)**
Only by foot	Walk
Bicycle and no higher-ranking mode	Bicycle
Motorcycle or scooter and no higher-ranking mode	Motorized individual traffic as driver
Car (as driver) and no higher-ranking mode	
Car-Sharing and no higher-ranking mode	
Car (as fellow passenger) and no higher-ranking mode	Motorized individual traffic as fellow passenger
Public Transit as bus, street cars, taxis, local trains	Public Transit (short-distance)
Public Transit (long-distance)	Public Transit (long-distance)
Airplane, Ships, others	Others

To provide the most common mode combinations and their categorization into the primary transport mode, as an example, the following figure shows the combinations in rows, and the number of trips with this combination. The column shows the classification of the primary mode, which was selected by the “ranking”-algorithm. Out of that data, it is noticeable, that the largest amount of trips is done single-modal, which means using only one mode of transportation. The columns are ordered from the left as "walking", "cycling", "Car as driver", "Car as fellow passenger" and "public transit".

Zeilenbeschriftungen	Fuß	Rad	MIV als Fahrer	MIV als Mitfahrer	ÖPNV	ÖV	Gesamtergebnis
PKW Fahrer			3278				3278
Fuß	2492						2492
Rad		2048					2048
PKW Mitfahrer				1323			1323
Fuß - Straßen/Stadtbahn					413		413
Straßen/Stadtbahn					271		271
Fuß - Bus - Straßen/Stadtbahn					134		134
Fuß - Bus					119		119
Bus - Straßen/Stadtbahn					98		98
Fuß - PKW Fahrer			90				90
Bus					81		81
Fuß - Regionalbahn/S-Bahn					52		52
Roller/Motorrad			47				47
Fuß - PKW Mitfahrer				44			44
Fuß - Rad		44					44
Regionalbahn/S-Bahn					30		30
Carsharing			25				25
Fuß - Straßen/Stadtbahn - Regionalbahn/S-Bahn					22		22
Fuß - Bus - Regionalbahn/S-Bahn					16		16
Fuß - Bus - Straßen/Stadtbahn - Regionalbahn/S-Bahn					14		14
Bus - Regionalbahn/S-Bahn					13		13
Fuß - Rad - Straßen/Stadtbahn					11		11
Rad - Straßen/Stadtbahn					11		11

Figure 13: Example: Definition of the primary mode out of multi-modal trips

3.5.3 Definition of Areas

The thesis concentrates on the survey areas of Karlsruhe urban core (Karlsruhe II), Karlsruhe suburban circle (Karlsruhe III) and "rural" area (Karlsruhe I). The omniphon survey defines the areas as the following districts (also shown in Figure 1 on p.5):

Table 4: Definition of the Areas by (Omniphon GmbH, 2012)

Area	**Districts of the City / Villages**
Karlsruhe I: Rural area	Hohenwettersbach, Grünwettersbach, Palmbach, Stupferich, Bergwald
Karlsruhe II: Urban core	Nordstadt, Weststadt, Südweststadt, Südstadt, Oststadt, Innenstadt West, Innenstadt Ost
Karlsruhe III: Suburban circle	Nordweststadt, Mühlburg, Daxlanden, Knielingen, Grünwinkel, Oberreut, Beiertheim-Bulach, Weiherfeld-Dammerstock, Rüppurr, Waldstadt, Rintheim, Hagsfeld, Durlach (ohne Bergwald), Grötzingen, Wolfartsweier, Neureut

3.5.4 Classification of Groups of Persons

The survey delivers the occupation status of the respondents in different options. From twelve categories of the omniphon survey, ten new groups were formed (Table 5). Some groups of persons (g.o.p.) can be put together, because their trip patterns and travel behaviour are expected to be similar. So, the g.o.p. of *unemployed* and *temporarily exempted from employment* are combined as one. The same is done to the *apprentices* and all *voluntary services* as well as the *pupils* and *preschool children*. In the case of *pupils* and *apprentices*, it makes sense to distinguish by age. The driving age of 18 years could have an impact on the mode choice and consequently on the travel behaviour. Following from that, these groups are divided in two age-dependent groups.

Table 5: Declaration of Groups of Persons

Group of persons after omniphon	**New group of persons**
unemployed	unemployed
Temporarily exempted from employment	
Apprentices/ Retrainee	Apprentices >= 18 years old Apprentices < 18 years old
Voluntary Military service/ Voluntary Civil Service/ voluntary social year	
House wife / House Husband	House wife / House Husband
Retiree /Pensioner/ early Retiree	Retiree /Pensioner/ early Retiree
Pupil	Pupil >= 18 Pupil < 18
Preschool child	
Student (University)	Student
Part-time/ marginally employed	Part-time/ marginally employed
Full time employed	Full time employed
other	

The group of "*other*" are taken out of considerations. Its proportion, as later analysis shows, is less than 2% of respondents in the scope and it is difficult to find common patterns as well as finding a number of "others" if its undefined.

3.5.5 Definition of Trip Patterns

For further calculation, the trip pattern of each person is needed. In the literature are various definition and terms for trip patterns. As Thill & Thomas relate, the trip pattern can either be seen as a "geographical construct for the definition of the multistage journey: a journey consists of a series of movements made between successive destination choices over some period of time", which they based on the definition of Lenntorp (1976). They further elaborate, that "it is a trip-sequencing of activities. This concept comprises complex relations and interdependence of timing, duration, location, frequency and sequencing of activities, nature and number of stops, and trip length" (Thill & Thomas, 1987). Compared to the concept of trip pattern, trip chaining is defined by McGuckin & Nakamoto as follows: "A trip chain is a sequence of trips linked together between two anchor destinations" (McGuckin & Nakamoto, 2005, p. 50). For this thesis, the term "trip pattern" is defined as Thill & Thomas define it but in a simpler way. It is a multistage journey of activities (trip purposes) of one person over some period of time (in this case: the target day of the survey. The following example should clarify the concept of a trip pattern:

> *To illustrate this, imaging that a mother of a five-year-old child works part-time. She brings the child to preschool in the morning, then goes to her job. After lunch, she goes grocery shopping, picks up her child and goes back home. In the afternoon, she spends some time with the child outside at a public swimming pool, before she gets home in the evening. The trip pattern of the mother and the child results like the following: Mother: W-H-A-E-H-W-F-W ; Child: W-H-W-F-W*

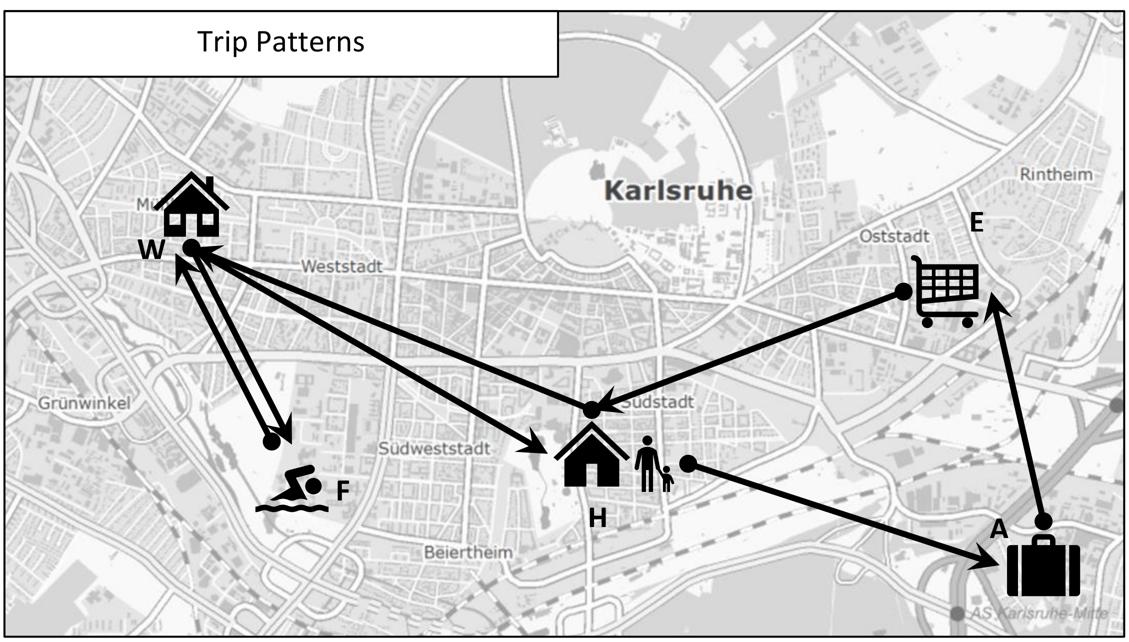


Figure 14: Illustration of Trip Patterns (map based on www.geodaten.karlsruhe.de/stadtplan)

For the child in the example, the purpose of the trip to preschool, might be not exactly classified – better would it be to classify the purpose to "Education" – but for regarding the potential of

AVs in pick-up and drop-off trips, it is a defensible classification as an "H-trip". For the mother, the trips to preschool are the purpose of actively transporting the child to the destination. The child, on the other hand, is the person transported and consequently passively transported. This difference will later play an important role in the modification process of the trip patterns.

3.5.6 Weighting Factors by omniphon

Statistical weighting factors (household correction, person correction and trip correction factors), which are given in the survey, are not taken into considerations. This thesis only uses the raw data from the survey. Moreover, the omniphon survey used the given distances with the given travel time to calculate the velocity of the persons. The calculated velocity is used to check the plausibility of the answers given by the respondents. This plausibility check is neglected within the frame of this thesis.

3.6 ANALYSIS OF THE SURVEY DATA

3.6.1 Differentiation of Areas

The first regarded layer of analysis, is the area of conducted households (urban, suburban, "rural"). The "rural" area is still close to the City of Karlsruhe, and may can not be compared to actual rural areas, but in comparison to the other areas in the scope of this thesis, it can be defined as rural. Other than expected, the suburban and the urban core distinguish clearly in their mobility behaviour. This is found by comparing the average modal splits and trip distances for the areas. Hence, the further calculations will regard them separately, because the results in each area distinguishes of each other.

3.6.2 Representation of Groups of Persons

Viewing on the survey data in the three areas in combination with the groups of persons, some groups are low represented by respondents. The following figure and table shows the number of respondents in each area in the scope.

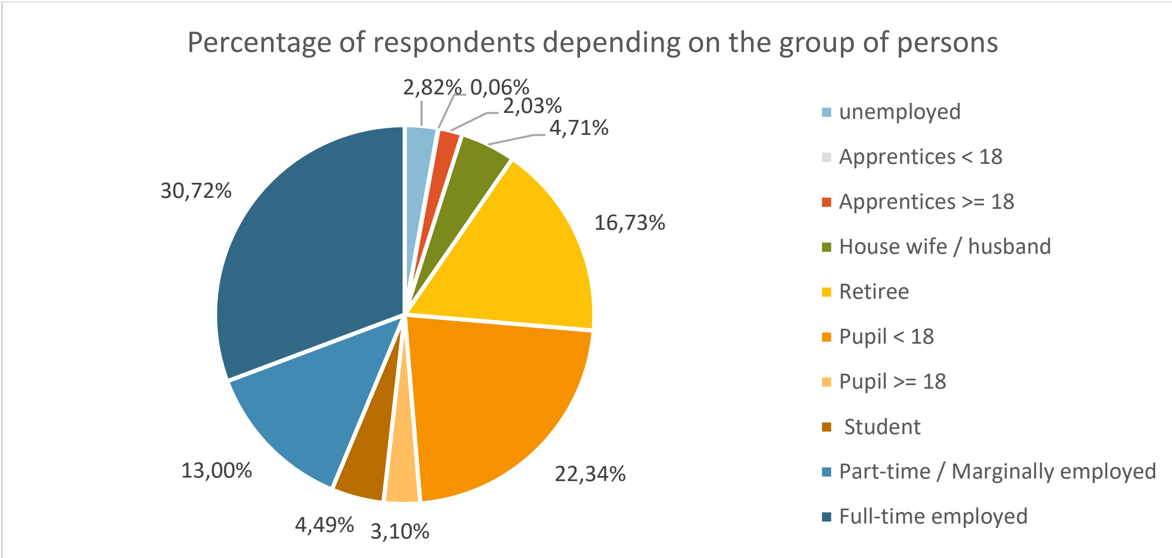


Figure 15: Percentage of Respondents depending on the Group of Persons

Table 6: Number of Respondents categorized in Groups of Persons

Group of persons	**Karlsruhe I**	**Karlsruhe II**	**Karlsruhe III**	**total**	
unemployed	35	21	44	100	2.82%
Apprentices < 18	-	-	2	2	0.06%
Apprentices >= 18	21	18	33	72	2.03%
House wife / husband	37	42	88	167	4.71%
Retiree	168	126	299	593	16.73%
Pupil < 18	233	200	359	792	22.34%
Pupil >= 18	34	14	62	110	3.10%
Student	31	65	63	159	4.49%
Part-time / Marginally employed	147	107	207	461	13.00%
Full-time employed	304	285	500	1089	30.72%
total	1010	878	1657	3545	100.00%

As seen in the table, the group of *apprentices under the age of 18* are underrepresented. Therefore, they will be put together with the *apprentices of the age 18+*. The four biggest groups *full time employed, pupils under 18, retirees* and *part-time/marginally employed* can be considered as well represented. To visualize the previous table, the Figure 15 shows the percentages of each group of persons.

3.6.3 Representation of Trip Pattern

In fact, trip patterns of each person can be different each day; but in general, persons of the same groups have often same patterns. So, regarding the trip patterns, a few patterns can often represent 75% of trips generated by that one group of persons. In some cases, it is not possible to reach 75% of trips without conducting numerous patterns. So, to keep the calculations lucid, the number of patterns per group is limited to ten. In Appendix 6, the covered amount of trip patterns per group of persons is listed and aggregated.

3.6.4 Data Availability of the Average Trip Distance

For the calculation of the scenarios, the mode choice probably shifts towards another mode of transportation. Due to the lack of given data, for some trip purposes and groups of persons in certain research areas, it does not exist an average trip distance for a certain mode of transportation. If the mode choice shifts to a mode, for which no average trip distance exists, the calculation of the traveled distance would result in none traveled kilometers.

To fix that error, the average trip distance for each trip purpose of every group of persons and area has to be provided for calculating the scenarios. The following procedure is done to fill the missing distance data. In the first step, all existing trip purposes and the given average trip distances (depending on area and group of persons) are listed. Within that step, the missing data is marked. In the second step, the modes of “MIT as driver” and “MIT as fellow passenger” are filled by the equivalent average trip distance, if only one of both is missing. In the third step, all other modes of transportation, and if both MIT modes have no average trip distance given, the average value for each mode over the whole area is inserted. Consequently, each trip purpose of each group of persons in each area has an average trip distance in order to calculate the future scenarios.

3.7 METHODOLOGY FOR THE MODIFICATION AND CALCULATION PROCESS

After the preparation and analysis, the factors that represent the impact of AVs on the overall traveled distance must be identified. Different assumptions allow modifying developments into different scenarios. First of all, the same construction for the calculation of the traveled distance is built up. The baseline Scenario is calculated, to serve as a comparable scenario without AVs. It is only affected by the changes in population.

Based on this scenario, the effects of the implementation of AVs are developed as a best-case and a worst-case Scenario. The way how the modifications for the scenarios are implemented in the calculation are explained in section 3.7.2. The following figure illustrates the methodology of the scenario development. The green fields will be affected by modification to represent mobility changes due to AVs.

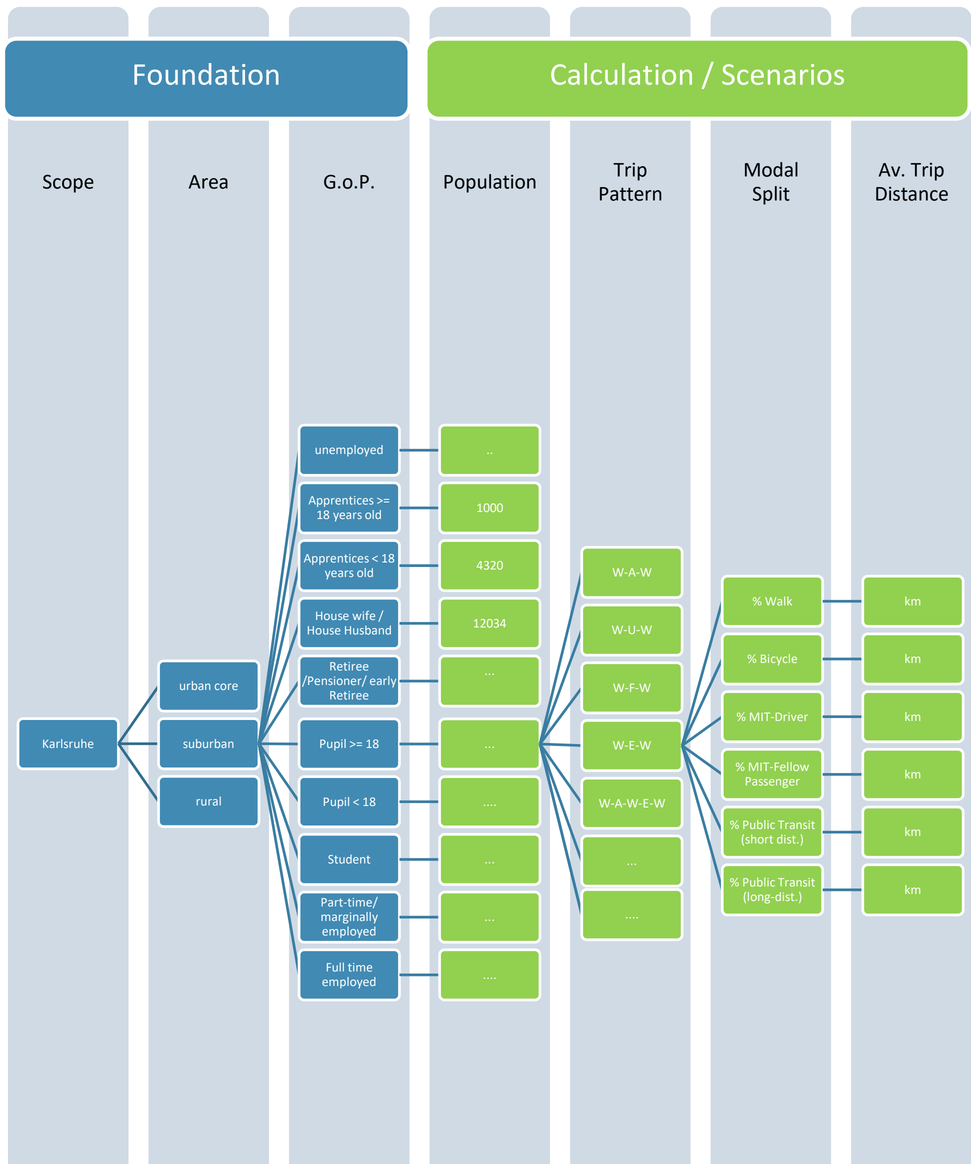


Figure 16: Illustration of Modification in the Methodology

In the calculation of the scenarios, the population of each group of persons depending on the area is multiplied with the proportion of each (max. 10) trip pattern of the group. This amount of people, who perform that trip pattern, are distributed by the modal split for each specific trip purpose of the trip pattern. Summing up all of that distribution of modal splits, an overall modal split depending on the trip proportions can be calculated for each trip pattern. By adding them up, the overall modal split for all represented person dependent on the trips can be formed.

To calculate the trip distances of each mode, the proportion of the population of each trip pattern has to be multiplied by modal split and the respective average travel distance of each trip in the trip pattern. The sum of the results delivers the total traveled distance for each mode of transportation and each trip pattern. By adding up all the distances of the trip patterns, an overall amount of traveled distance per mode can be defined.

To get information of the vehicle-traveled, person-traveled and unoccupied-traveled distances, the calculation for each type of traveled distance has to be calculated separately. This is possible by calculating different related, average traveled distance as described in section 3.7.2.3.

3.7.1 Development of Population Distribution Model

To calculate the predicted traveled kilometers, the population development for the future has to be considered. On that account, the population data for 2012 is needed as well as a prediction of the future development. Finding a source for actual matching population data to the developed groups of persons turns out to be more difficult than expected. Some information is provided by the City of Karlsruhe, which offers some statistical data of the population on its website. The data is available regarding each district of the city separately, which allows summing up the numbers for the three conducted areas (Stadt Karlsruhe, Amt für Stadtentwicklung - Statistikstelle, 2017b). For other cases, different sources are necessary to be combined in order to construct a population model including each group of persons.

For that reason, the distribution of groups of persons for the year of the survey (2012) has to be modelled. After that, the population's future development is modelled, based on the "dynamic scenario" of the population prediction of the City of Karlsruhe. This scenario is predicting the year of 2035 under the assumptions of fast development and growth with additional influx of people. In terms of traffic, this development could be seen as the more challenging scenario compared to the "mild scenario", presented in the report (Stadt Karlsruhe - Amt für Stadtentwicklung, 2016).

In fact, that it is unpredictable when the pure full-automated traffic will take place, the end of the population prediction at the year 2035 is neglectable. A further extrapolation of the prediction seems unrealistic. Therefore, it is assumed, that the population develops as the "dynamic" scenario until the year, when the pure full automated traffic will be reality.

The calculation of population distribution follows the steps below:

1. Collecting the total population of the scope for the year of the survey 2012 (Stadt Karlsruhe, Amt für Stadtentwicklung - Statistikstelle, 2017b), the begin of the "dynamic scenario" 2015 as well as the end of the "dynamic scenario" 2035 (Stadt Karlsruhe - Amt für Stadtentwicklung, 2016).
2. For the same years, the demographic distributions are extracted from the sources in the groups of age 0-17, 18-64, 65+.

Table 7: Population Distribution (demographic) for 2012, 2015 and 2035

Age	**2012**	**2015**	**2035**
65+	54,881	57,098	73,093
18-64	209,939	212,394	225,046
0-17	42,227	43,350	52,131
	307,041	**312,842**	**350,270**

3. The distribution of the population into three research areas is extracted from the statistic website of the City of Karlsruhe. The "rural" area, Karlsruhe I, has 3.9 % of the population, 36.01 % are located in Karlruhe II, the city core, and 60.09 % are located in the area Karlsruhe III (Stadt Karlsruhe, Amt für Stadtentwicklung - Statistikstelle, 2017b). This area related distribution is assumed to stay constant during the scenarios.
4. To distribute the demographic groups of the second step towards the defined groups of persons, an assumed "distribution key" used, which is firstly calculated on the year of 2015. The "distribution key" (Table 8) is a first approach to distribute the groups of persons. The following table shows the first distribution process for the whole scope.

Table 8: Population Distribution (demographic) into Groups of Persons (2015)

Age	Population	Distrib.	Groups of Persons	Population G.o.P.
65+	57,098	100%	Retiree	57,098
18-65	212,394	1.0%	Pupil >= 18	2,124
		1.5%	Apprentices >= 18	3,186
		4.0%	unemployed	8,496
		7.0%	Student	14,868
		7.2%	House wife / husband	15,292
		22.7%	Part-time / Marginally employed	48,171
		56.6%	Full-time employed	120,257
0-18	43,350	5.0%	Apprentices < 18	2,168
		95.0%	Pupil < 18	41,183

Calculated from that, the percentage of each group of persons on total population is determined. Each area is regarded separately. Information to certain groups are considered, for instance the amount of full-time employed and part-time employed person approaches the values of the given numbers in the Zensus 2011.

For the retirees, the statistical website of the City of Karlsruhe has only the number of people of the age of 65 and older. The assumption, that the group of persons *retirees* could set equal to 100% of the inhabitants of age of 65 and older will have a neglectable error. In the survey data, almost 93 % of persons of age 65 and older are in the group of retirees. In the group of under 65-year-old persons, only 3.7 % of the respondents are categorized as retirees (Appendix 3).

5. In Step 5, the previous distribution is adjusted for each area by comparing the given values for the retirees and unemployed persons from 2012 and the calculated values in 2015. Manual and iterative adjustments are done to elaborate area specific differences. The "growing factor" in between those two years are considered in the adjustment.
6. Following the groups of retirees and unemployed persons, the other groups of persons are adjusted. The adjustment incorporates the demographic development of Step 2, the number of apprentices compared to different sources (number of apprentices: 6445, Statistik-bw.de), the ratio of full-time (71.4%) and part-time (28.6%) employment and the fulfillment of the total population. The ratio of full-time and part-time employment is

derived from the total number of employees (37.1 million.) in Germany and the sum of part-time and marginally employees (10.6 million) (Statistisches Bundesamt, 2017).

7. Based on the year of 2015, the population for 2012 as well as for 2035 are developed similarly.

This distribution may not represent the reality but seems to be logical in itself. Due to certain simplifications in the whole calculation process, the error in the population model is neglectable. For the further calculations, the year of 2015, is not needed anymore. The population of 2035 serves as the base of the baseline scenario NO AV, the best-case scenario and the worst-case scenario. As a scenario of reference, the population of 2012 is used to calculate a baseline 2012 scenario, calculated with the raw data of the survey.

The calculated distribution of the population is shown in the following table.

Table 9: Results of the Population Model

		2012	2015	2035
KA I	unemployed	151	154	172
	Apprentices < 18	83	84	108
	Apprentices >= 18	299	305	260
	House wife / husband	588	648	726
	Retiree	2384	2355	3020
	Pupil < 18	1576	1606	1826
	Pupil >= 18	81	83	93
	Student	479	488	547
	Part-time / Marginally employed	1845	1904	2077
	Full-time employed	4492	4577	4837
KA II	unemployed	3400	3469	3885
	Apprentices < 18	995	1126	1261
	Apprentices >= 18	1128	1149	1286
	House wife / husband	5528	5643	5814
	Retiree	13676	13517	18729
	Pupil < 18	13378	13630	16194
	Pupil >= 18	995	1014	883
	Student	11045	11321	13243
	Part-time / Marginally employed	17910	18474	19170
	Full-time employed	42498	43301	45656
KA III	unemployed	4890	4982	5515
	Apprentices < 18	1476	1504	2568
	Apprentices >= 18	1882	1918	1642
	House wife / husband	6458	6580	7367
	Retiree	41460	41547	51358
	Pupil < 18	24724	25379	30099
	Pupil >= 18	1255	1278	526
	Student	8488	8591	9535
	Part-time / Marginally employed	27640	28161	28836
	Full-time employed	66239	68054	73038
		307041	**312842**	**350271**

For the three areas together, the following figure illustrates the development dependent on the groups of persons. The increase of the retiree's population seems to be certain by the demographic change. In contrast, the dynamic scenario also expects an increasing number of the population under 18-year-old, which leads especially to an increase of the pupils under 18. Due to school reforms, the number of pupils over 18 decreases a little. The two groups of apprentices are in later processes consolidated.

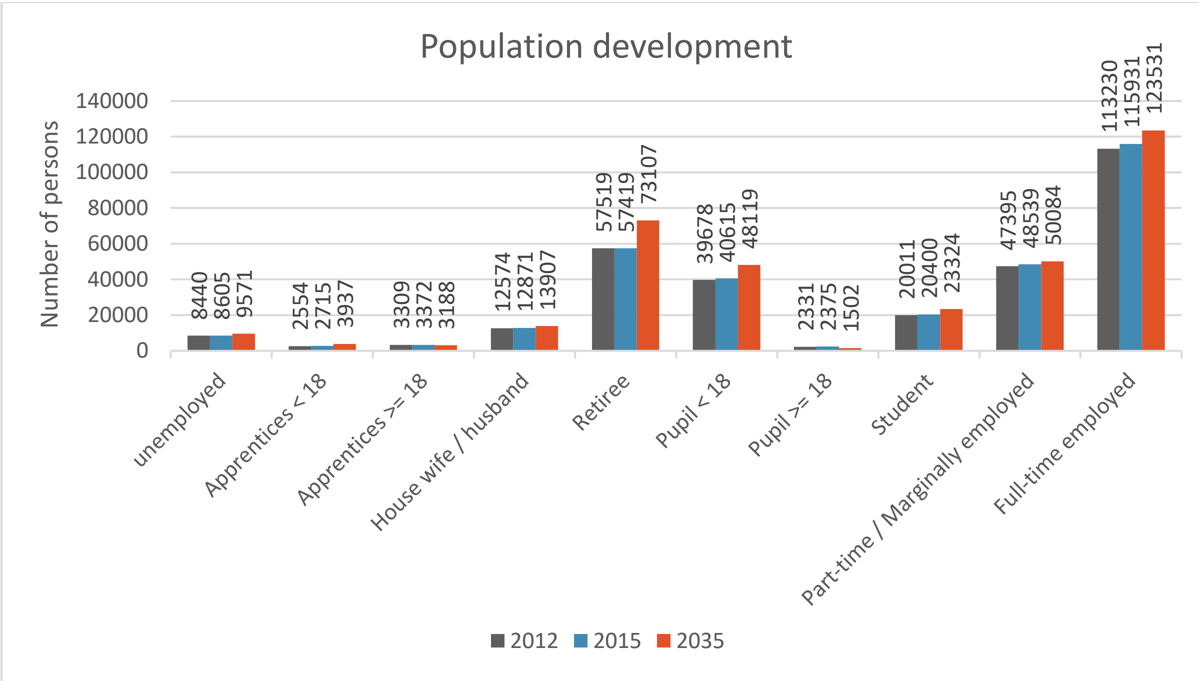


Figure 17: Population Development

In Appendix 5, the graph highlights the growing factors in between the years of 2012-2015 and 2015-2035.

3.7.2 Application of the Modification Parameters

This section covers the parameters, which are assumed to be mainly impacting the scenarios of by automated traffic. The section especially elaborates, how these factors are applied on the scenarios. For the modification of the modal split, a transformation matrix from the conventional modes of transportation to the new ones is used. The average trip distance is modified by using three different parameters to resemble the influences of AVs. For the trip patterns, certain theoretical rules are set in terms to be reproducible. The following sections describe the methodology of modifications in detail.

3.7.2.1 Population

The demographic development will surely have an impact on traffic, especially when the calculation regards different groups of persons. The population prediction in the future scenarios is based on the previous elaborated population model. As already mentioned, the calculated population of 2012 serves for the baseline 2012 scenario, for the others the calculated population of 2035 serves as foundation.

3.7.2.2 Modal Split

For calculating the modifications of mode choices in the scenarios, each conventional mode of transportation has to be assigned to a new mode of transportation. To make this process transparent each trip purpose has a matrix of modification parameters, which assigns the mode choices. These matrices look like the following example for an assumed development of mode choice for the trip purpose of shopping in the worst-case scenario:

Table 10: Modification - Assignment of Modes of Transportation

Conventional Mode of Tr. / **New Mode of Tr.**	**Walking**	**Cycling**	**Car as Driver**	**Car as fellow passenger**	**Public Transit**	**%**
Walking	90%	0%	0%	0%	0%	**90%**
Cycling	0%	70%	0%	0%	0%	**70%**
AV-NS	3%	10%	100%	30%	5%	**148%**
AV-CS	2%	10%	0%	40%	10%	**62%**
AV-RS	5%	10%	0%	30%	10%	**55%**
Public Transit	0%	0%	0%	0%	75%	**75%**
total	**100%**	**100%**	**100%**	**100%**	**100%**	

In this example, 90% of people, who walk nowadays, would walk in the future scenario again. The other 10% choose to take autonomous vehicles to reach their destination. In detail, 5% take a Ride Share AV, 2% take a Car Share AV and 3% would choose to take the private AV. For cyclists, only 70% choose the bicycle after/before shopping. Assuming they have baggage to carry, 30% of these change to AVs; 10% to each AV service. For people, who drive their own conventional cars today, the worst-case scenario expects them, to have their own AV-NS and use it in the future, too. Fellow passengers are assumed to be more likely to use shared mobility services, therefore they split up, almost equally in those three AV types. Public Transit users follow the same procedure. The change towards the AV services is based on the assumption, that especially with baggage the people prefer a more comfortable way of transportation. AVs, compared to public transit, allow door-to-door transportation. So, they reduce the walking distance to the next station and are more comfortable than overcrowded buses or streetcars.

The last row of the matrix has to sum up as 100 percent, to guarantee that all trip demand of today's state is assigned to new mode choices in the future scenarios. The results stated in last column are not as easy to interpret as they seem, but they can be used to roughly indicate trends of future mode choices. The problem in interpreting them is, that the sum of the percentages depends on the actual mode choices, which are multiplied with this assignment matrix. This leads to a weighting of the resulting percentages. So, it is wrong to think, that the AV-NS in this example increase up to 48%. In the cases of walking, cycling and public transit it really represents the loss of attraction towards today's state. For the new modes it is more complicated.

Measures of the VEP

In terms of modifying the modal split, the significance of future measures in the urban and infrastructure planning is undeniable. Therefore, the idea for developing the scenarios was, similar to the Study of the University of Stuttgart, that the traffic development plan (in German: Verkehrsentwicklungsplan, short "VEP") is assumed as theoretically implemented. All of its mentioned measures would be expected to exist in the year of 2025. These measures are expected to affect a shift in the modal split up towards the active transportation as well as public transit while reducing the individual motorized traffic to a certain degree.

In practice, the problem is, that the data base of the omniphon survey is not directly related to the traffic simulation model, on which the VEP is based on (see Figure 18). Resulting from that, it is not possible to develop a baseline scenario including the trends described in the VEP in the framework of this thesis. To incorporate the effects of the measures mentioned in the VEP, the whole data set of the omniphon survey has to be modified. This process seems too complex and too time-consuming within the thesis. The difference in the modal split of the VEP-based model and the omniphon survey is shown in the following figure. The expected changes in the VEP are consequently not transferable. On the left, the modal split of the VEP is shown, on the right, the modal split of the omniphon survey. Red is illustrating the cars (motorized individual transportation), blue stands for the public transit, light green the trips done by cycling and dark green stands for the mode of walking.

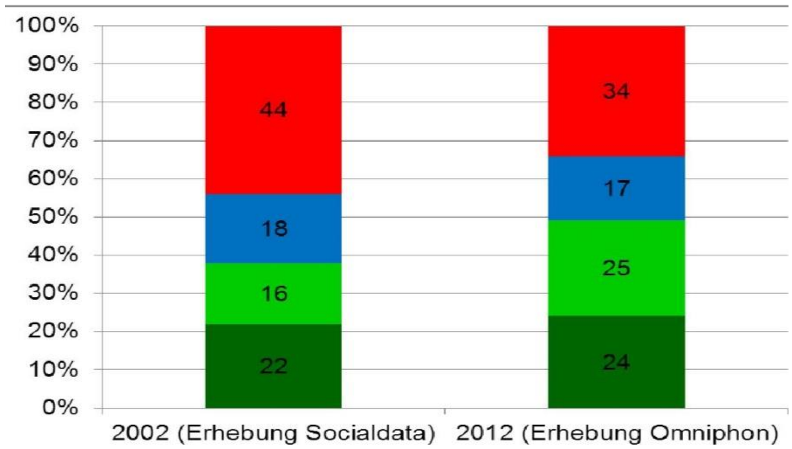


Figure 18: Difference in Modal Split - VEP based Model (2002) and the omniphon survey (2012) (Stadtplanungsamt Karlsruhe, 2013)

Following from that issue, the impact of the planned measures in the VEP Karlsruhe has to be neglected in the calculation of future scenarios.

3.7.2.3 Average Travel Distance

The average traveled distance is calculated by taking all trip distances out of the survey data. The average trip distance depends on the area, groups of persons, the trip purpose and the mode of transportation. So, for each mode and each trip purpose of each group of persons in each area an average trip distance is calculated (see also section 3.6.4). To modify the average trip distance for the future scenarios, three parameters are taken into considerations: a general increase factor for average distances (f_m), an average occupancy rate of vehicles (r_{occ}) and a proportion of unoccupied relocations for AVs ($p_{unocc.}$).

The *increase factor for the average distance (f_m)* is chosen to be dependent on the trip purpose, assuming that for certain purposes AVs will increase the acceptance of longer trips. The modification of parameter f_m is specifically applied in the worst-case and best-case scenario at the trip purposes of work (A), shopping (E) and recreational activities (F). It is assumed that only these purposes will affect trip distances caused by AVs. The implementation of the modification factor f_m follows the rule, that if the origin and the destination is one of the previous mentioned purposes, the average of both f_m values is used as increasing factor. Is only one of the three purposes either origin or destination of the trip, the value for that purpose is used. If none of the three purposes is origin or destination, the parameter is zero.

For *the occupancy rate (r_{occ}),* a correlation to the mode of transportation is obvious. The occupancy rate for pedestrians and cyclists is set as “1”.

For the public transit it is difficult to define an *average occupancy rate,* due to various forms of public transit (buses, streetcars, etc.). Nevertheless, the average occupancy rate of public transit should be assumed in terms of the final analysis of the modal split depending on the traveled vehicle distance. Defining an average occupancy rate for public transit includes a huge amount of influencing factors; on the one hand, the vehicle size and seat capacity is an important factor that varies a lot in different public modes of transportation – on the other hand, the average occupancy rate depends on the settings such as the demand on the line, user density in the area, time of the day, weekday, social-economic factors, etc. To estimate an average occupancy rate for the public transit in Karlsruhe, three literature approaches were taken into considerations. The first approach is based on “using bus data from the [American Public Transportation Association] APTA 2005 Public Transportation Factbook, [and dividing the] total annual passenger miles by total annual vehicle revenue miles to derive an average occupancy rate on Transtown buses of 10 passengers per mile” (Vincent & Callaghan Jerram, 2006, p. 223). Afterwards, the 10 passengers per vehicle-mile are converted towards 6.21 passengers per vehicle-km. The second approach is based on the low-density areas, in which priority is to “provide basic mobility” instead of high efficient transportation modes. Litman elaborates further, that “Buses operate at times and locations where demand is low, and there are few incentives to attract discretionary travelers to transit. As a result, average occupancy is relatively low, averaging about 5.2 passengers per bus-mile (excluding demand response services), and so may appear inefficient when evaluated based on average operating costs, energy consumption or pollution emissions per passenger-mile” (Victoria Transport Policy Institute, 2017, Litman). Converting to passengers per vehicle kilometer, the value lowers to 3.23. The values of the two approaches seem to be in the same magnitude. Compared to them, the third approach is based on a study in the Greater Toronto Area (GTA). Kennedy calculates the quotient of passenger kilometers by provided seat kilometers (independent of the mode). Consequently, the result is a value that can be applied on different modes (bus, streetcar, subway). He describes the calculation as follows: “Based on a mean local transit journey of 7.4 km by Toronto residents, the 388.3 million [Toronto Transit Commission] TTC trips in 1994 produced 2,873 million passenger-kms. Relative to the total seat-kms provided of 9,320 million, this indicates a mean occupancy rate of 0.31 for the TTC system, which is similar to that of automobiles” (Kennedy, 2002, p. 478). This rate describes, that in average 31% of the seats in public transit is occupied. This might be plausible for the Greater Toronto Area, which has approximately 6.4 million residents and high-efficiency public transit lines (Bus-Rapid-Transit ‘BRT’ and subway). The traffic demand is concentrated on these few high efficiency modes, due to the limited number of public transit lines. For German average, the Federal Environment Agency estimates the rate as 20% for City buses, and 21% for streetcars. Adapting this approach for a common bus (with approximately 38 seats) and a streetcar (with approximately 95 seats) the occupancy rate r_{occ} results in 7.6 for the bus, and 19.95 respectively for the streetcar. Probably the standing capacity could also be used for calculating more accurate numbers, especially for the streetcars. Moreover, the ratio of bus kilometers to streetcar kilometer is unknown. So, it is not possible to calculate the average of a general occupancy rate for public transit. Derived from that thoughts, the occupancy rate for public transit could be estimated to be within that range of 7.6 and 20 passengers per vehicle.

The modifications of the *occupancy rate* for motorized individual traffic – speaking of the conventional vehicles (as driver and as fellow passenger) in the baseline scenarios and the AVs (NS, CS and RS) in the best-case and worst-case scenario – are set in the respective chapters. The occupancy rate depends on various factors. To give one example of affecting factors, a study shows, that the occupancy rate can be defined as a function of distance. Nevertheless, the effect was found to be minor for conventional vehicles (Oetting, 2002). The occupancy rate, regarding the shared AVs (CS, RS), additionally depends on user demand, that is affected by various factors (time of the day, weather, fluctuations in demand, acceptance, distance, etc.). Comparing autonomous Ride Share services to not-shared vehicles, researches state, that the 45% of trips can be reduced due to the fact, that “especially short trips are pooled in our scenario. Since there is a general majority of short car trips (below 10 kilometers), the number of zones that can be reached by these trips is limited. Consequently, these trips are more likely to be pooled because there is a higher likelihood for another trip with the same origin and destination within the same time slot. Longer trips have a higher range of possible destinations and are therefore harder to pool together" (Heilig et al., 2017, p. 19). Consequently, especially for Ride Share vehicles, the occupancy rate is required to be further researched. Although, different interdependencies (to distance and demand) affect the occupancy rate, these effects are neglected, by setting the occupancy rates for Ride Share vehicles as a constant value.

In contrast to the correlation to trip distance, the influence of trip purpose on the occupancy rate is considered in further calculations. Different studies show a dependency on the trip purpose. The trip purpose related occupancy rates are derived from the following three sources:

Table 11: Comparison: Occupancy Rates depending on Trip Purpose

Source / **Trip Purpose**	**(Oetting, 2002)**	**MiD 2008**[1]	**Axhausen & Frick**[2] (based on Mikrozensus 2000, CHE)
A	1.3	1.2	1.15
U	-	1.7	1.12
E	1.4	1.5	1.62
F	1.8 - 2.0	1.9	1.90
P	-	1.5	2.27
H	-	1.9	2.50
Average	**1.26**	**1.5**	**1.59**

[1](Institut für angewandte Sozialwissenschaften (infas) & Deutsches Zentrum für Luft- und Raumfahrt e.V., 2008, p. 91)

[2](Axhausen & Frick, 2004, p. 22)

The occupancy rates, that applied on the scenarios, are stated in detail in each scenario in the next chapter. Based on the trip purpose of destination of the trip, the occupancy rate are set. Only if the destination is "home" (W), the occupancy rate depends on the origin of the trip (e.g. A-W: for the destination (W) is no occupancy rate given, therefore the occupancy rate of the origin "work" (A) is used for the calculation).

Due to the fact, that only autonomous vehicles can relocate unoccupied, the *additional proportion of unoccupied relocations (p_{unocc})* is specifically modified in the best-case and worst-case scenario. The proportion is based on an assumed probability of unoccupied relocations back to origin. In the calculation, the second (unoccupied) trip is not seen as an extra trip, but as proportion of the first trip, which adds up to the first trip as an extra unoccupied trip length. The "additional" in the term is used to express, that the proportion depends on the actual occupied trip but is added as an extra length. In the following thesis the "additional" is often not written. So, speaking of the proportion of unoccupied trips, means the same. The real proportion of unoccupied trip distance, can differ from the estimated average value of p_{unocc}. In addition to that, a certain percentage for unoccupied user pick-up processes will be added. This could include unoccupied trips from parking location to user-pick-up-location, user-drop-off-location to parking location (valet-parking) as well as for sharing services with unoccupied trips to serve the next user in sequence (see also Figure 8, Figure 9, Figure 10). The implementation of the p_{unocc} is set almost independent on trip purpose, except for H-trips. The following example should clarify the term of *additional proportion of unoccupied relocations:*

(a) Given is a trip from home to work (W-A), with an average distance of 5 km. Assuming that the AV-NS is parked 50 m away from the home of the person. The next available parking lot close to the working place is 150 m away. The vehicle picks up the user autonomously at the door of his home, drops him off at working place and afterwards searches the next available parking lot. Consequently, the vehicle serves 4% of the actual occupied trip, as an extra empty trip distance. This leads to an occupied trip distance of 5 km, and a total trip distance of 5.2 km.

(b) Imagine, that another person of the same household wants to use the vehicle after the trip described in (a), so, the vehicle has to relocate unoccupied to origin. For that case, the assumption is, that this case happens one in two times. Resulting in an extra average trip distance of 50%.

The average trip distance combining both cases will increase by 54%. The occupied distance is still 5 km, but in average, the unoccupied distance results in 2.7 km. Following, the average total vehicle-related trip distance is 7.7 km.

The modification parameters are set in sections 4.1 (baseline 2012 & baseline NO AV), 4.2.3.2 (best-case) and 4.3.3.2 (worst-case). These parameters allow calculating four types of traveled distances: the person-related traveled distance, the occupied vehicle-related traveled distance, the total vehicle-related traveled distance and the unoccupied vehicle-related traveled distance. The following formulas show the calculation of the distances:

Person-related traveled distance: $d_{av.,scenario}^{pers.} = d_{av.,survey} * [1 + f_m]$

Occupied vehicle-related traveled distance: $d_{av.,scenario}^{veh.(occ)} = d_{av.,scenario}^{pers.} / r_{occ}$

Total vehicle-related traveled distance: $d_{av.,scenario}^{total\ veh.} = d_{av.,scenario}^{veh.(occ)} * [1 + p_{unocc}]$

Unoccupied vehicle-related traveled distance: $d_{av.,scenario}^{veh.(unocc)} = d_{av.,scenario}^{total\ veh.} - d_{av.,scenario}^{veh.(occ)}$

With $d_{av.,survey}$ = average trip distance (calculated from the survey data)

$Index:\ veh./pers.$ = vehicle / person – related

f_m, r_{occ}, p_{unocc} as described previously on p.57

For the interpretation and analysis of the impact on traffic, the total vehicle-related traveled distances in the focus. It is defined as the distance, that all vehicles of a certain mode in the scope together have to travel to serve the all trips (and their trip distances) of persons, who choose that mode of transportation. The total person-related distance is defined as distance, that all persons in the scope travel with a certain mode. It is calculated in all scenarios. For the best-case and the worst-case scenario, the unoccupied traveled distance is calculated in terms of deriving the overall proportion of unoccupied relocations.

To illustrate the difference between person-related and vehicle-related distance, imagine three persons are picked from the survey. These answered, that for their trip to work (5 km) they used the car, one as fellow passenger, two as driver. In the calculation of the person-related travel distance, each person traveled 5 km. In sum, they caused an overall travel distance of 15 km (person related). In comparison, assuming that a car has an average occupancy rate of 1.2 persons per vehicle, the calculated vehicle-related travel distance would be 15 km divided by 1.2 is equal to 12.5 km. So, 15 person-related km is served by 12.5 km of vehicle movement. In this example, the reality differs from the calculated values, assuming that the fellow passenger is actual one passenger the two *drivers. In that case the person-related kilometers are still 15 km, but the vehicle-km are only 10 km. To adjust the calculations, the occupancy rate in this example must be 1.5.*

This error is due to the use of an average occupancy rate, but the survey data does not include any information about the actual occupancy rate.

For the mode choices of walking, cycling and public transit, the respective average travel distance data of the omniphon survey $d_{av.,survey}$ is multiplied by the modification parameters. For the new mode choices (AV-NS, AV-CS, AV-RS) no traveled distance exists in the survey, therefore the following assignment is applied. For the AV-NS, the data set of “Car as a driver” ($d_{av.,survey}(car\ as\ driver)$) is the respective average travel distance for the implementation in the formulas. For the AV-CS and AV-RS, the values of the mode “Car as a fellow passenger” ($d_{av.,survey}(car\ as\ fellow\ passenger)$) are used for the calculation. The following table illustrates the assignment.

Table 12: Modification - Assignment of Av. Travel Distances

Av. Travel Distance – conventional mode choice	**Av. Travel Distance – new mode choice**
Walking	Walking
Cycling	Cycling
Car as a Driver	AV-NS
Car as fellow passenger	AV-CS AV-RS
Public Transit	Public Transit

Due to the fact, that the survey data does not have values for the distances for long-distance public transit, the mode choice is neglected. In addition to the lack of data, the mode choice of long-distance public transit is not significant on the road traffic in urban areas. Most of it is carried on railroads or a few buses, that do not affect the urban traffic a lot.

3.7.2.4 Trip Pattern

For the trip patterns, it is difficult to make the modification process reproducible, which is necessary to satisfy the requirements of scientific research. To handle this challenge, the trip patterns are modified by certain rules. These can include reduction of the probability of a certain trip pattern for one specific trip purpose by one group or persons and reassign the "gained" amount of probability to another trip pattern, that satisfy certain criteria. One criterion could be the number of destinations, e.g. to reassign the probability to a trip pattern, that has the same trip pattern base, but has two more destinations in the pattern.

Example: To illustrate that, the trip pattern W-U-W of students has the probability of 20%, and the scenario assumes that the group of students gains new mobility through the implementation of AVs. Therefore, 10% of these students, which have that trip pattern, change their mobility behaviour to the following W-U-W-F-W pattern. So, 10% of the 20% result in 2% of the students, who change to the W-U-W-F-W pattern. The pattern W-U-W will have 18% of probability, while the W-U-W-F-W grows about +2%.

Another example, is shown in Table 13. In this example, the 20% of the percentage of the two-trip patterns move to the four-trip patterns with similar base pattern. The arrows illustrate how the differences are balanced, to keep the same represented amount of trip patterns. Patterns, that are written in blue colour (W-E-W, W-P-W), do not have a similar four-trip pattern. In cases like that, a new pattern is constructed (W-E-W-F-W). This is meant to represent the mobility gain, that due to easier mobility access, people are more likely to add another trip purpose to their daily routine.

Table 13: Example: Modification of Trip Patterns

Base Data		**Modification Scenario**		**Difference**
Trip Patterns	%	Trip Patterns	**%**	
-	31.52%	-	31.52%	0.00%
W-F-W	13.10%	**W-F-W**	10.48%	-2.62%
W-E-W	8.27%	W-E-W	6.61%	-1.65%
W-P-W	5.97%	W-P-W	4.77%	-1.19%
W-F-F-W	3.03%	W-F-F-W	3.03%	0.00%
S-W	2.42%	S-W	2.42%	0.00%
W-A-W	1.76%	W-A-W	1.41%	-0.35%
W-F-W-F-W	1.79%	**W-F-W**-F-W	4.41%	2.62%
W-F-E-W	1.80%	W-F-E-W	1.80%	0.00%
W-A-W-F-W	1.17%	W-A-W-F-W	1.52%	0.35%
		W-E-W-F-W	2.85%	2.85%

Other rules could consider certain trip purposes get reduced, as for example the purpose of picking up or drop off someone (H). This seems like a typical case that results from the availability of AVs.

These assumptions seem probably more theoretical than close to reality but are necessary to make the procedure transparent and reproducible. The rules that are constructed for the scenarios are explained in the next chapter.

4. DEVELOPMENT OF THE SCENARIOS

In this chapter, two scenarios – one for drawing a positive development for the traffic impacts, one for the negative development – are described and calculated besides two reference scenarios. The procedure will elaborate the modification factors based on literature references and further assumptions. The following table gives a hint, what the different scenarios are based on.

Table 14: Inputs of the Scenarios

	Baseline 2012	**Baseline NO AV**	**Best-Case**	**Worst-Case**
Population Model	2012	2035	2035	2035
Mod. Modal Share	No	No	Yes	Yes
Mod. Av. Trip Distance	No	No	Yes	Yes
- Occupancy Rate r_{occ}	(Yes)	(Yes)		
- Increase factor f_m	(No)	(No)		
- Proportion p_{unocc}	(No)	(No)		
Mod. Trip Patterns	No	No	Yes	Yes

To cover different aspects of impacts of AVs, ten different calculations are done. The focus of the research is, as already mentioned, the total vehicle-related traveled distance. Therefore, each scenario is calculated with these average vehicle-related traveled distances for each trip purpose and each group of persons in the areas.

Table 15: Types of Calculations for the Scenarios

	Baseline 2012	**Baseline NO AV**	**Best-Case**	**Worst-Case**
Person-related distance	x	x	x	x
Total vehicle-related distance	x	x	x	x
Unoccupied travel distance			x	x

Similar, for each scenario the total person-related traveled distance is calculated. Two more calculations are done for the best-case and worst-case scenario, which calculate unoccupied travel distances for the AVs. The previous Table 15 sums up the types of calculations.

4.1 BASELINE 2012 SCENARIO & BASELINE NO AV SCENARIO

4.1.1 Baseline 2012 Scenario

A baseline 2012 scenario is generated based on the prepared data set without any modifications. It is used as a reference point for three future scenarios as well as to evaluate different aspects of the methodology itself. These aspects include the population model (calculated population of 2012), the methodology of using only the most common trip patterns as well as the classifications in areas and groups of persons. The evaluation of that scenario is covered in section 5.1.

4.1.2 Baseline NO AV Scenario

The scenario baseline NO AV is calculated after modifying the distribution and increase of the population (calculated population of 2035). In the baseline NO AV scenario, it is assumed that the most common trip patterns are the same as in the omniphon survey of 2012. The mode choice percentages and average trip distance also stay equal to the baseline 2012 scenario. The influence of measures from the VEP Karlsruhe has to be neglected, as already stated on page 56.

Consequently, this scenario can be seen as the future traffic prediction for the case, that AVs not achieve the state of a market entrance. The scenario also is based on the assumption, that the mobility behaviour of people does not change – neither the modal split, nor the trip patterns or trip distances.

4.1.3 Assumptions for the Occupancy Rates

For the calculation of the overall vehicle-related traveled distance in both baseline scenarios, the occupancy rate is required. Derived from Table 11, the following occupancy rates are used for the listed trip purposes. The values for driver and fellow passenger are set equal. Due to the missing information about the actual occupancy rate, the person-related distance of each mode is divided by the estimated occupancy rate to calculate the vehicle-related traveled distance. It is worth mentioning, that the occupancy rate of 1.2 is not realistic for a car, if the respondent is a fellow passenger, because a conventional car needs a driver. So, at least two persons have to be in the vehicle. However, the survey does have data of fellow passengers alone, without the data of the actual driver as well as have data of drivers without the fellow passenger's data set. Therefore, the occupancy rate is set equal for both modes. Table 16 shows the chosen occupancy rates for the modes of "Car as Driver" and "Fellow Passenger".

Table 16: Occupancy rates for MIT depending on the Trip Purpose (baseline Scenarios)

Trip Purpose	Driver	Fellow Passenger
A	1.2	1.2
U	1.4	1.4
E	1.5	1.5
F	1.9	1.9
H	1.9	1.9
P	1.4	1.4
S	1.2	1.2

For the public transit, the following assumptions based on the elaborations in section 3.7.2.2 are made: To represent the varying demand on public transit in the three areas, the occupancy rates for public transit differ depending on the area. Consequently, for Karlsruhe I, the occupancy rate is set as 8, while the city core Karlsruhe II is estimated as an occupancy rate of 12. The outer circle of the city, Karlsruhe III, is estimated to have an average occupancy rate of 10 persons/vehicle.

4.2 BEST-CASE SCENARIO

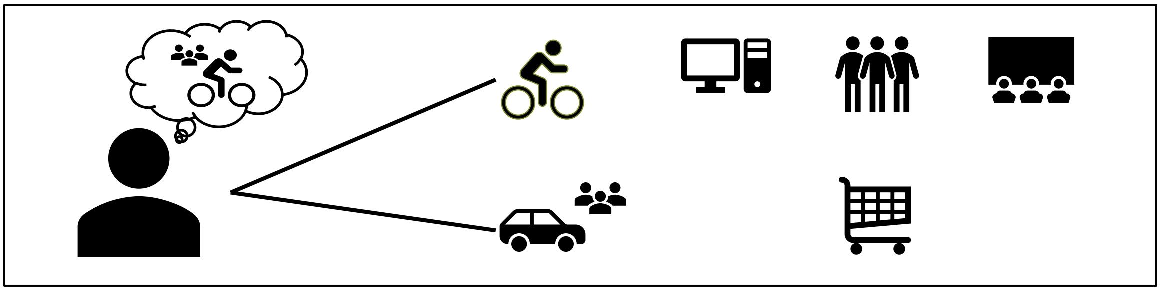
4.2.1 Underlying main Idea

The best-case scenario follows the vision of the so-called “three revolutions” of urban transportation, that includes the aspects of automation, electrification and shared mobility (Fulton, Mason, & Meroux, 2017). Especially the shared mobility has a significant role in this scenario, while the level of automation is set the same in the worst-case scenario, and electrification is not relevant for calculation.

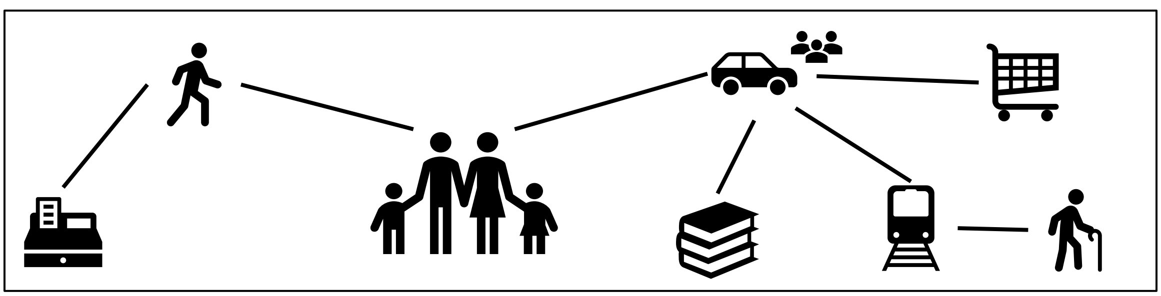
The key implications of that scenario are the development from owning a vehicle towards sharing a vehicle, eco-conscious that lead to the awareness of the problem of unoccupied trips and trust in autonomous sharing vehicles in aspects of safety and privacy. Furthermore, the modifications are based on well-developed infrastructure for Ride Share and Car Share services. The shared AV modes are more attractive to people than not shared AVs, probably caused by regulations (parking, ban on not shared AVs in the city core, etc.), cheaper cost per kilometer or a changed mindset. In addition to that, the AV is seen as an extension for public transit instead of a substitute.

4.2.2 Persona - Fictional Examples

The following examples of fictional persons should illustrate the basic ideas. The technique of so-called "persona" is often used in marketing-research to illustrate and predict certain user groups.



Thomas (26), who just graduated and now works for a small IT-company in the urban core, which is 2 km away from his apartment, used to take his private bike or walked for his trips (job, cinema, meeting friends). For grocery shopping, he often took the streetcar, because his bike had no pannier rack. Since AVs were implemented in daily life, he joined a Ride Share provider with the app on his mobile device. Because his bike is old already, he thinks about getting a Bike Share membership, which is also provided by his Ride Share service. Now, he still uses the bike for daily trips and when he needs to transport his groceries, he demands an AV-RS via app, because it directly delivers him and his baggage to his door, without walking to the next streetcar station.



Elisa, who is a mother of two children and lives in the urban areas (Karlsruhe I), is a housewife. Her husband works just around the corner in a local shop, where he can walk to. For almost all of her daily trips, she went by her own car, before AVs were implemented. Since then, she did not need to own a private AV. For her daily trips, such as grocery shopping, or private errands, she has a membership of the local Car Sharing provider, which has a station close to her house. Instead of picking-up her children at school, she lets them pick-up by the AV-CS most of the time. When they were younger, she often went with them in the CS vehicle, now they are able to use it independently. For weekend trips, they sometimes use the AV-CS to the main train station, where they take the train to the grandparents which live in Heidelberg.

4.2.3 Assumptions for the Modification Parameter

4.2.3.1 Modal Split

Different to the findings of Heilig et al., for the calculation of the best-case scenario the modal share of walking and bicycling does not change by implementing AVs, respectively to the baseline scenario. In their study, they state an increase of walking, bicycling and public transit while having an autonomous mobility-on-demand service (Heilig et al., 2017, pp. 20–21).

In terms of public transit, Friedrich & Hartl assume that high-performance public transit systems are preserved and improved by connecting it with AVs (Friedrich & Hartl, 2016, p. 64). Regarding the public transit system in Karlsruhe, it is dubious, if the system can be called "high-performance" system. Subways or Bus Rapid Transit (BRT) could be classified as high-performance systems. In spite of that, for calculating the best-case scenario, the public transit is assumed to gain attractiveness. Ride Share services, which might be owned by public transit companies, could connect the network of public transit to more households and generate new customers. This explanation could lead to the assumption of gaining attractiveness.

Speaking of Ride Share, the best-case scenario assumes that the willingness of people to share a ride is increasing within the next years. Also, today's car owners (user of cars in the questionnaire) are more interested in using CS services or RS services instead of owning a private AV. Reasons that lead to that development could include higher purchase costs of AVs, less provided parking space in urban cores, attractiveness of the CS/RS services by cheap trip prices and a shift in mindset.

Derived from that assumptions, the following table describes the basic modification matrix for the best-case scenario.

Table 17: Basic Modification Matrix for the Modal Split (best-case)

Conventional Mode of Tr. / New Mode of Tr.	Walking	Cycling	Car as Driver	Car as fellow passenger	Public Transit	%
Walking	100%	0%	0%	0%	0%	100%
Cycling	0%	100%	0%	0%	0%	100%
AV-NS	0%	0%	45%	5%	0%	50%
AV-CS	0%	0%	20%	15%	0%	35%
AV-RS	0%	0%	30%	65%	15%	110%
Public Transit	0%	0%	5%	15%	85%	105%
total	**100%**	**100%**	**100%**	**100%**	**100%**	

For certain trip purposes, this basic table is adjusted, as seen in the accompanying excel file. The quantified, purpose-related adjustments can be briefly justified by following assumptions:

- Trips to work (and back home) are more likely to be done by AV-NS (+15%) and AV-CS (+5%), because the travel time is used as working time in a mobile office. Fewer people are willing to share their trips to work compared to other trip purposes. Public Transit and Ride Share lose each -10% of former fellow passengers.
- Trips to shops (and back home) by foot or bike are assumed to lose attractiveness towards RS services. The advantage of easier transport of baggage than the mode of walking or cycling, results in a gain for the autonomous RS services for the purpose of shopping. In numbers, former fellow passengers additionally change 5% from AV-CS to AV-NS. Walking (5%) and Cycling (10%) shift towards the mode of AV-RS, compared to the basic modification matrix.
- For pick-up and drop-off trips (H), the Ride Share (+10%) gains additional demand from former public transit users. Explanation could be, that the RS is cheaper than public transit in some cases as well as more comfortable and subjectively safer for people. Furthermore, AV-NS gets additionally 5% of former fellow passengers.

4.2.3.2 Trip Distances

The modification of average trip distance is depending on three factors: the increase factor of the trip distance f_m, occupancy rate r_{occ} and proportion of unoccupied relocations p_{unocc}.

First of all, the increase factor of the trip distance f_m is set as the following. The average travel distance of the mode of walking will not be affected by the implementation of AVs in this scenario. In contrast, the average trip distance for cycling increases due to the impact of e-bikes. Based on the statement "E-bike riders in general travel 32% farther than bicycle riders" (Weinert, Ma, Yang, & Cherry, 2007, p. 65), this scenario estimates that possibly 50% of today's cyclists will use an e-bike. Consequently, the total increase of trip distance is assumed as f_m=16% for trips done by cycling, independent of trip purpose.

The impact of AVs on the trip distance of public transit is not regarded in any of the reviewed literature. As one idea, the public transit trips, that require to change the train or bus, are often the longer trips and more uncomfortable. So, as an assumption, these trips are more likely to be replaced by other modes of transportation, which would reduce the average trip distance. Following from that, the average trip distance of public transit related trips is reduced about f_m= 5% for all trip purposes.

The trip distance for AVs are modified for trips of the purposes (A), (E) and (F). Due to the decrease of importance in aspects of travel time and distance, people are more likely to accept longer trips. Especially, trips to work (A) and back home are expected to increase their average trip distance. In these cases, for the trips done by AVs broad-brush assumption of f_m=5% is implemented. Reasons for the increase of trip distance are due to the gain in the value of travel time, so the trips to work could already be used for certain work tasks or for recreation. Trips to shopping locations are likely to increase (f_m=2%) as well, due cheap and easy alternative to transport more purchased things with an AV over a further distance. This mainly results from the mode shift of active transportation and public transit to AVs. Farther shopping locations gain attractiveness by better reachability. The recreational activities are difficult to predict in terms of the change of trip distances, because of its various specific purposes. These include sport facilities, special events, cultural activities, private visits, restaurant, etc., which could be affected differently by AVs. Especially, for outdoor activities the trip distances could increase. Also, for occasions/events, at which people are drinking alcohol, the willingness for spontaneous farther trips could result in an increase of average trip distance. To quantify the increase, the factor f_m= 3% is estimated.

The effect of slightly longer trips for AV-RS, due to the additional distance to collect different users along the route, is neglected within the calculation, assuming that the route choice algorithm and trip managing system works highly optimized.

The following table sums up previous explanations.

Table 18: Modification of f_m for the AV-modes in the best-case scenario

Trip Purpose	AV-NS	AV-CS	AV-RS
A	5.0%	5.0%	5.0%
E	2.0%	2.0%	2.0%
F	3.0%	3.0%	3.0%

The *occupancy rate* is modified similar to the baseline scenarios. The difference is only existing in the H-trips. The requirement of a driver ceased by the implementation of AVs. Consequently, the occupancy rate lowers compared to the conventional vehicles in the baseline scenarios. The occupancy rate for the AV-RS is derived from (Friedrich & Hartl, 2016), who found an occupancy rate of up to r_{occ}=3.7, in scenarios with only Ride Share vehicles on the road. This number is based on the idea, that the AV-RS have six available passenger seats. For the elaborated best-case scenario in this thesis, the occupancy rate is set to r_{occ}=3.2, due to other available AV-modes. The independence of the trip distance is a simplification, because it is not predictable, which trip purposes are pooled together in one AV-RS.

Table 19: Modification of r_{occ} for the AV-modes in the best-case scenario

Trip Purpose	AV-NS	AV-CS	AV-RS
A	1.2	1.2	3.2
U	1.4	1.4	3.2
E	1.5	1.5	3.2
F	1.9	1.9	3.2
H	1.5	1.5	3.2
P	1.4	1.4	3.2
S	1.2	1.2	3.2

For the public transit, the values are assumed to be one person per vehicle higher than in the baseline scenarios, resulting in Karlsruhe I: 9, Karlsruhe II: 13 and Karlsruhe III:11 persons/vehicle.

In addition to that, the trip distance increases by *the proportion of unoccupied trips*, that autonomous vehicles do in terms of valet parking. In this scenario, it is assumed that parking facilities for AVs are provided in a central spot in the urban core. So, AVs do not have to travel in suburban areas to find a parking lot. For AV-NS the parking and pick-up process is declared as an extra 2% of total trip distance. Another underlying assumption is, that people are aware of causing unoccupied trips. So, they only use it, if the unoccupied trips are not exceeding an inappropriate amount. In some cases, the AV-NS delivers the person to its destination and afterwards serve for another member of the household. These cases are assumed to happen in one of five trips. Following from that thoughts, the proportion of unoccupied trips is assumed to be 20%. Both effects result in a total proportion p_{unocc} of 22% for AV-NS. For H-trips the probability of returning to the origin is assumed to be higher compared to other trip purposes. As stated in the main idea of the scenario, people in the best-case scenario are aware of that issue, which leads to the low ratio of that case. Following from that, the p_{unocc} is set to 33% for H-trips.

For the AV-CS, the proportion of unoccupied trips exists in consequence of picking-up the next user in sequence. The amount of unoccupied trips depends on different aspects, especially such as user demand, local distribution of users and vehicles of the VA-CS fleet. For the best-case scenario, the optimistic assumption of a p_{unocc} of 7% for AV-CS is based on the following two statements: "Case-study results indicate that a system of SAVs [Shared autonomous vehicles] may […] incur about 11% more travel (to reach the 'next in line' traveler)" (Fagnant & Kockelman, 2014, p. 12). One year later, they presented a study in Austin, Texas, that showed an increase of "8.7 % of its VMT [Vehicle miles traveled]" (Fagnant & Kockelman, 2015, p. 172). Following of these examples, the 7% increase of trip distance in terms of unoccupied relocations might be optimistic, but could be realistic in the scope of Karlsruhe, due to an already wide-spread, station-based CS service and associated wide spread vehicle fleet.

The proportion of unoccupied trips for autonomous ride share vehicles (AV-RS) is estimated to be less than AV-CS, due to the pooling of people in AV-RS. Depending on the number of AV-RS and user demand, the p_{unocc} could vary a lot. Within the best-case scenario this issue is seen optimistically. Deducing from that, the p_{unocc} of AV-RS is stated as 4% for the best-case scenario.

Table 20: Modification of p_{unocc} for the AV-modes in the best-case scenario

Trip Purposes	AV-NS	AV-CS	AV-RS
All Purposes	22%	7.0%	4.0%
H	33%	-	-

Concluding from that deliberations, the factors are applied in the formulas together with the average trip distances of survey data to calculate the person-related, vehicle-related and the unoccupied average traveled distances.

4.2.3.3 Trip Patterns

The modification of trip patterns follows certain theoretical constructs as mentioned in section 3.7.2.4. Each of the following paragraphs will describe one of the three theoretical constructs to modify the trip pattern distribution.

Firstly, for the best-case scenario, it is assumed that a few trips in the patterns will disappear because AVs vehicles will replace the need of them. Specifically, the H-trips (pick-up and drop-off) will be reduced within this scenario for all groups of persons except of “pupils under 18 years” and “retirees”. These two groups are assumed to be the passive transported person, so the trip of that person will still exist. The issue of defining some trips as an H-trip, even if the person is the subject that is transported to the destination, is already mentioned in section 3.5. By only reducing the H-trips by 50% for the all other groups except for the two mentioned, the active transportation of another person is attempted to be modelled. In other words, 50% of the trips to pick-up or drop-off another person are taken over by the AVs in this future scenario. In cases of trip patterns, that are constructed as “W-H-W+X” followed by more trip purposes, the trip pattern loses 50% of their probability towards a trip pattern with the same trip purposes but without the “W-H-W” part. If the whole trip pattern only exists of “W-H-W”, the 50% of the probability moves to the pattern of “W-F-W”, assuming that people will use their gained free time, if they do not have to transport another person.

Secondly, for shopping trips (E) the probability of trips gets reduced by 25%, due to more delivery services caused by AVs and digitalism (online shopping, delivery on demand, food delivery).

Thirdly, due to the availability of AVs, a general gain in mobility is expected. To modify that effect, the trip pattern of no trips (-) is modified. 1% of its probability is distributed to all the other trip patterns, in proportion of their previous probability. For the groups of retirees and pupils, the amount of 2% of the no-trip-pattern is distributed to the other trip patterns. These groups are more likely to benefit from AVs; retirees due to their higher susceptibility for disabilities and pupils due to new independent mobility chances.

For the first stated, the survey data was analyzed to find the distribution of mobility disabilities. As the following graph shows, people with the age over 60, are more likely to have disabilities, which affect the mobility.

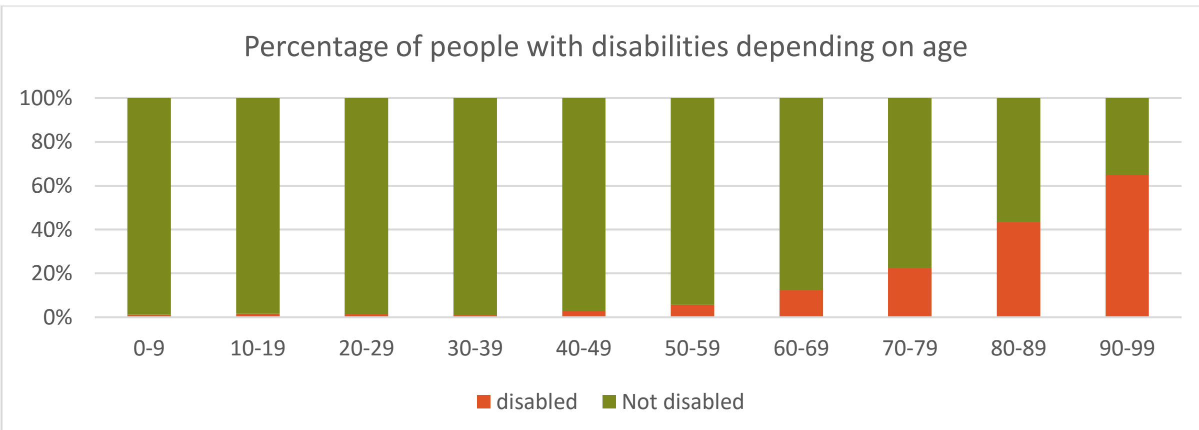


Figure 19: Percentage of people with disabilities

Further analysis of the people with disabilities shows, that the percentage of none trip per day is at the around 35 %. Compared to the people without any disability (no trips: 18%), that's almost twice as much. This already shows, that disabilities lead to lack of mobility. Therefore, the retirees are assumed to gain new mobility by AVs as previous elaborated.

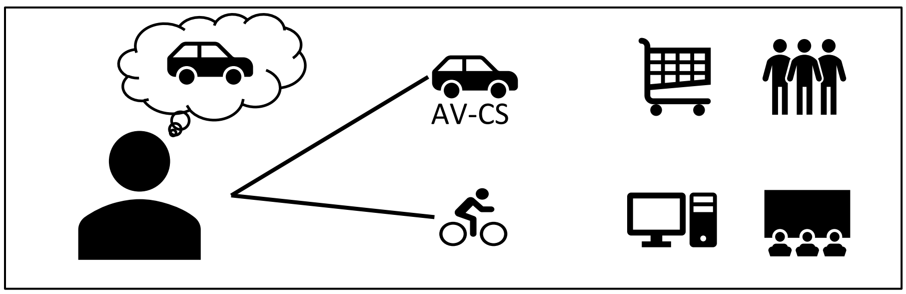
4.3 WORST-CASE SCENARIO

4.3.1 Underlying main Idea

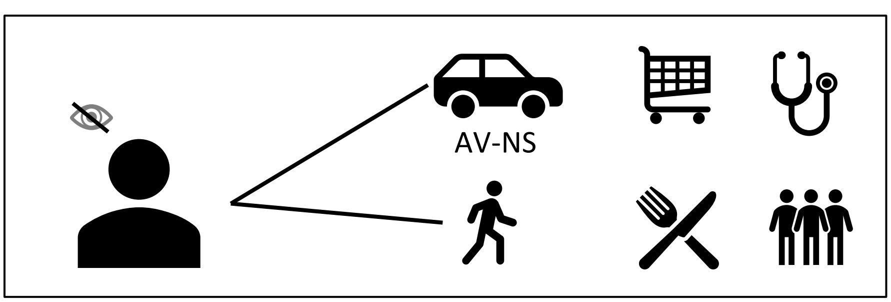
The main idea of the worst-case scenario is based on slow development of the mind shift towards sharing services. The people are lazy regarding active transportation and enjoy the comfort of AVs. The mobility behaviour is, compared to the best-case scenario, more egotistically shaped and user optimized. The majority of the people see privacy and comfort over environmental issues and over sharing a vehicle. In the era of full autonomous traffic, the purchase cost of a private AV is not significant more expensive than a conventional car today, therefore, a people preferring to own a vehicle. In the comparison of RS and CS, the majority of people are more likely to prefer Car Share, due to privacy aspects and the low supply of RS services.

The impact of AVs leads to reduction of demand on Public Transit. Different aspects lead to a shift in mode choice towards the AV. These include the gain of comfort, reduction of travel time and having a new alternative for people, who are dependent on Public Transit.

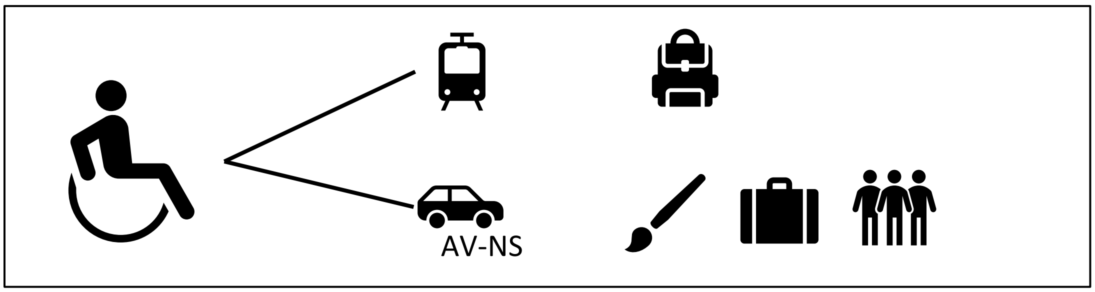
4.3.2 Persona - Fictional Examples



Thomas (26), who was already presented in the best-case scenario, develops in the worst-case scenario in a different direction. Instead of joining a Ride Share service, he gets a membership of a Car Sharing service. He earns a good salary at his IT job, so he is willing to pay a bit more for his gain on privacy and comfort compared to a Ride Share service. His bike is still in use on his way to work and short distance errands, but on the weekends, when he meets his friends, he often uses an AV-CS to get home late at night. For grocery shopping, the AV-CS gives him new opportunity to transport more purchased items in addition to an improvement of comfort. Due to a job offer outside of Karlsruhe, he thinks about buying a private AV. The company, that want to hire him is willing to pay his working time during his commute. For daily commuting, he calculates, that a private AV would be feasible.



Peter (71), who is a retiree living in the area of Karlsruhe III, ever since he started to work had an own car. When the AVs started to gain popularity, he was doubtful in the technology, but accepted the new technology and bought a private AV-NS. With the years, his vision got weaker, so he is happy about the new mobility, that the AVs give him. Due to his lifelong independent travel behaviour enabled by his own car, he was not willing to change towards the shared AV modes or public transit, when his vision abilities got worse. For short distance trips, he still walks, but in other cases he uses his AV-NS.



Lena (17), pupil and due to an inherent disability depending on a wheel chair, goes to a school on the other side of the city. When her parents did not have an AV, she was always dependent on buses and streetcars. The public transit challenged her in cases, when stations were not constructed disabled-friendly. For her daily trip to school, she is able to use disabled-friendly stations. In contrast, for her weekly trip to an art school, she is not able to take the bus alone. The only disable-friendly alternative by public transit takes her 30 minutes longer. In that case, she uses the AV-NS of her parents. It is specifically designed for people with wheelchairs, to allow them to enter the car without another person's help. While her parents are at work, Lena is able to reach every destination (meeting friends, etc.) on her own. After the art course, Lena is picked up by the AV-NS again, which parks in an outsourced parking facility and on the way home, it could pick up her mother from work.

4.3.3 Assumptions for the Modification Parameter

4.3.3.1 Modal Split

In contrast to the best-case scenario, 10% of people of former active transportation modes decide to shift to the AV modes. These are likely to be RS-based instead of using a taxi, in cases of sudden rain or special occasions.

The scenario further assumes, that people that are drivers today, will in the future also use their own AV-NS. Especially in a car-affine country as Germany, a lot of people consider a car as a status symbol, which is more than just a mode of transportation. Today's fellow passengers distribute almost equally – some of them will have access to an AV-NS in their household, others will see AV-CS as best option, and 30% will choose autonomous Ride Share services. An explanation could be, that former fellow passengers take the oppportunity of more independent modes of transportation, as well as enjoying the new opportunity of traveling by themselves.

For today's user of public transit, certain percentage equally switch to the AV modes, due to already mentioned reasons.

Derived from these specific assumptions for the worst-case scenario, the following table describes the basic modification matrix.

Table 21: Basic Modification Matrix for the Modal Split (worst-case)

Conventional Mode of Tr. / New Mode of Tr.	**Walking**	**Cycling**	**Car as Driver**	**Car as fellow passenger**	**Public Transit**	**%**
Walking	90%	0%	0%	0%	0%	90%
Cycling	0%	90%	0%	0%	0%	90%
AV-NS	3%	3%	100%	30%	5%	141%
AV-CS	2%	2%	0%	40%	5%	49%
AV-RS	5%	5%	0%	30%	5%	45%
Public Transit	0%	0%	0%	0%	85%	85%
total	**100%**	**100%**	**100%**	**100%**	**100%**	

As in the best-case scenario, certain trip purposes have been modified specifically. For the following trip purposes specific modifications of the basic matrix are explained:

- For trips towards or from work (A) (except from education [U]) are assumed to have an additional proportion of AV-CS use at the expense of AV-RS by today's fellow passengers.

The proportion is estimated as 20%. Higher comfort and privacy wants could be the reason for that shift in work-related trips. People could sleep, make phone calls, work on mobile devices etc. without distraction or other people in the same vehicle on their way to work. The exception for U-A trips tries to consider the higher acceptance of pupils and students to share a ride. So, the trip origin "education" (U) is chosen to represent a certain group of persons, which might be an additional parameter that influences the shift in mode choice (see section 5.6.1, point v).

- For shopping trips (E) especially today's cyclists will change towards all three modes of AVs. Only 70% will use their bicycle in the future, while each AV mode result in +10% of today's cyclists. Similarly, the people from public transit shift to the AV-NS, AV-CS, AV-RS with 5%, 10% and 10%, respectively. The explanation for this shift is based on the higher ability of baggage transport. People are more likely to use an easier door-to-door mode of transportation in cases, in which they carry things (e.g. grocery shopping).
- For recreational activities (F) the mode choice of public transit also moves towards the modes of AV-NS and AV-CS. One reason could be that some destinations for recreational activities are secluded from the network of public transit, so, AVs serve in higher utility. Furthermore, some recreational activities could require extra space for transporting equipment in a vehicle. Public transit often seems more impracticable.
- For H-trips (pick-up and drop-off), a significant amount of 60% of today's fellow passengers will be served by not shared autonomous vehicles (AV-NS). Respectively, 30% of today's fellow passengers will be served by CS vehicles. A shift of 10% of the public transit users towards AV-RS is also assumed. The reason for that significant changes for H-trips, is the assumption, that people, who normally are required to be picked up or brought somewhere have a higher need of privacy and subjective safety. For example, a mother, who daily picks up her child after school, might feels insecure about letting the child use an AV-RS. Therefore, children are more likely to get picked up by private AVs. Similarly, the elderly grandmother is probably rather taking an AV-CS as a mobility-on-demand service instead of being picked up by someone else.

4.3.3.2 Trip Distances

For the worst-case scenario it is assumed, that longer trips are shifting to the modes of AVs. As consequence, the trips done by public transit lose longer trip distances and the average decreases. These effects are modified with the *increase parameter f_m*. Imagining a person, who is in a bar in the city center late at night and it starts raining. Due to the lower price of autonomous mobility-on-demand (AMOD) services for a high-quality and comfortable mode compared to public transit, the person will be more likely to switch to an AV mode instead of walking to the next station in rain. For public transit, the AVs could lead to the cessation of low demand stations. These are often located outside of the city center, that means they cause larger trip distances. The mode shift in both cases, lead to a decrease in the average trip distance; f_m= - 5% for public transit.

For the average trip distance of cycling, the worst-case scenario follows the assumption of an increase f_m= 4%. The explanation is based on (Weinert et al., 2007, p. 65), similar to the best-case scenario, with the distinction that the worst-case scenario expects only 12.5% of the cyclists will switch towards e-bikes.

The parameter f_m for the modes of AVs will, as in the best-case scenario, distinguish depending on trip purpose. The worst-case scenario estimates higher tolerance towards longer distance for (A), (E) and (F) trips. AVs could lead to gain attractiveness for further shopping destinations. The AVs allow transportorting more purchased items for further distances for cheaper prices than today's modes of transportation. Similar to the shopping trips (E), the recreational trips (F) will approach longer trip distances. Some destinations, which are not well-connected to other modes of transportation get within easy reach by AVs. Examples could be outdoor activities like downhill biking, hiking, etc. or trips to bathing lakes close to Karlsruhe. Moreover, due to the loose of importance in travel time, this effect adds up for recreational activities.

Consequently, the increasing factor f_m for the AV modes is set as the following table shows.

Table 22: Modification of f_m for the AV-modes in the worst-case scenario

Trip Purpose	AV-NS	AV-CS	AV-RS
A	8%	8%	8%
E	4%	4%	4%
F	6%	6%	6%

The *occupancy rate* is modified similar to the best-case scenario and is set equal for both modes - the AV-NS and AV-CS. How the rate would change only affected by the implementation of AVs, is unapparent. In contrast, the occupancy rate for the AV-RS services is assumed to be lower than in the best-case scenario. Reasons are the lower willingness to share a ride, that affects the demand on RS vehicles in addition to lower ability to pool the fewer people within one route. Derived from (Friedrich & Hartl, 2016), the r_{occ} is set to 2.8, which is assumed by relating to scenarios with different AV services in their study. The statement written in the best-case scenario, “The independence of the trip distance is a simplification, because it is not predictable, which trip purposes are pooled together in one AV-RS” is also applied for the worst-case Scenario. Table 23 sums up the thoughts for the occupancy rates.

Table 23: Modification of r_{occ} for the AV-modes in the worst-case scenario

Trip Purpose	**NS**	**CS**	**RS**
A	1,2	1,2	2,8
U	1,4	1,4	2,8
E	1,5	1,5	2,8
F	1,9	1,9	2,8
H	1,5	1,5	2,8
P	1,4	1,4	2,8
S	1,2	1,2	2,8

For the public transit, the values are assumed to be less than in the baseline scenarios, resulting in Karlsruhe I: 6.5, Karlsruhe II: 9.5 and Karlsruhe III: 7.5 persons/vehicle.

The *proportion of unoccupied trips* p_{unocc} distinguishes the two scenarios most visible. Regarding the three modes of AVs, the worst-case scenario expects the increase, especially for the private AVs. Due to the availability of the vehicle for only one household, the efficiency in terms of occupancy lowers drastically. The fact that a household with a certain number of people are using their private AVs in sequence will make that mode inefficient. After serving an occupied trip, the AV-NS has to relocate back to the origin unoccupied. For the worst-case scenario is assumed, that one in two trips is relocating back to the origin unoccupied (p_{unocc}=50%). Furthermore, the unoccupied parking process and pick-up of the vehicle owner adds a certain percentage to the pure origin-destination distance. Decentralized parking facilities, longer parking lot searches are included in an extra 4% of unoccupied trip proportion. So, the p_{unocc} results in 54%. For H-trips, it is assumed, that three of four vehicles relocate back to the origin. This leads to total p_{unocc} of 79% for H-trips.

Compared to the best-case scenario, the Car-Share services with AV-CS are not developed well enough to serve on high efficient level. The rate of unoccupied trips is higher than on the best-case scenario due to fewer cars in the CS fleet, which results in longer trips to pick up users. Aspects of low-efficient algorithms in demand and supply management could be a cause for that. Derived from that idea, the p_{unocc} is assumed to be 15%.

In terms of Ride Share, low demand on the services causes fewer options to pool people's routes. Higher amounts of detours have to been done in order to pick up users. Also, the rate of unoccupied trips increases compared to the best-case of high demand on RS. Followed from that, p_{unocc}=8% is assumed for the AV-RS.

To sum up, the following table conclude the assumed development of proportion of unoccupied trips.

Table 24: Modification of p_{unocc} for the AV-modes in the worst-case scenario

Trip Purposes	**AV-NS**	**AV-CS**	**AV-RS**
All Trip Purposes	54%	15.0%	8.0%
H	79%	-	-

4.3.3.3 Trip Patterns

To begin with, different from in the best-case scenario, the trips, that have the purpose of picking up or dropping off a person, are not assumed to cease but to be replaced by other trip purposes. This should simulate, that persons that normally have to spend time to transport other persons, now will use the gained time to fulfill other activities. Instead of ceasing, 50% of the trip patterns including an H-trip are replaced by another trip pattern. The normal case is, that the 50% of proportion of the trip pattern with the trip purpose (H) is replaced by (F) in the new pattern, if the respective pattern does not exist already. If a comparable (same number of trips & similar trip purposes) exists, 50% of proportion will move to the comparable trip pattern. If no comparable trip pattern exists, a new one is shaped as mentioned before with a replacement of (H) by an (F). Example:

> *Given trip pattern: W-H-W-A-W. If a pattern exists that exactly is formed like W-F-W-A-W, that pattern would get 50% of proportion of the given pattern. If that is not the case, and a pattern like W-A-W-F-W exists, this will get the proportion. If none of the above exist, but any that looks like W-A-W-X-W or W-X-W-A-W (X = any trip purpose), these will take the proportion.*

Similar to the best-case scenario, the groups of persons of pupils under 18 years and retirees are excluded, because they are assumed to be the persons that are transported.

The second theoretical construct is, that 20% of the two-trip patterns are shifted to four-trip patterns (X-X-X to X-X-X-X-X, e.g. W-A-W to W-A-W-F-W). That follows the idea, that people gain new mobility induced by AVs. It is easier for them to travel to different locations. Additional activities and trips are the consequence. If these four-trip-patterns does not exist, new ones are formed by adding an "-F-W" ending. As in the previous modification, the shift of 20% proportion could also be done to a comparable trip pattern that exists of four trips.

Third, similar to the best-case scenario, the general gain in mobility is tried to be modelled by distributing the probability of no-trip-pattern (-) to all the other trip patterns weighted by their previous probability. For the groups of retirees and pupils, the amount of 4% of no-trip-pattern are distributed to other trip pattern; for all other groups of persons: 2%. The worst-case scenario expects, that more people make use of the new transportation modes than in the best-case scenario.

4.4 OVERVIEW: MODIFICATIONS IN SCENARIOS

4.4.1 Modal Split

The following table sums up the two basic matrices of the best-case (on the left) and worst-case (on the right) scenario. These are equivalent to Table 17 and Table 21.

Table 25: Overview: Modifications for the Modal Splits

Conventional Mode of Tr. / New Mode of Tr.	Walking	Cycling	Car as Driver	Car as fellow passenger	Public Transit	%
Walking	100%	0%	0%	0%	0%	100%
Cycling	0%	100%	0%	0%	0%	100%
AV-NS	0%	0%	45%	5%	0%	50%
AV-CS	0%	0%	20%	15%	0%	35%
AV-RS	0%	0%	30%	65%	15%	110%
Public Transit	0%	0%	5%	15%	85%	105%
total	100%	100%	100%	100%	100%	

Conventional Mode of Tr. / New Mode of Tr.	Walking	Cycling	Car as Driver	Car as fellow passenger	Public Transit	%
Walking	90%	0%	0%	0%	0%	90%
Cycling	0%	90%	0%	0%	0%	90%
AV-NS	3%	3%	100%	30%	5%	141%
AV-CS	2%	2%	0%	40%	5%	49%
AV-RS	5%	5%	0%	30%	5%	45%
Public Transit	0%	0%	0%	0%	85%	85%
total	100%	100%	100%	100%	100%	

As mentioned before, the last column does not represent the exact gain of mode choice, but it can be an indicator for the trend. To give an example: Comparing both scenarios, the trends are visible. While the best-case has low demand on AV-NS (50%), the AV-NS has higher demand of 141%.

4.4.2 Trip Patterns

For the trip pattern modification, both scenarios elaborated three key rules. These are:

…for the best-case:

- 50% of the pick-up/drop-off (H) trips are reduced for all groups of persons except retirees and pupils under 18.
- 25% of the shopping trips (E) are reduced.
- 1% (2% - for retirees and pupils) of the unmade trips (-) are distributed to other trip patterns.

…for the worst-case:

- 50% of the pick-up/drop-off (H) trips are replaced by recreational trips (F) for all groups of persons except retirees and pupils under 18.

- 20% of two-trip patterns (X-X-X) are shifted towards comparable four-trip patterns (X-X-X-X-X).
- 2% (4% - for retirees and pupils) of the no-trip-patterns (-) are distributed to other trip patterns.

4.4.3 Average Trip Distance

The table below sums up the set of parameters for each scenario, which are required to modify the average trip distances.

Table 26: Overview: Modifications for the Average Trip Distance. (f_m , r_{occ} and p_{unocc})

	Mode	Baseline NO AV			Best-Case			Worst-Case		
		f_m	r_{occ}	p_{unocc}	f_m	r_{occ}	p_{unocc}	f_m	r_{occ}	p_{unocc}
Average Travel Distances	Walking	-	1.0	-	0%	1.0	-	0%	1.0	-
	Cycling		1.0		16%	1.0	-	4%	1.0	-
	Conventional Vehicles		A: 1.2 U: 1.4 E: 1.5 F: 1.9 H: 1.9 P: 1.4 S: 1.2		-			-		
	AV- No Share	-			A: 5% E: 2% F: 3%	A: 1.2 U: 1.4 E: 1.5 F: 1.9 H: 1.5 P: 1.4 S: 1.2	X: 22% H: 33%	A: 8% E: 4% F: 6%	A: 1.2 U: 1.4 E: 1.5 F: 1.9 H: 1.5 P: 1.4 S: 1.2	X: 54% H: 79%
	AV- Car Share				A: 5% E: 2% F: 3%		X: 7%	A: 8% E: 4% F: 6%		X: 15%
	AV- Ride Share				A: 5% E: 2% F: 3%	X: 3.2	X: 4%	A: 8% E: 4% F: 6%	X: 2.8	X: 8%
	Public Transit	-	I : 8 II: 12 III: 10	-	I-III: -5%	I : 9 II: 13 III: 11	-	I-III: -5%	I : 6.5 II: 9.5 III: 7.5	-

(X = all trip purpose; Area: I-III = Karlsruhe I-III)

5. RESULTS & FINDINGS

This section will present results of the different scenarios, illustrate findings, try to evaluate the methodology and discuss limitations and assumptions. The focus of the analysis of results is focused on the motorized transportation; the active transportation and public transit play a minor role.

The traveled distance, will not be analyzed by the exact number of traveled kilometers. Due to the calculation of only a certain part of the population (60% - as later elaborated in section 5.5.5) the exact calculated kilometers are not in the focus. The analysis concentrates on the quantifying the changes of distances and comparisons between the scenarios.

Derived from the total person-km and vehicle-km, the ratio of them delivers the average occupancy rates. By calculating a fictional average occupancy rate $r_{occ,f}$ over all modes of transportation, the efficiency of the total transportation system in the scenario is highlighted. The modes of active transportation (Walking and Cycling) have the same values for the person- and vehicle-related distance. This is caused by an occupancy rate of 1.0. In other words, the person is the "vehicle" itself. It is possible to have an occupancy rate of 2.0 on a bike, but this case is neglected within the calculation.

For the best-case and worst-case scenario, the role of the Ride Share service has to be defined. Does it act as motorized individual transportation or as public transit? Ride Share probably could be declared as public transit, because it does not fit the term of "*individual"* transportation, due to the pooling of people. Hence, each user is transported on its individual route between origin and destination. In that aspect, and an easier way to illustrate the results, autonomous Ride Share vehicles are still included in the MIT for the analysis.

5.1 BASELINE 2012

5.1.1 Evaluation of the Methodology in Comparison to the Omniphon Results

The baseline 2012 serves as a comparison to the results, that omniphon presented in their report. For the evaluation, the focus is set on the modal splits. In the following figures, results of the omniphon report (see also Figure 3) are illustrated next to results of the calculated baseline 2012 scenario.

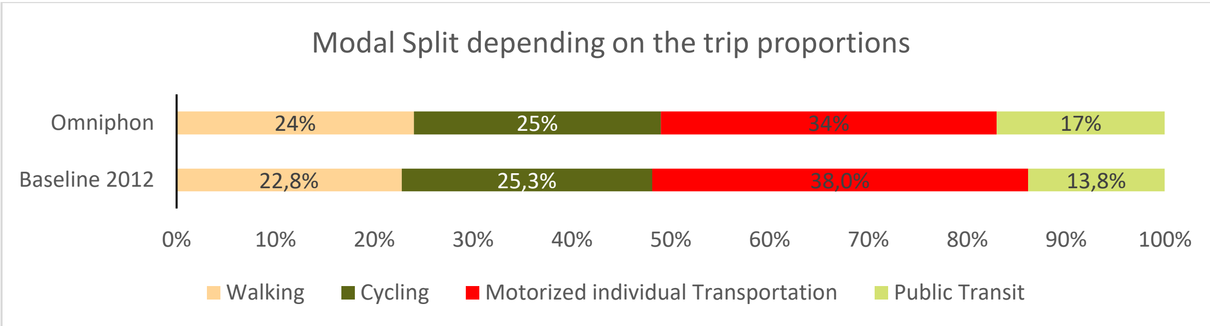


Figure 20: Modal Split (trip proportion) of baseline 2012 and omniphon result

The comparison of the results shows, that the population model and the trip pattern analysis are close to the results of the omniphon report. In Figure 20, the results differ for the MIT and public transit within 4%. For further calculations, this error is acceptable. The results in the distribution of person related traveled distances (Figure 21) differ in a maximal range of 6.9%.

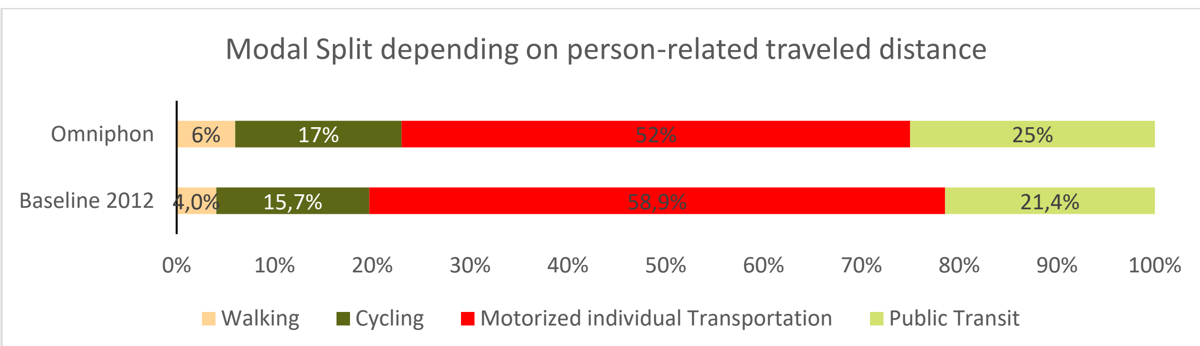


Figure 21: Modal Split (person-related traveled distance) of BL 2012 and omniphon

The calculated person-related traveled distances have higher difference than the modal split based on trip proportions, due to higher trip distances of MIT compared to the modes of walking and cycling. Therefore, the differences increase from Figure 20 to Figure 21.

The differences in results can have various sources. First of all, omniphon based their calculation on the actual data of each single trip. Within this thesis, the trips are formed to trip patterns with average trip distances. The average traveled distance per vehicle and trip pattern is calculated. Based on the sum of all trip patterns, the proportion of all modes on the total traveled distance is leading to the modal split illustrated in Figure 21. Another aspect is, that the omniphon results include weighting factors for different aspects (household, person, season, population, weekday, etc.). Omniphon faced similar problems regarding the lack of data in population. They state in their report, that they do not have certain numbers for students, pupils and apprentices as well as for the proportion of part-time employed and full-time employed (Omniphon GmbH, 2012). Therefore, they used person-depended weighting factors to implement the population distribution into their survey results. Furthermore, the baseline 2012 scenario is applied only for the most common trip patterns and persons that were able to be classified in groups of persons. This probably neglect some minor specific travel behaviour, that could lead to the deviation of the percentages.

To conclude, within this thesis the population model and the methodology of using only the most common trip patterns is sufficiently accurate.

5.1.2 Overview

The calculations reveal following outcomes in modal splits. These depend on three different values. The modal split on the left shows the percentages of mode choices depending on the number of trips (same as Figure 20). The modal split in the middle is illustrating the mode choice regarding the person-kilometers (same as Figure 21). The modal split on the right takes the vehicle-kilometers into consideration.

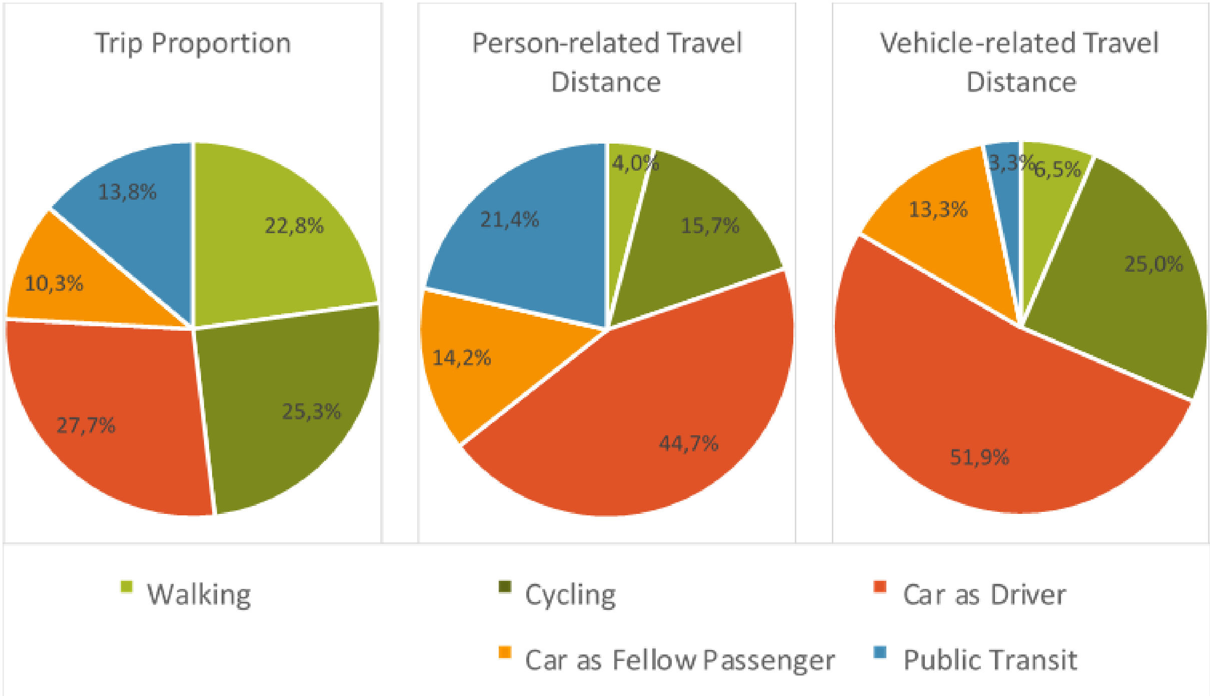


Figure 22: Modal Splits - baseline 2012

The one on the left and in the middle, were discussed previously in terms of the evaluation of the methodology, that is used in this thesis. The modal split on the right, should illustrate the actual distribution of the overall traveled vehicle-kilometers of the five modes of transportation.

For the motorized individual transportation (Car as Driver combined with Car as Fellow Passenger), 38% of the trips result in 65.2% of the total vehicle-kilometers. This is why the MIT is causing the challenges in traffic management. MIT has a higher proportion of the total vehicle-kilometers than its proportion of trip numbers or person-kilometers (58.9%).

Compared to MIT, the public transit is able to serve 21.4% of the total traveled person-kilometers by providing vehicles that only travel 3.3% of the total vehicle-kilometers, due to higher occupancy rate. That is the amount of 13.8% of the trips, that people do – based on the calculation.

The proportions of the active transportation (Walking and Cycling) show, that the distances done by walking and cycling are shorter compared to the other modes. The increase on the proportion of vehicle-related distance from the person-related distance is caused by the decrease of the vehicle-related distance of other modes. The person-km are equal to the vehicle-km for the active transportation as shown in the Figure 23.

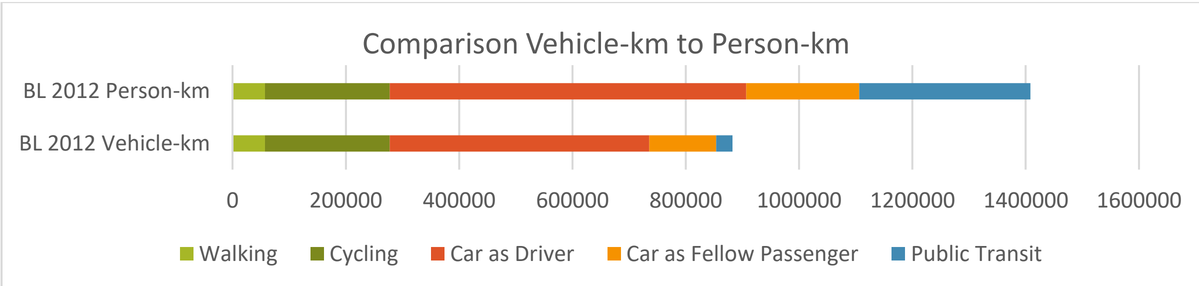


Figure 23: Comparison of vehicle-km to person-km in baseline 2012

5.1.3 Occupancy Rate

The calculated fictional average occupancy rate for this scenario is 1.6 persons per vehicle.

The separately calculated values for each mode are as follows: the active transportation modes of walking and cycling have the value of 1.0 persons/vehicle. In average for conventional MIT the occupancy rate is 1.44 persons per vehicle, while public transit in average serves 10.45 persons per vehicle.

5.2 BASELINE NO AV

5.2.1 Traveled Distance

Compared to the baseline 2012, the traveled distance person-km increase about 13.3% in average, due to the population growth. The detailed view on the increase (Table 27), separated on modes of transportation, shows characteristic behaviour for the researched scope, which is mainly inner-city area: The walking distance (16.8%) increases the most compared to other modes, followed by the public transit (14.9%). Similar the vehicle-kilometers increase in the same value range.

Table 27: Traveled Distance - Comparison baseline NO AV to baseline 2012

	Walking	**Cycling**	**MIT**	**Public Transit**
Person-km	16,8%	13,0%	12,5%	14,9%
Vehicle-km	16,8%	13,0%	11,9%	14,7%

The calculated occupancy rates for the baseline NO AV scenario does not differ compared to the baseline 2012 scenario.

5.2.2 Modal Splits

Resulting from calculations of the baseline NO AV scenario, three modal splits are illustrated. The modal split on the left depends on the trip proportions. It is almost the same as in the baseline 2012 scenario. A minor shift in modal splits is the consequence of the population growth and demographic change, and is also affected by the difference in the increases of the traveled distances, described in the previous paragraph.

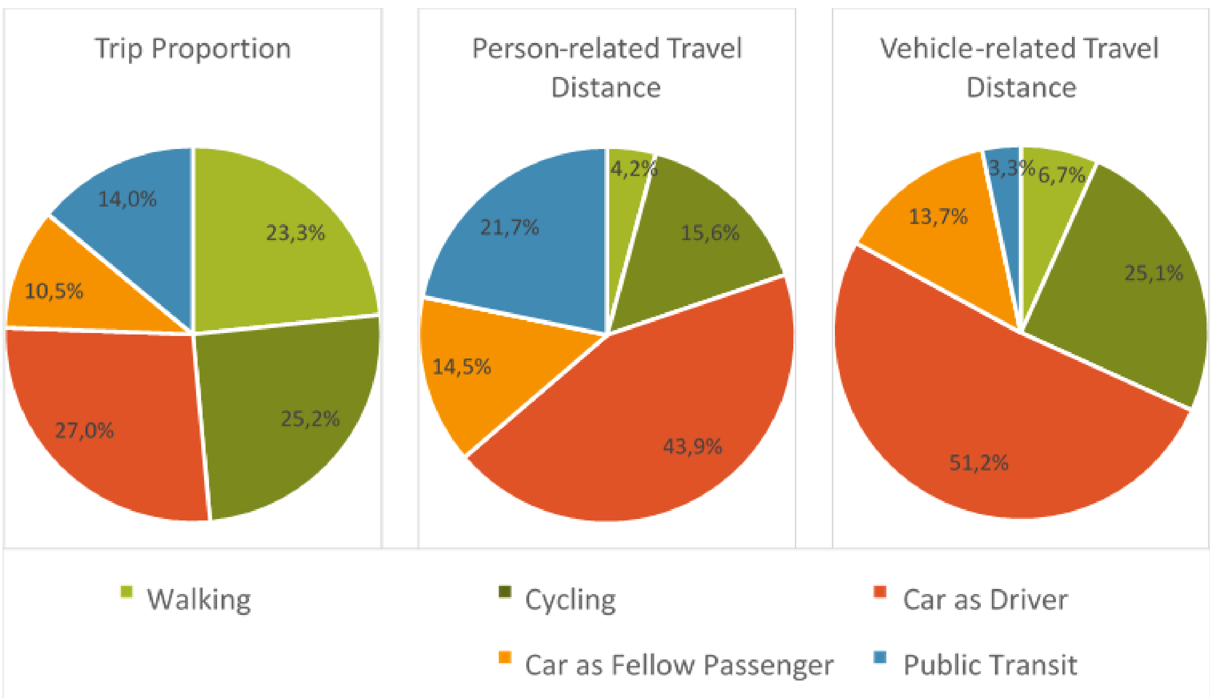


Figure 24: Modal Splits - baseline NO AV scenario

Compared to the baseline 2012, minor changes are illustrated in Figure 25. The minor changes in the trip proportion influences the traveled person and vehicle-kilometers. These shifts are caused by the different distribution of groups of persons in the new population model.

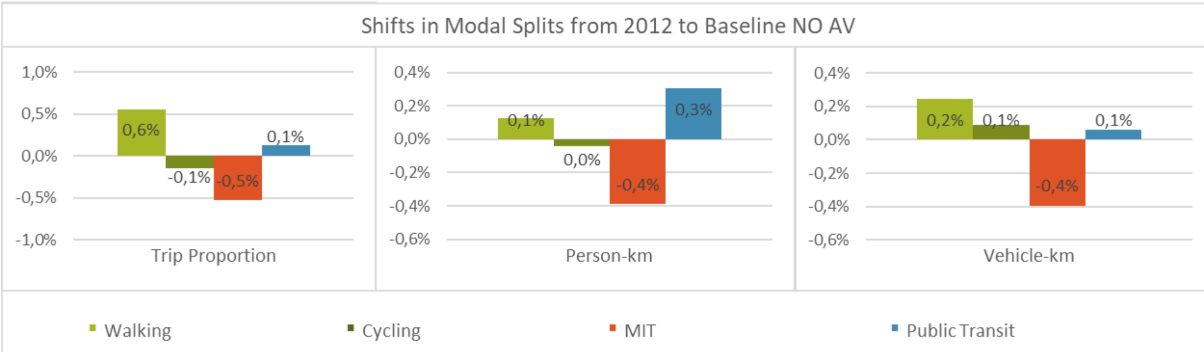


Figure 25: Shifts in Modal Splits - BL 2012 to BL NO AV

For the further analysis, the results of the baseline NO AV scenario are used as reference values to indicate the effects of the full autonomous traffic.

5.3 BEST-CASE SCENARIO

In the best-case scenario, the five conventional modes change to six modes. Instead of “Car as a Driver” and “Car as a Fellow Passenger”, the three modes of autonomous vehicles are implemented.

5.3.1 Traveled Distance

Towards the reference scenario (baseline NO AV), the overall person-related traveled distance in total almost stagnates. Only an increase of 1.8% in person-kilometers is caused by the implementation of AVs. Consequently, the calculated best-case scenario can be interpreted, that people’s mobility demand does not increase by the AVs. The change of traveled distances (person-km and vehicle-km) towards the baseline NO AV scenario for each mode of transportation is illustrated in Table 28.

Table 28: Traveled Distance - Comparison best-case to baseline NO AV

	Walking	**Cycling**	**MIT**	**Public Transit**
Person-km	-5,8%	9,2%	1,8%	-2,4%
Vehicle-km	-5,8%	9,2%	-12,8%	-10,6%

For the vehicle-related traveled distance, the AVs reduce the overall distance by 6.8% over all modes compared to the baseline NO AV scenario. Especially the MIT gets more efficient. The influence of the Ride Share (Figure 26) is reducing the traveled vehicle-distance of the MIT, even though the amount of the person-kilometers of the MIT slightly increases (1.8%, Table 28). Due to the higher efficiency of the AV-RS, the MIT can reduce its traveled vehicle distance by 12.8% towards the baseline NO AV scenario. Also, the Public transit is expected to decrease the vehicle-km compared to the baseline.

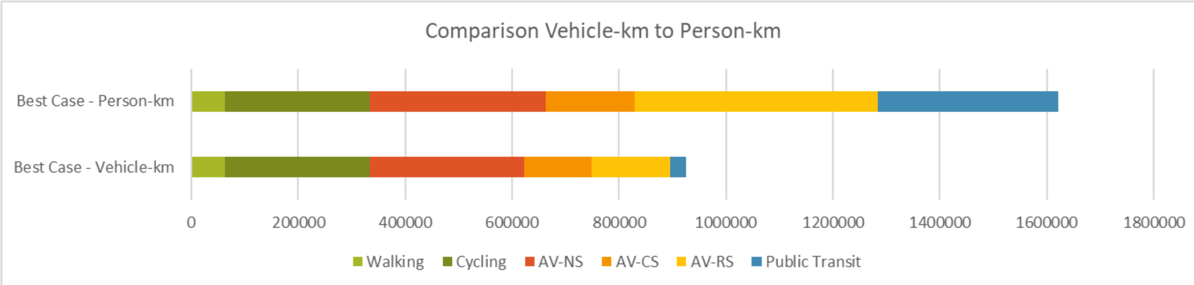


Figure 26: Comparison Vehicle-km to Person-km (best-case)

5.3.2 Modal Splits

In the best-case scenario, the modal splits seem to get more diverse. The Ride Share inherit a large amount of the trips done by MIT, while the privately owned AVs and Car Sharing AVs are less popular. Around 50% of the trips done by MIT are assigned to the AV-RS. The other 50% of MIT trips are roughly divided into 2/3 to private AV-NS and 1/3 to AV-CS.

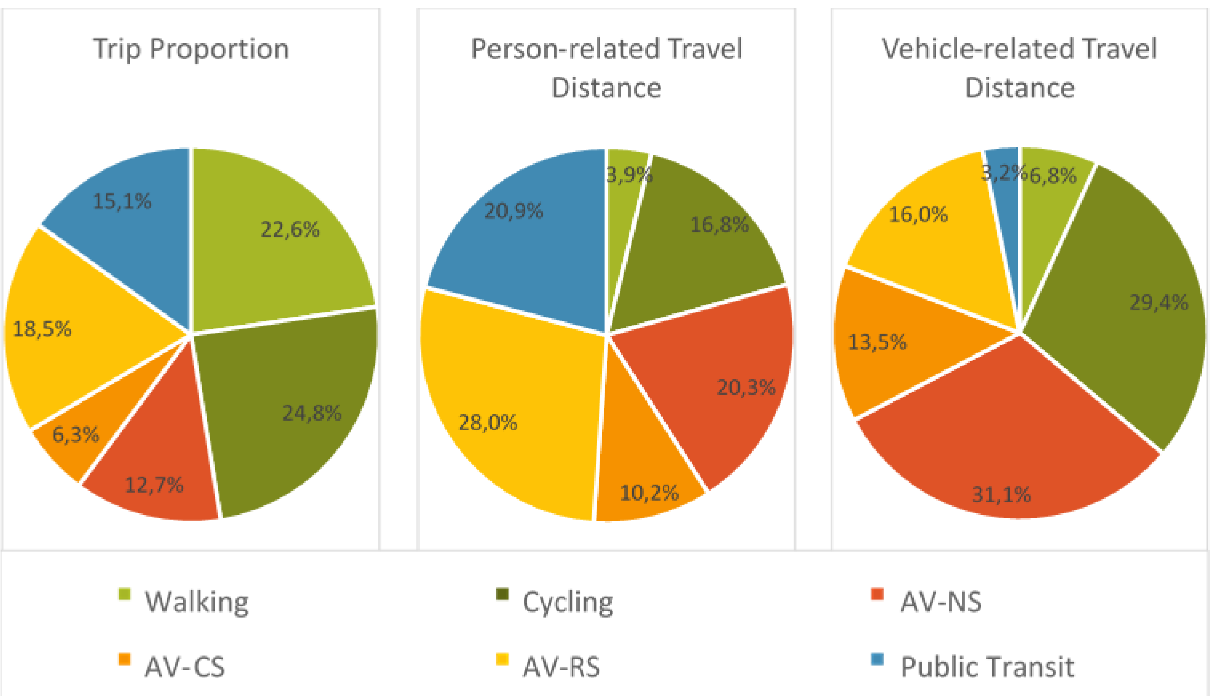


Figure 27: Modal Splits - best-case scenario

Regarding the trip proportion (Figure 27 and Figure 28, on the left), the active transportation modes lose percentages (Walking: -0.7% - Cycling: -0.4%) compared to the baseline NO AV scenario. The MIT stays the same, while public transit gains popularity. The traveled proportion of person-km (Figure 27 and Figure 28, in the centre) are especially growing for the cyclists (caused by the estimated larger range of e-bikes). The proportion of person-km traveled with MIT-modes stays equal. Comparing the proportion of vehicle-km of MIT, an increase of efficiency can be interpreted. Even though, the MIT does not change in the trip proportion, nor in the proportion of traveled person-km, the proportion of vehicle-km is reduced (see Figure 28).

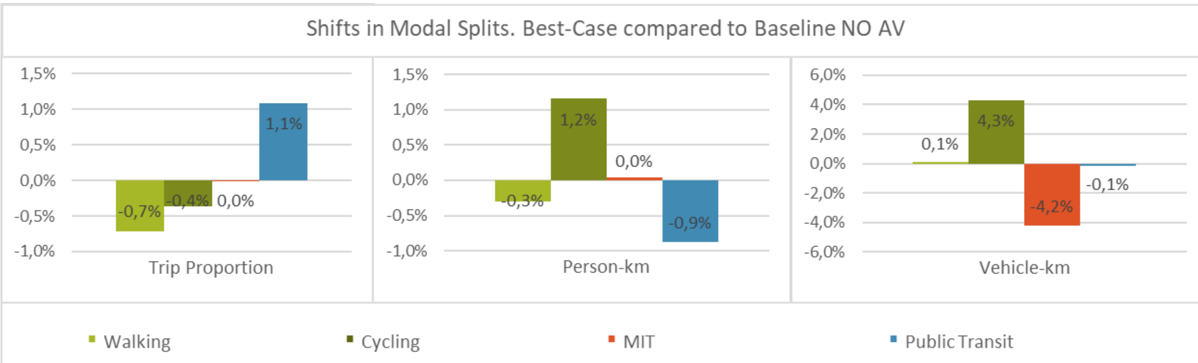


Figure 28: Shifts in Modal Splits: best-case compared to the baseline NO AV

For the modal split of the vehicle-km (Figure 27, on the right), the amount of traveled distance done by AV-NS is 33% of the overall traveled vehicle distance, which resembles only 12.7% of the trips. This illustrates the inefficiency of the privately owned AVs. In contrast, the autonomous Ride Share vehicles cause only 16% of the vehicle-km by serving 18.5% of the trips, that result in 28% of the overall person-km. The highest efficiency is obviously the public transit, that serves almost 21% of the person-km, by only inducing 3.3% of the total vehicle-km.

5.3.3 Unoccupied Trips

Derived from the results, the overall percentage of empty (unoccupied trips) of all AV-modes is 11.8% of the traveled vehicle kilometers. In detail, for the privately owned AVs (AV-NS) 18.1% of their vehicle-kilometers are caused by empty relocation due to driverless parking processes, empty returns to the origin and pick-up tasks of the user. For the autonomous Car Share vehicles (AV-CS) a total percentage of 6.5% of traveled-vehicle kilometers are unoccupied. The autonomous Ride Share vehicles are showing the lowest rate of empty trips. Only 3.8% of traveled vehicle-kilometers are caused by empty trips.

The following figure visualizes the stated numbers. The transparent partition of the bars, resembles the percentage of unoccupied trips, while the full coloured partition resembles the occupied vehicle kilometers.

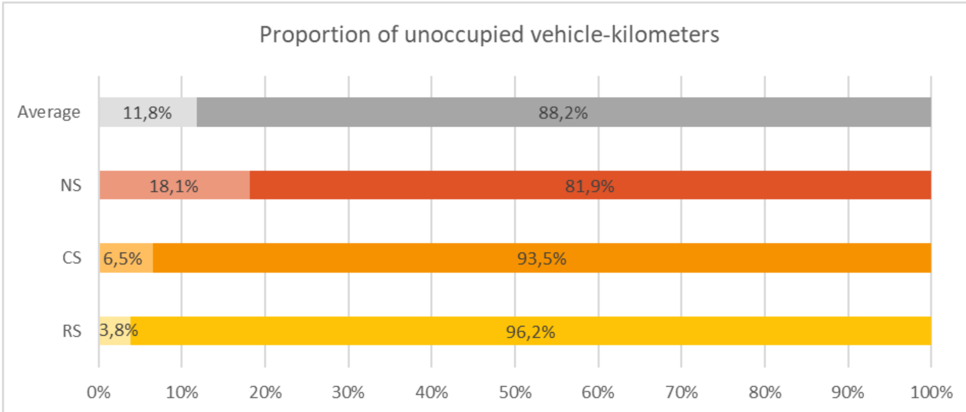


Figure 29: Proportion of unoccupied vehicle-km (best-case)

5.3.4 Occupancy Rate

The calculated fictional average occupancy rate for this scenario is 1.75 persons per vehicle. This can be seen as growth in efficiency for the whole transportation system compared to the reference scenario (1.6).

The separately calculated values for each mode are as follows: the active transportation modes of walking and cycling have the value of 1.0 persons/vehicle. The AV-NS has an average occupancy rate of 1.14 persons per vehicle, the AV-CS a $r_{occ} = 1.32$ and the AV-RS $r_{occ} = 3.08$, respectively. The occupancy rate for the public transit results in the value of 11.4 persons per vehicle.

5.4 WORST-CASE SCENARIO

The following sections describe the results of the calculated worst-case scenario and changes compared to the baseline NO AV scenario.

5.4.1 Traveled Distance

In the worst-case scenario, the traveled distance increases drastically compared to the baseline scenario. The person-related traveled distance increases by 28.3% in total. Caused by that aspect and higher amount of private, not-shared AVs (elaborated in the next section) and lower occupancy rates, the vehicle-kilometers over all modes ascend to additional 71.2 % of the total vehicle-kilometer compared to the baseline scenario. As seen in Table 29, the MIT is causing more person-km, and following from that, also 105.4% more vehicle-km. The development of public transit in comparison shows a decrease of 11.9% in person-km by causing an increase of 16.3%

vehicle-km. That can be interpreted as lose of efficiency, and lower occupancy rates in the public transit system.

Table 29: Traveled Distance - Comparison worst-case to baseline NO AV

	Walking	Cycling	MIT	Public Transit
Person-km	8,2%	7,0%	50,3%	-11,9%
Vehicle-km	8,2%	7,0%	105,4%	16,3%

As shown in Figure 31, the amount of AV-NS vehicle in the person-related traveled distance (50.5%) and in the vehicle-related traveled distance (65.9%) represent the largest part of the modal splits. Regarding Figure 30, the ratio of person-km to vehicle-km of the AV-NS are remarkable. The vehicle-km exceed the person-km, which can be interpreted as an average occupancy rate below one ($r_{occ} < 1.0$). This effect is the consequence of the empty trip proportion. In more detail, the results of unoccupied trips are covered in section 5.4.3.

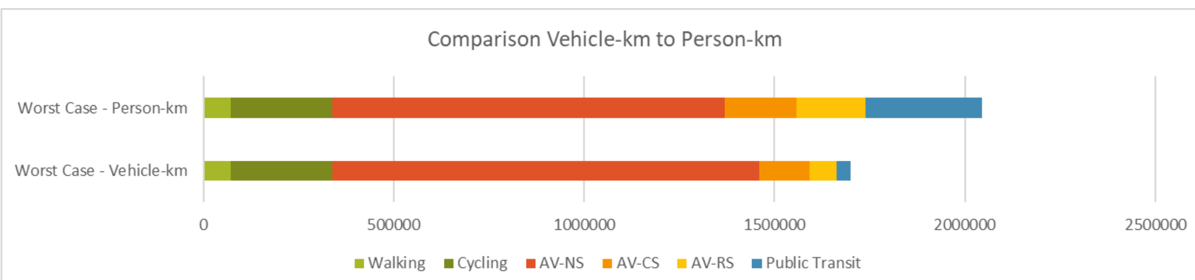


Figure 30: Comparison Vehicle-km to Person-km (worst-case)

Additionally, the difference of the person-km and vehicle-km is smaller than in the previous scenarios. That lead to the calculation of a fictive average occupancy rate over all modes. Furthermore, specific occupancy rates for each mode are calculated in section 5.4.4.

5.4.2 Modal Splits

Regarding the modal splits of the worst-case scenario, the percentages of the private AVs are salient. Around one third of all trips is performed by private AVs. These cause almost two-thirds of the overall vehicle-kilometers, by covering the half of the total generated person-kilometers. The Ride Share and Car Share services, are only covering 6.2% / 6.5% of the trips and around 9%

of the total person-km each. The active transportation, that is used in 43.5% of the trips, is resulting in only 16.5% of the traveled person-km.

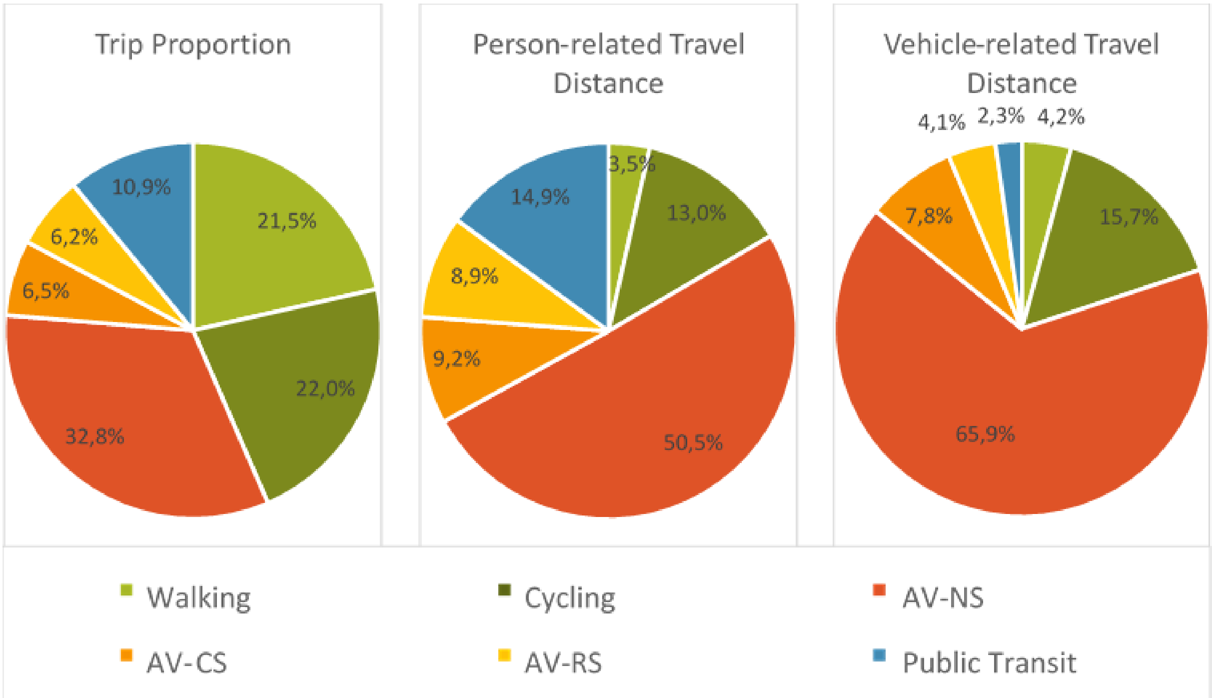


Figure 31: Modal Splits - worst-case scenario

This modal split compared to the baseline NO AV scenario leads to a shift of the values illustrated in the following figure. The MIT gains percentages in all modal splits, while all other modes lose. The trip proportion of the MIT grows by 8.1% towards the baseline scenario, while walking loses 1.9%, cycling 3.2% and public transit 3.0%, respectively. In the modal split depending on person-km, the MIT ascends by 10.1%, at the expense of 0.7% of walking-km, 2.6% of cycling-km, and 6.8% of traveled person-kilometers by public transit. Regarding the vehicle distance, the proportion of MIT increases by 12.9%, reducing active transportation by 11.9% in total, and 1.1% of public transit.

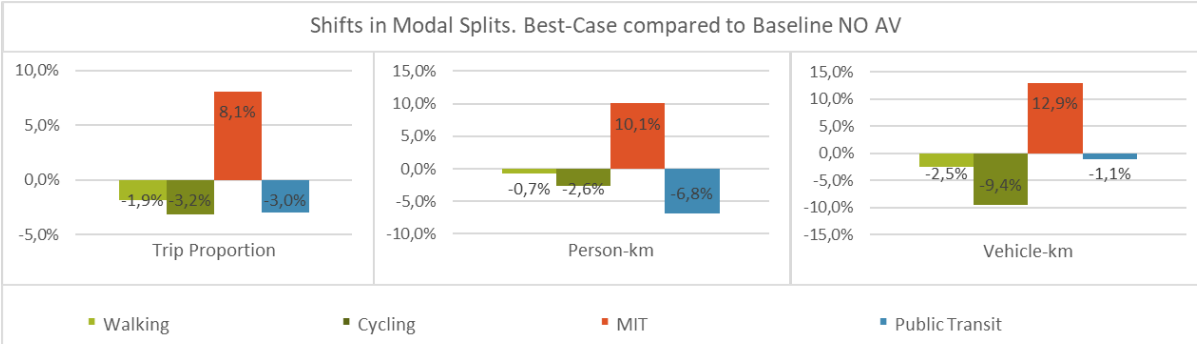


Figure 32: Shifts in Modal Splits: worst-case compared to the baseline NO AV

5.4.3 Unoccupied Trips

In the worst-case scenario, the AV-modes cause a higher number of unoccupied trips. Derived from calculations, the overall percentage of unoccupied trips of all AV-modes is 31.4% of the traveled vehicle kilometers, mainly caused by privately owned AVs with 35.1% unoccupied vehicle-kilometers. For autonomous Car Share vehicles (AV-CS) and Ride Share, the percentages of empty vehicle-kilometers doubles compared to the best-case scenario. The AV-CS has a total percentage of 13%, the AV-RS a total percentage of 7.4% of unoccupied traveled-vehicle kilometers.

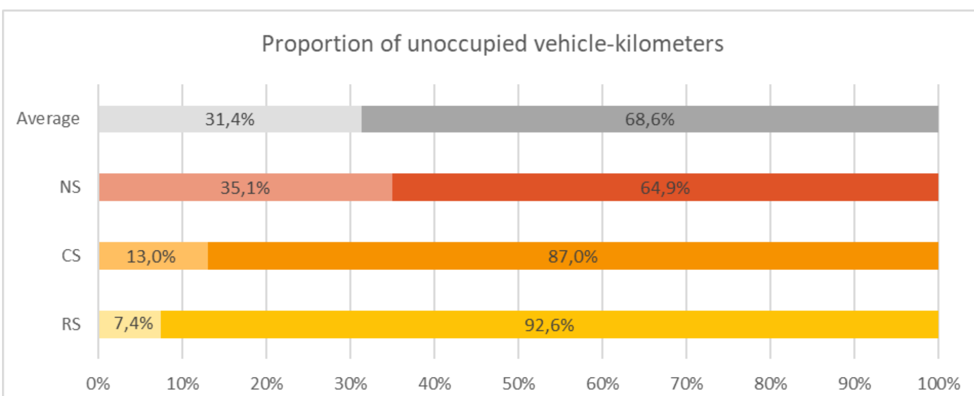


Figure 33: Proportion of unoccupied vehicle-km (worst-case)

The transparent partition of the bars in Figure 33 visualize the percentage of the unoccupied trips, while the full coloured partition resembles the occupied vehicle-kilometers.

5.4.4 Occupancy Rate

For the worst-case scenario, the fictional average occupancy rate is $r_{occ,f}$ =1.2 persons/vehicle.

If the occupancy rate is calculated for each mode separately, following values result. Walking and cycling are obviously stated as r_{occ}=1.0, public transit in average serves 7.9 persons per vehicle, the Ride Share approximately 2.6 persons per vehicle, while Car Share vehicles are in average occupied by 1.4 persons. The private autonomous vehicles in contrast, have an average occupancy rate of 0.92 persons per vehicle, caused by a high proportion of unoccupied trips.

5.5 COMPARISON OF ALL SCENARIOS

Regarding one scenario alone does not allow to overview the consequences of the impact of full autonomous traffic. Therefore, the following section tries to compare the scenarios and highlight the key results.

5.5.1 Modal Split

Regarding the modal split of trip proportion, the baseline scenarios do not differ from each other, as already mentioned. In these scenarios, red stands for the “Car as Driver” and orange for “Car as a Fellow Passenger”. In the best-case scenario, specifically, the MIT-modes split up in the three modes of AVs. The proportions almost stay equal to the baseline NO AV scenario, but with a strong Ride Share proportion, while in the worst-case scenario, public transit as well as active transportation lose percentages towards AVs. The Ride Share (6.2%) could be seen as covering an amount of former public transit trips (14%), while public transit in the worst-case scenario lowers to 10.9%.

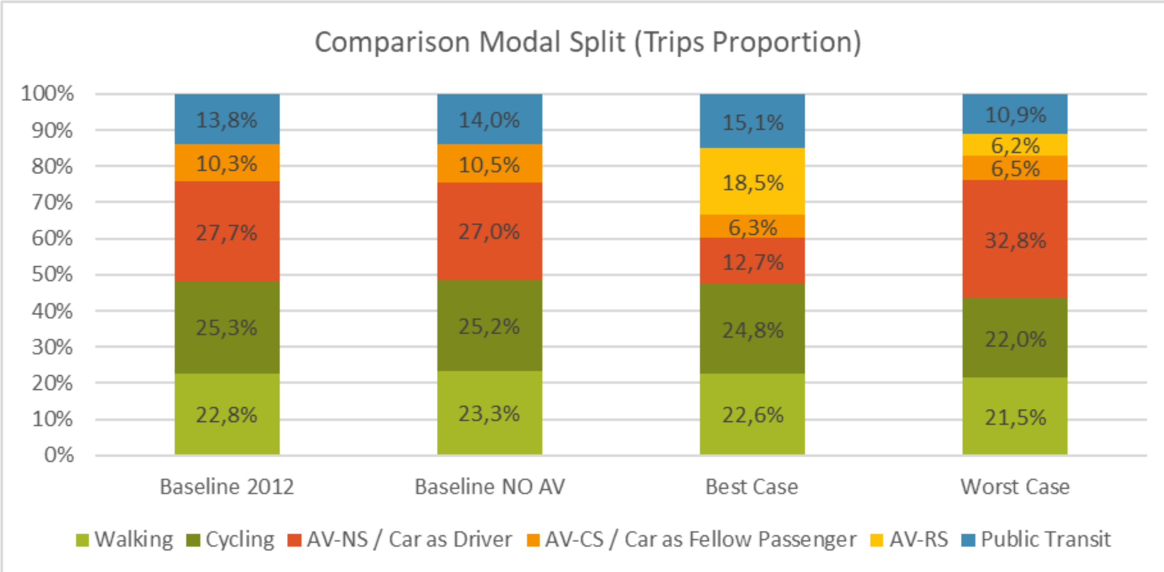


Figure 34: Modal Split (Trip Proportion) for all scenarios

5.5.2 Traveled Distances

5.5.2.1 Person traveled distance

To begin with the travel distances, the results for calculated person kilometers are shown in the following figure. Noticeable is, that the amount of traveled person-kilometers of the baseline NO AV and best-case scenario do not differ significantly. The person-km of the MIT stay almost equal, but instead of "Car as a Driver" and "Car as a Fellow Passenger", the three modes of AV inherit the same number of person-kilometers. The worst-case scenario on the other hand, leads to an increase of the person-km, specifically by the implementation of privately owned AVs. Consequently, in the worst-case scenario, AVs induce the traveled distances of the population. These demand needs to be served by vehicles, that could transport the persons, to satisfy the traveled person-km.

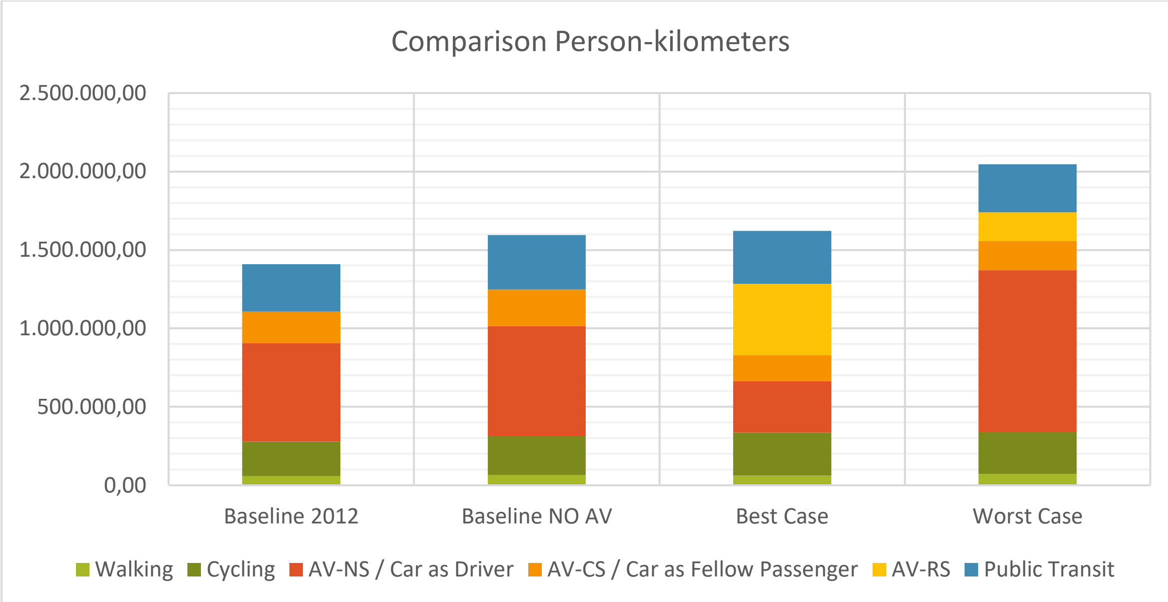


Figure 35: Comparison of person-kilometers (All scenarios)

In the next step, the analysis of the results focuses on the changes of the total amount of person-kilometers, which are illustrated in Figure 36. Three comparisons of each two scenarios are conducted.

On the left, the baseline NO AV is compared to the baseline 2012. All modes of transportation are expected to increase almost equally, with minor advantages for the walking and public transit. In the development of the baseline NO AV scenario, neither modifications on the trip distances, nor on the modal split or trip patterns. So, the only parameter that caused the increase of the person-km is the population growth.

In the centre, the best-case scenario is compared to the baseline NO AV scenario. The key finding of that comparison is, that the increase in of the MIT is only at 1.8%. So, by implementing the AVs in the way, that is matching to assumptions of the best-case scenario, the traffic conditions stay quite stable. The increase of the cyclists-km (9.2%) is mainly based on the assumption of the market penetration of e-bikes. The person-km of the public transit is calculated to lose, and probably shift towards the Ride Share services.

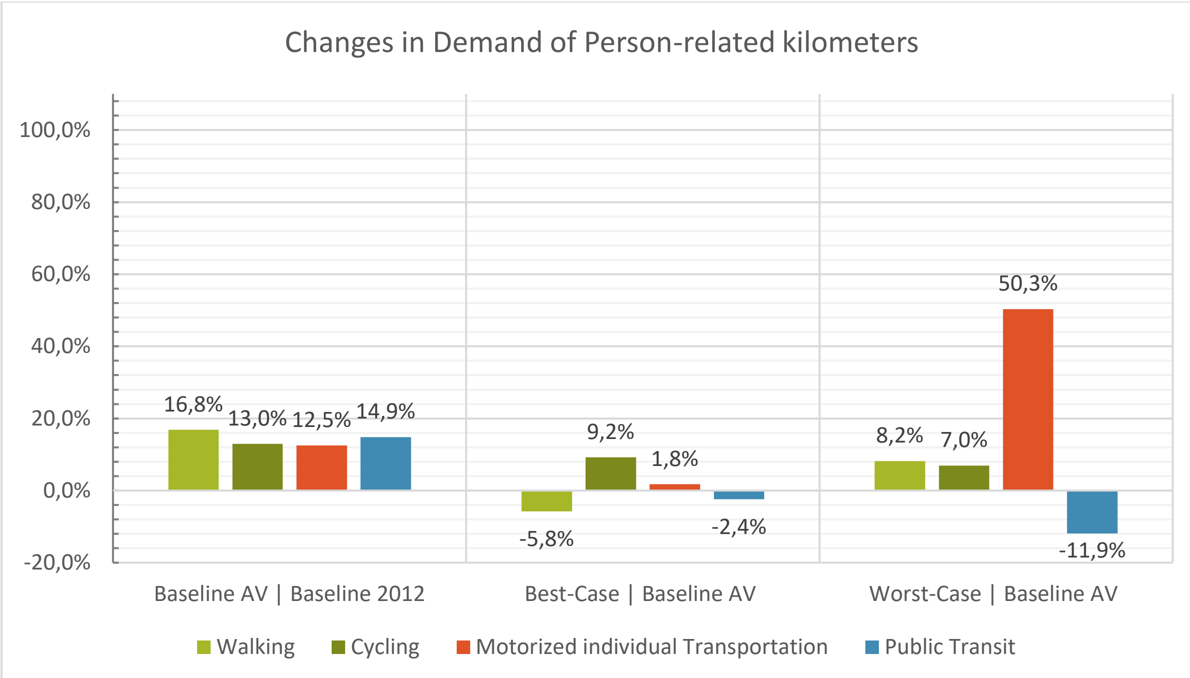


Figure 36: Changes of Person-related kilometers

On the right, the comparison of the worst-case and the baseline NO AV is shown. An enormous jump (50.3%) in person-kilometers of the MIT. Due to the new mobility gain in individual transportation, this scenario shows the consequence for public transit. It loses 11.9% of its person-kilometers.

Concluding, while in the best-case scenario the person-kilometer for the MIT only slightly increased, the worst-case scenario estimates a challenging increase of MIT traffic to the expense of public transit. The best-case scenario could be seen as quite stable traffic conditions compared to the worst-case scenario.

5.5.2.2 Vehicle traveled distance

After regarding the person-kilometers, in the following, the results of calculated vehicle-kilometers are presented. As seen in Figure 37, the total vehicle-km of the worst-case scenario are almost twice as much as in the baseline 2012 calculation. Whereas, the best-case scenario is almost on the same level as 2012. Towards the baseline NO AV scenario, the best-case scenario leads to a decrease of the vehicle-kilometers. In further detail, the Figure 38 illustrates the changes for the modes of transportation separately.

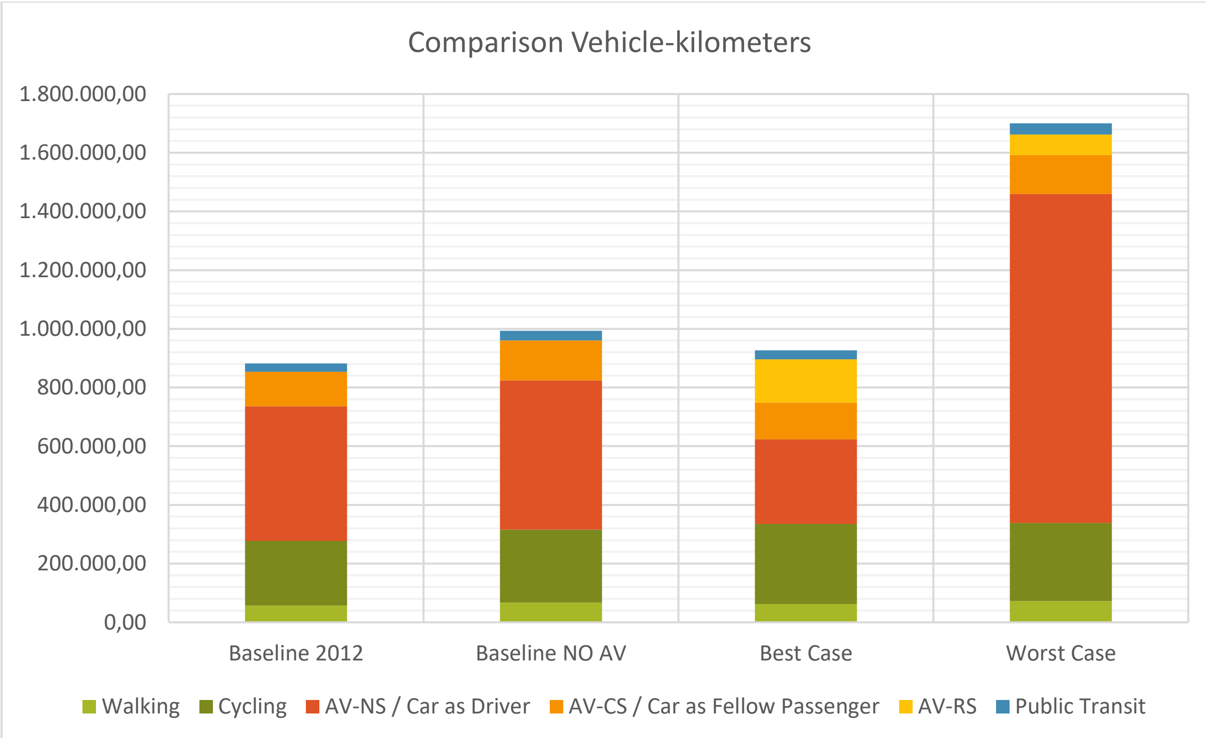


Figure 37: Comparison of vehicle-kilometers (All scenarios)

Figure 38 illustrates the changes in vehicle-kilometers in comparison of the scenarios. In the same order as in the previous figure, the comparisons are depicted, beginning from the left: baseline NO AV/baseline 2012, best-case/baseline NO AV, worst-case/baseline NO AV.

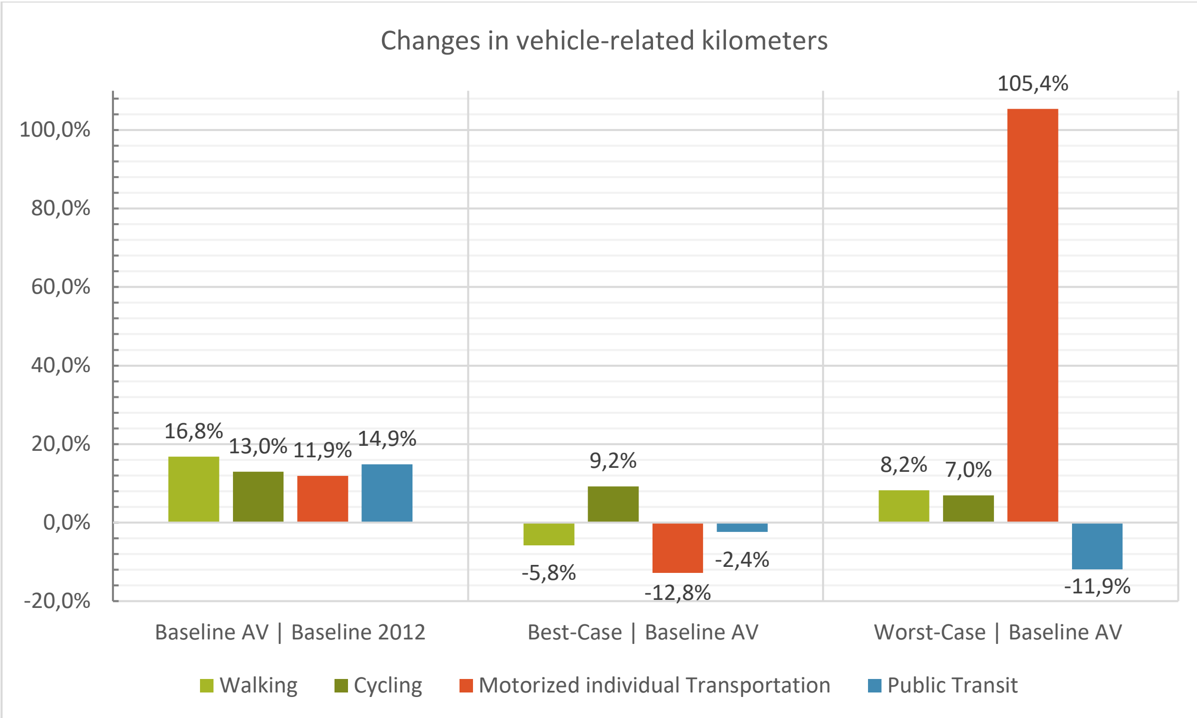


Figure 38: Changes of vehicle-related kilometers

For the first comparison, a similar increase as in the person-km is shown. No further explanations needed, due to only minor changes compared to the person-kilometers.

For the second comparison, the best-case scenario reduces the vehicle-kilometers for all modes except the cycling. The MIT can be reduced by 12.8% by AVs under certain assumptions for the best-case scenario. In terms of road traffic, the reduction of MIT is the main objective to handle congestion and space capacity issues. The mode of walking seems to lose traveled-km most likely by the modifications of the trip patterns. As it seems, H-trips, that are most likely done by walking, are reduced in the trip pattern modification. That could explain the decrease of the traveled kilometers of the mode "walking".

For the third comparison, the worst-case ends up with doubled MIT vehicle-kilometer value compared to the baseline scenario. This heavy increase of vehicle kilometers leads to a larger increase of road traffic. The public transit, in comparison, reduces by 11.9%. Both active transportation modes increase their traveled distance. For the mode of walking, this change can only be explained by the increase of trips, that have higher percentage of walking as mode choice, even though, the modal split of walking is modified to lose 10% popularity.

5.5.3 Unoccupied Trips

Comparing the scenarios regarding the unoccupied trips, the baseline NO AV scenario is used to serve as a reference point of the traveled vehicle distances in Figure 39.

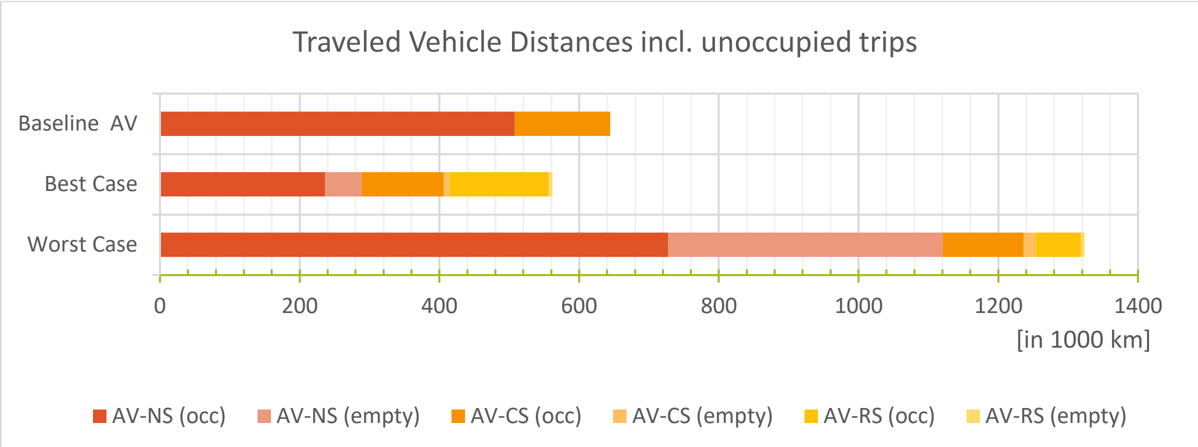


Figure 39: Comparison -Traveled Vehicle Distances inclusive unoccupied trips

The saturated coloured parts of the bars are resembling the occupied trips. In the baseline NO AV scenario, the red bar stands for the conventional mode of "Car as Driver", while the orange bar stands for "Car as fellow passenger". Due to the requirement of a driver in these two modes, no unoccupied trips exist.

In the best-case scenario, the overall traveled vehicle distance is reduced, and the proportion of unoccupied distance is, derived from Figure 40, calculated as 11.8%. In contrast, the worst-case scenario doubles the traveled vehicle-kilometers, of which 31.4% are unoccupied. The AV-NS in the worst-case scenario has an average proportion of 64.9% occupied and 35.1% unoccupied vehicle-distance (also illustrated in Figure 33).

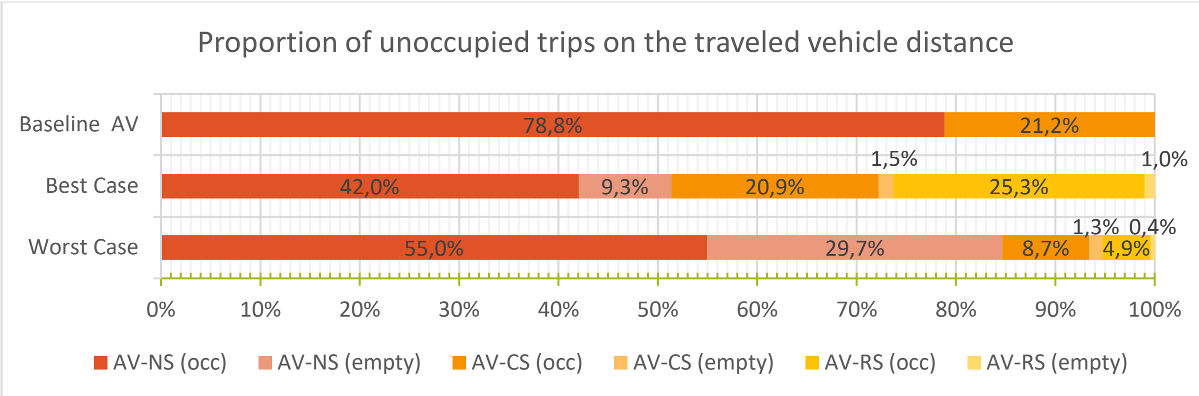


Figure 40: Comparison - Proportions of occupied & unoccupied Traveled Distances

The best-case scenario has 25.3% occupied AV-RS vehicle-kilometers with only 1% unoccupied vehicle-kilometers, whereas the worst-case scenario has approximately 5% of vehicle-kilometers performed by AV-RS, with 0.4% unoccupied vehicle-kilometers.

To sum up, Figure 40 illustrates, that large portions of the vehicle-kilometers are caused by unoccupied trips, while in the best-case scenario the AVs operate in a more efficient way. Especially for the large amount of AV-CS and AV-RS the calculated values for unoccupied vehicle-kilometers compared to the occupied distance justifies the potential of these modes.

5.5.4 Occupancy Rates

Comparing the fictional occupancy rates, the efficiency of the transportation systems as a whole can be ranked. As for the baseline scenarios, a fictional occupancy rate over all modes is calculated as 1.6 persons per vehicle. The best-case scenario improved slightly the efficiency to 1.75 persons per vehicle in average over all modes of transportation. In contrast, the worst-case scenario has an average occupancy rate over all mode of 1.2 persons per vehicle. Main reason is the high proportions of empty trips, that occur especially in privately owned AVs, which have in average an occupancy rate of 0.92 persons per vehicle-km.

5.5.5 Representation of the Population

The calculations, based on the most common trip patterns, are analyzed in terms of finding the amount of the represented persons with the most common trip patterns. Therefore, the represented population was calculated, by multiplying the population of each group and area with the probability of their most common trip patterns. As the following tables shows, it is found, that in all scenarios roughly 60% of the population are represented.

Table 30: Represented Population in the Scenarios

	Population	Represented Population	in %
Baseline 2012	307042	182379	59,4%
Baseline No AV	350271	209313	59,8%
Best Case	350271	209144	59,7%
Worst Case	350271	208651	59,6%

5.6 DISCUSSION

This section outlines some key underlying assumptions that have been made in this research and could affect the results. First of all, the results are compared to results of other studies. Next, the assumptions and limitations of the methodology are in the focus. Additional to the general assumptions and limitations mentioned in section 5.6.2, further limitations in the calculation process of the scenarios were found and are elaborated in section 5.6.3.

5.6.1 Integration in Context of other Results of Research

Compared to other studies, the decrease of vehicle-kilometers in the calculation (12.8% for MIT in the best-case scenario) is not as significant as, for example, in the study of Heilig et al., who found a reduction of 20% of all vehicle-kilometers. Furthermore, they predict the reduction of 45% of all trips (Heilig et al., 2017, pp. 20–21), which can not be compared, because the actual number of trips was not an objective of this thesis. In contrast, the worst-case scenario shall serve as warning, that AVs could lead to an increase of vehicle-kilometers. Instead of reducing, the calculation implies an increase of 105.4% of the motorized individual transportation. Comparable development for a worst-case scenario in the study of Heilig et al. is not stated.

The OECD study (OECD - International Transport Forum, 2015) found results, that are not exactly comparable due to different basic conditions. Nevertheless, it is worth mentioning, that in their Study, the Car Share fleet will increase vehicle-kilometers by 89%, but replacing trips performed by public transit, too. The Ride Share service in that study is supposed to provide the vehicle-kilometers that are served by private vehicles, traditional taxis and buses today. As result, the vehicle-kilometers traveled by the Ride Share services increase by only 6%.

The proportion of unoccupied vehicle-kilometer is compared to the study of Friedrich & Hartl. The calculated values for the best-case scenario (11.8%) and for the worst-case scenario (31.4%) differ significantly from their study, which states a range of 1–6% of unoccupied vehicle-kilometer including all types of AVs. They further differ, that for shared AVs, the proportion is in between 4% – 9% of unoccupied vehicle-kilometers (Friedrich & Hartl, 2016). The result of the best-case coincide with them. The calculated range of 3.8% – 6.5% matches the other studies results. The worst-case in contrast, differs significantly with a range of 7.4% – 13%. The main difference, as earlier mentioned, is that Friedrich & Hartl neglect the issue of unoccupied trips of privately owned AVs. That's why, the overall unoccupied vehicle-kilometers is stated as 1–6%.

To sum up, the calculated results are showing correlations to other conducted studies, especially for the best-case scenario. For the adverse consequences on traffic, different researches are mention them, but seldom quantify the outcomes. Therefore, the calculation of the worst-case scenario could be highlighted as a first attempt of quantifying negative consequences.

5.6.2 Limitations based on the general Assumptions

The calculation is based on survey data, so it is not projecting the exact behaviour of every individual in the scope. In fact, by analyzing one sample of the system and extrapolate it to the size of the scope, the extrapolation carries errors due to small sample size. Since automated vehicles are an ongoing research topic, the exact prediction of the impact of AVs is not possible.

Due to the limitation of not knowing how the future of AVs actually develops, the following general assumptions were considered for this study:

I. The automated vehicles that are meant in the thesis are defined as SAE automation Level 4 or 5 (see Chapter 2.1). These Levels allow the drivers to concentrate on other things while traveling. The drivers impact on the vehicle in terms of breaking, steering, accelerating or monitoring the environment is not needed. This is followed by the assumption that every person is allowed to be a passenger in an AV, neglecting the regulations of a driver license, duty of supervision for parents, etc.

II. The year of the market entrance as well as the year reaching the status of a completely full-automated traffic can not be predicted with certainty. Furthermore, it might will never reach the point of a full-automated traffic. Following, the population numbers and mobility behaviour for the point of time, at which the AV enter the market as well as at which the full-automated traffic takes place, can not be predicted. The elaborated population model is an approximate estimation.

III. The other urban transportation systems as the cycling network, public transit (especially the new subway, which is currently in construction) are not regarded in detail. As mentioned on p.56, the effects of the VEP can not be regarded in the calculation of the three scenarios. Besides that, future infrastructure projects could have also impacts on mobility behaviour, travel distances, etc. that would influence the outcome of calculations, but can not be considered.

IV. Due to the type of survey, which only conducted households around Karlsruhe, the data of commuter traffic is not included. Commuters, who live somewhere else and work in Karlsruhe, can hardly be modelled. Therefore, other sources have to be consulted. Also, through-traffic, which has neither its origin nor its destination within the scope, is not observed in this thesis.

V. Changes of ticket prices, or other not predictable pricing costs are neglected in the calculations in terms of public transit, Car Share or Ride Share services.

5.6.3 Limitations of the Calculation

In comparison to the general assumptions, it’s also not exactly quantifiable how parameters as the traveled distances, and mobility patters will change. Furthermore, the following paragraph lists some specific issues of the calculation process:

i. Due to the lack of data of certain groups of persons (seen in Table 6 and Figure 15), some groups of persons and their analyzed trip patterns are not representative. Nevertheless, they are applied for the whole group of persons and used for calculating the overall traveled distances. A larger sample size could neglect this error in future research.

ii. The modal splits illustrating the traveled vehicle-kilometers contain the error, that the public transit is not calculated with an accurate occupancy rate. The average occupancy rate for all different kinds of public transit has to be researched in further detail, to obtain a more accurate value. Within this thesis, the occupancy rate was roughly assumed based on the explanations in 3.7.2.3.

iii. Due to the survey data of households, which does not differ the motorized traffic into trucks and passenger cars, it is assumed, that the calculated value is primarily done by passenger cars. Moreover, delivery services, postal service, transportation of goods, etc. are not included in the data set. Especially to the trend of digitalism (online shopping, etc.), the sector of delivery service and other logistic traffic could grow drastically. Based on the survey of households, the calculation is limited to implement these other sources (mainly freight delivery) of traffic.

iv. Due to the unpredictable point of time, when full-automated traffic is reached (see point III. of the previous page), the population growth can not be predicted. The forecast for the population (of the City of Karlsruhe) reaches to the year of 2035. The calculation implies, that the population develops as the “dynamic” scenario of the forecast and stays the same after reaching the years of 2035.

Furthermore, the developed population model carries a certain error due to the lack of available data. The distribution into groups of persons by the “distribution key” is a theoretical construct, therefore, as example, the numbers of students seem to be too low. In addition to that, the year of 2015 as starting point for the prediction is vague. As stated in the introduction, the year of 2015 has an untypical peak, based on which the prediction of 2035 was developed.

v. During the modification process, it was noticed, that the modification of the mode choice for the scenarios is not only depending on the trip purpose, as for example the average trip distance. The change of the mode choice further depends on personal preferences, value of transportation costs and various factors related to the group of persons. Therefore, it would be more reasonable to define the modification factors by the groups of persons additional to the trip purpose.

vi. As in section 5.5.5 shown, only 60% of the population is represented by using the ten most common patterns. The more uncommon trips are not considered within the calculation. At this point, it is worth mentioning, that the uncommon patterns are assumed to consist of more trip purposes than the common trips. This lead to more available combinations of the trip purposes, and lower probability to have similar trip pattern. Therefore, for the 40% of uncommon trips, the caused traveled distances can not be linear extrapolated, because they are estimated to cause higher amount of traffic due to longer patterns.

6. RECOMMENDATIONS

6.1 FUTURE CHALLENGES CAUSED BY AUTOMATED TRAFFIC

Some challenges for traffic planners, urban planners and city authorities that AVs entail, can be derived from the elaborated calculations, others are extracted from other researches and literature.

As illustrated by the best-case, the reduction of traffic volume induced by AVs together with the reduction of vehicle-kilometers is only possible with higher amounts of Ride Share trips. The increasing travel demand is not solved by implementing private AVs or AVs as Car Sharing vehicles – the occupancy rate has to be increased as well. Similar conclusions are drawn by the study of (Friedrich & Hartl, 2016). Is that not the Case, traveled vehicle-kilometers could increase drastically. As in the worst-case calculated, the traveled vehicle distance for MIT could double.

6.1.1 Ride Share Acceptance

As the calculation shows, the key element to regulate future traffic volumes seems to be the idea of Ride Share. Ride Share is based on its higher occupancy, higher conventional (private) car reduction ratio and comparable small increase of the trip distance, the most efficient transport mode of the motorized individual traffic. As mentioned in the section 0, the acceptance of persons to use a Ride Share service is nowadays limited and correlated on factors as e.g. gender, age, etc. as well as local supply and infrastructure. The challenge for the future is, to support the development of Ride Share services as well as promote Ride Sharing to the population.

6.1.2 Competition between Car Share and Ride Share

An issue arising by having to sharing services could be the competition of them. Car Sharing services and Ride Share services, if not be operated by the same provider, could stay in competition of users. As earlier mentioned, both services are expected to operate more efficient, if the user demand is high and the surrounding conditions stay constant. A competition in that field could reduce the efficiency of each CS / RS provider.

Moreover, the AV-CS does not reduce the vehicle-kilometers as much as the AV-RS. The Car-Share has the potential to reduce car ownership indeed, and that leads indirectly to less use of cars for short trips, but it does not have a noticeable direct impact on traffic reduction in the calculation. The occupancy rates of Car Share are expected to be higher than not shared AVs, but Ride Share is predicted to have more potential in actual on-road traffic reduction.

6.1.3 AVs compete with PT

As seen in Figure 38, the traveled kilometers with AVs cause as twice as much traffic as in the baseline NO AV scenario, while the public transit decreases. The issue of the conventional public transit is, that it can often not offer door-to-door connection. This issue will result in the lost of acceptance and consequently a lost in the traveled kilometers. The shift towards AVs, and the inefficiency of AVs seen in the worst-case, cause this high amount of new MIT road traffic. For the public transit, which already depends on financial support in order to provide the basic mobility for the public, will get less feasible. Buses, that are able to transport numerous people, will cease and be replaced by more, smaller autonomous vehicles, which exacerbate the traffic situations.

6.1.4 Parking Space

The issue of the worst-case scenario regarding parking can be split up in two aspects. First, the decentralized parking and high rate of return-to-origin trips will cause a high number of unoccupied trips, and consequently more traffic. Second, if the change from owning an AV-NS does not switch to shared AVs (as in the worst-case), the parking situation in the City core will exacerbate. So, the parking issue either increases traffic congestion by empty parking trips or increases pressure on parking space in city centers.

6.2 MEASURES AND RECOMMENDATIONS TO HANDLE THE CHALLENGES

6.2.1 Measures to Support Ride Share

To face the challenge of the lack of acceptance to use Ride Share, promotion and advertisement to inhabitants could lead to a rising mode choice. Especially, the older generation is skeptical. Therefore, Ride Share services have also to be available for the “offline” generation, who is not affine to smartphones. Another example could be, to enable a woman-only Ride Share service to increase the subjective safety feeling and acceptance of female users. Services as BlaBlaCar already offer this option. To support Ride Share services, City authorities could search and invest in partnerships with start-ups, big car manufactures and public transit services, that offer Ride Share services or Ride Selling Fleets. Within the process of establishing a functional Ride Share network, researches could focus on the required number of AV-RS. Besides the cost for each AV as a Ride Share vehicle, that is around €60,000 (Friedrich & Hartl, 2016), the investment costs will exceed the Cities budget quickly. Due to the high investment, it is recommended to think about financial constructs such as founding an operational company including partnerships with car manufactures, energy companies and policy authorities as well as the public transit companies. Especially, policy authorities should include public transit operators within these partnerships, because if Ride Share is not part of the public transit network, it will replace parts of the network.

Another point is, that these partnerships could help to develop of specific Ride Share vehicles, which satisfy the user demand of guarantee private space, storage space for luggage in addition to higher number of seats. The comfort and privacy space could again lead to higher user acceptance.

6.2.2 Measures to Support Car Sharing

Similar to the RS, the vehicles in a Car Share fleet have to be match the purpose of the trip. Specific interior design meets the requirements of the user, as for example, a business person wants a comfortable working space with table; a family needs space for all members and preferable a design to interact with each other. The size and resulting energy consumption can be modified for different trip purposes and user groups. So, instead of having a fleet of one type of AV, the Car Share fleet can be optimized to provide smaller, electrified cars in urban areas and short trips, and higher range and larger cars for rural areas and long-distance trips.

Further measures to support Car Sharing could be exclusive job memberships, parking facilities for Car Sharing vehicles only or combined memberships with bike share providers or public transit, for example.

6.2.3 Measures to Support Public Transit

As already discussed in 2.5.8, the public transit could face the challenge of rethink its form of mobility. Especially in the worst-case scenario, the public transit is competing with the AVs (as described in 6.1.3). To strengthen the role of the public transit, the Ride Share services need to be implemented into the public transit system. In the analysis, the Ride Share is declared to the MIT, but if it is part of the public transit system, it can be seen as a new chance for public transit. Especially in the best-case, the Ride Share vehicles serve larger number of trips. Concepts of smaller and more flexible buses, acting as Ride Share vehicles are already planned. Instead of operating on defined routes, the public transit vehicles could operate as an autonomous-mobility-on-demand service, which is more flexible than the conventional public transit. Furthermore, some futuristic visions see the public transit vehicles as small individual cells, which can be connected together as one vehicle while driving and split up as a single cell for the last-mile. So, as long as the trip can be pooled, the cell connects with other cells to one bulk of cells, until the user routes go different paths.

As part of the services of general interest, the city authorities have to provide a functional public transit network, that is affordable for users. Therefore, law regulations could control the competition between CS / RS and public transit (Friedrich & Hartl, 2016, p. 64). Especially in terms of costs, the public transit which is subsidized by governmental/federal authorities, needs to provide affordable prices. To guarantee the prices for public transit, CS / RS services prices have to be regulated somehow in case of substitution of public transit by AVs.

6.2.4 Traffic Management

Policy authorities could regulate the traffic and prices of privately owned AVs by road tolls or parking fees. Road tolls could depend on occupancy rate and peak hour fees in urban cores. That could lead to higher willingness to share the ride within dense areas. Furthermore, the restriction of private AVs or even Car Share AVs could be a measure to reduce traffic on hot spots (Friedrich & Hartl, 2016, p. 65), for example, around shopping malls or main train stations. Measures could go so far, that private ownership of cars in city centers is probably banned, as policy-makers in Oslo announced (Lang et al., 2016). This leads to a shift of attractiveness towards the shared mobility services.

6.2.5 Infrastructure

As an infrastructural measure, it is necessary to support the development of the cellular network in the rural area or Wi-Fi network in the urban area. The autonomous vehicles depend on their ability to connect and communicate with each other (V2V), with the infrastructure (V2I) and other facilities (V2X). This leads to other infrastructural measures. The authorities have to develop a concept, how the infrastructure should be equipped. The idea of the connected vehicles, the traffic signals, lane keeping systems, dynamic speed limitations, dynamic platooning, early warning systems, as well as many other processes can be coordinated by the idea of connected vehicles. The policy-makers have to answer certain questions, at the example of the parking process:

- Where will "smart" parking facilities be provided, in the city centre or outside?
- Is the goal to create an urban core without parking space in terms of gaining new space for urban planning?
- Are parking lots get equipped with sensors to get the information, whether they are occupied or not?
- Will parking for shared AVs be prioritized in certain areas (e.g. lower fees, priority parking lots)?
- Will the parking facilities be equipped with magnetic induction charger for e-vehicles?

Other infrastructural measures include a digital traffic management system, which allows sharing traffic and other information as well as the ability to optimize the route choices, signalization, the search for parking lots and the connection to public transit. Algorithms to manage the traffic demands under consideration of travel times, environmental, economical and traffic-political aspects.

Regarding signalized intersections that may in future communicate with autonomous vehicle will face the problem of the recognition of pedestrians and cyclists. Which technique enables the intersection to identify them is unclear, also whether it is necessary to identify them. Possible techniques could be based on Bluetooth or other smartphone-based connections, or video techniques.

For now, city authorities should focus on measures to enable the communication channels between infrastructure and vehicles. In further development on higher automation levels, the requirements of infrastructure will specify. Parking facilities could already be prepared in terms of valet parking, because this level of automation could be on the market within the next years. This case means, that in front of a parkade the users leave the car, while it can search a free parking lot in the parkade autonomously.

6.2.6 Parking Space

In both scenarios, demand on parking space in the City core caused by the traffic from the surrounding areas could be reduced.

In the best-case scenario, due to the shift to shared autonomous vehicles (SAV), the parking space for privately owned AVs can be reduced, and either be used for shared vehicles or even gained space for urban development. As Fagnant's & Kockelman's analysis shows, "each SAV could serve the same number of trips as 10 household-owned vehicles" (Fagnant & Kockelman, 2015, p. 172). In an earlier paper, they stated and replacement of 12-13 privately owned vehicles by one SAV (Fagnant & Kockelman, 2014, p. 12). Other studies state similar number, as for example Rigole, who writes: "An SAV-based personal transport system has the potential to provide an on-demand door2door transport service with a high level of service using less than 10% of today's private cars and parking places, which is consistent with results reported in the literature" (Rigole, 2014). Following from that assumptions, the parking space could lead to gain of 90% new land for new urban development. Some of that might still need to be used for prioritized central parking facilities, because of the requirement of central parking facilities in terms of reducing the number of unoccupied parking trips.

In the worst-case scenario, in contrast, the reduction of the demand in parking space causes new traffic by unoccupied returning trips. The prohibition or reduce of parking space for Not-Shared AVs could consequently cause larger issues in traffic conditions than it supports shared AVs.

6.3 FURTHER RESEARCH

Finally, the following is suggested as future directions for researches that directly have impact on the presented methodology:

- Researching the parameters of that are used to calculate the average travel distances (increase factor, that is caused by the new utility of the travel time; the occupancy rate of the three types of AVs; the proportions of unoccupied relocations of AVs)
- Researching the change of trip patterns through AVs,
- Researching the mobility behaviour in terms of the mode choice, when AVs (Level 4 or Level 5) enter the market.
- Elaborating a future population prediction, regarding the areas of research and groups of persons.

7. CONCLUSION

In sum, autonomous vehicles will change various aspects of our daily life in near future. In diverse fields, such as environmental management, safety, digitalism, technology and governance, authorities will face the challenging future with autonomous vehicles. Specifically, the field of traffic and transportation will be influenced. This thesis tries to quantify possible developments caused by AVs, in order to answer whether the consequences for the traffic situation will ultimately be positive or negative.

This thesis examines the effect of universal automation of motorized vehicles, so no drivers are needed in terms of any driving task (Level 4 or Level 5). Based on the mobility survey of 2012 for the example of Karlsruhe, a method for an estimation was developed to quantify the consequences in two scenarios. The given survey data had to be analyzed and prepared for the construction of the scenarios. As two parameters, the average trip distance and the modal split depending on each trip purpose of each group of persons in each area are used in the modification. As a third parameter of modification, the analyzed trip patterns are picked. These modification parameters are differently adjusted in terms of resembling an efficient implementation of AVs for the best-case scenario, and on the other hand, resembling an inefficient way of using AVs regarding the traffic volume.

The main results are shown in Figure 37 and Figure 38, which illustrate the traveled vehicle-kilometers in the comparison of the scenarios. On the one hand, autonomous vehicles have the potential to reduce traffic as seen in the best-case scenario. For the example of Karlsruhe, under the condition of the applied assumptions, the overall traveled vehicle distances can be reduced by 12.8% for the motorized individual transportation (MIT). On the other hand, the worst-case scenario could approximately double the overall traveled vehicle distances for the motorized individual transportation (increase by 105.4%). This wide range of difference results, illustrate the uncertainty of the estimation.

Furthermore, the results indicate that the AVs are more likely to exacerbate the traffic conditions, by causing more trips and a large amount of unoccupied vehicle-kilometer. For the scenarios the amount of unoccupied traveled vehicle-kilometers is (illustrated in Figure 40) stated as 11.8% for all modes of AV in the best-case and 31.4% for the worst-case. In fact, the most efficient mode of AVs is the autonomous Ride Share vehicle, for which the calculated average occupancy rate results in 3.08 persons per vehicle in the best-case. In combination of the mode choice of 18.5% of the trips and only 1% of the vehicle-kilometers unoccupied, the Ride Share services relieve the traffic situation in the best-case.

For the worst-case the average occupancy rate for AV-RS results in 2.6 persons per vehicle, while the privately owned, not shared AVs (AV-NS) have an occupancy rate of 0.92 persons per vehicle, caused by the high proportion of unoccupied vehicle-kilometers. In addition to that, the modal split shows (Figure 34), that the largest number of trips is done by AV-NS. As consequence, the traffic situation gets more inefficient and congested. Furthermore, the public transit gets substituted by AVs, which leads to larger space use on the road network.

Besides the impact on the traffic and transportation network, that is elaborated here with the focus on the daily life of households, the impact of autonomous vehicles includes far more than this thesis covers. Within the sector of transportation, the behaviour of commuters, delivery and logistic services, transportation of goods, etc. are necessary to be further researched. Risks and chances in other sectors, as briefly mentioned in the section 2.5, include safety aspects, privacy and digital security issues, mobility gain of certain groups as well as environmental issues requires further political decisions and regulations (e.g. when is the safety of an AV acceptable? Is a driver license needed – for underage children – for blind people, etc.?) With that knowledge, various aspects need to be taken into considerations for future management of implementing autonomous vehicles. The estimated range of traffic consequences acquired in this project should reveal the factors that have to be regarded and which parameters can be influenced in terms of leading the development in the right direction. The field of traffic and transportation will definitely face another outstanding change by the implementation of autonomous vehicle in near future and will carry a large potential for benefiting the society, but on the other hand could flood our roads challenge the traffic network in its capacity. Both pathways are possible, it is in the hands of policy authorities and traffic planners to steer the future in a positive future for a society with full automated traffic on the roads.

APPENDICES

Appendix 1: Vehicle per Person for the three areas (Stadt Karlsruhe, Amt für Stadtentwicklung - Statistikstelle, 2017b)

Area	**Population**	**Vehicle**	**Vehicle/pers.**
Karlsruhe I	11978	7835	65%
Karlsruhe II	110558	45134	41%
Karlsruhe III	184511	102622	56%
total	307047	155591	

Appendix 2: Population of Karlsruhe - Number of unemployed persons, Source: (Stadt Karlsruhe, Amt für Stadtentwicklung - Statistikstelle, 2017b)

Gesamtstadt	Arbeitslose
Karlsruhe	8.509

Stadtteile	Arbeitslose
01 Innenstadt-Ost	391
02 Innenstadt-West	316
03 Südstadt	765
04 Südweststadt	555
05 Weststadt	644
06 Nordweststadt	260
07 Oststadt	496
08 Mühlburg	649
09 Daxlanden	366
10 Knielingen	246
11 Grünwinkel	280
12 Oberreut	526
13 Beiertheim-Bulach	152
14 Weiherfeld-Dammerstock	131
15 Rüppurr	173
16 Waldstadt	341
17 Rintheim	192
18 Hagsfeld	187
19 Durlach	839
20 Grötzingen	156
21 Stupferich	33
22 Hohenwettersbach	28
23 Wolfartsweier	67
24 Grünwettersbach	61
25 Palmbach	29
26 Neureut	334
27 Nordstadt	233

Appendix 3: Population of Karlsruhe - Number of people of the age 65 +, Source: (Stadt Karlsruhe, Amt für Stadtentwicklung - Statistikstelle, 2017b)

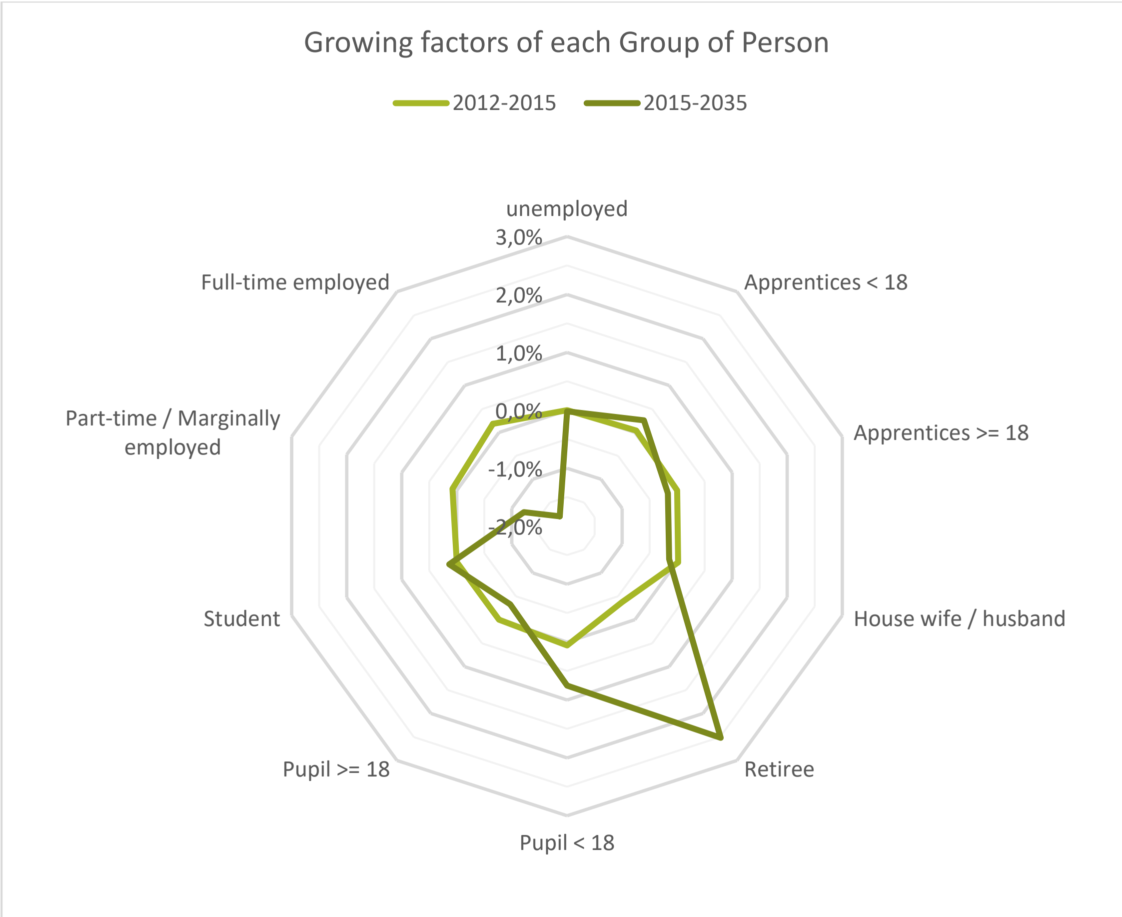
Gesamtstadt	Personen
Karlsruhe	54.881

Stadtteile	Personen
01 Innenstadt-Ost	883
02 Innenstadt-West	1.180
03 Südstadt	2.192
04 Südweststadt	2.926
05 Weststadt	2.924
06 Nordweststadt	2.735
07 Oststadt	2.580
08 Mühlburg	3.179
09 Daxlanden	2.960
10 Knielingen	1.712
11 Grünwinkel	2.433
12 Oberreut	1.792
13 Beiertheim-Bulach	1.220
14 Weiherfeld-Dammerstock	1.674
15 Rüppurr	2.604
16 Waldstadt	3.141
17 Rintheim	1.163
18 Hagsfeld	1.089
19 Durlach	6.543
20 Grötzingen	2.193
21 Stupferich	604
22 Hohenwettersbach	445
23 Wolfartsweier	615
24 Grünwettersbach	1.000
25 Palmbach	330
26 Neureut	3.659
27 Nordstadt	1.105

Appendix 4: Retirees - Percentage of over 65-year-old persons

Group of persons	**<65**	**65 +**
unemployed	3,01%	0,08%
Apprentices < 18	0,20%	0,00%
Apprentices >= 18	2,67%	0,08%
House wife / husband	5,19%	3,46%
Retiree	**3,78%**	**93,09%**
Pupil < 18	26,48%	0,00%
Pupil >= 18	3,54%	0,00%
Student	4,23%	0,00%
Part-time / Marginally employed	15,87%	1,26%
Full-time employed	35,02%	2,04%
total	100,00%	100,00%

Appendix 5: Growing factors of each Group of Person



Appendix 6: Covered percentages of Trip Patterns in the calculation - depending on the G.o.P.

Area	Groups of Persons	% of covered Trip Patterns
Karlsruhe I	unemployed	74,0%
	Apprentices < 18	0,0%
	Apprentices >= 18	76,5%
	House wife / husband	67,5%
	Retiree	70,8%
	Pupil < 18	73,3%
	Pupil >= 18	64,8%
	Student	77,0%
	Part-time / Marginally employed	47,0%
	Full-time employed	61,0%
Karlsruhe II	unemployed	52,4%
	Apprentices < 18	0,0%
	Apprentices >= 18	77,4%
	House wife / husband	54,9%
	Retiree	70,1%
	Pupil < 18	61,5%
	Pupil >= 18	78,2%
	Student	66,0%
	Part-time / Marginally employed	41,9%
	Full-time employed	52,7%
Karlsruhe III	unemployed	74,9%
	Apprentices < 18	100,0%
	Apprentices >= 18	69,4%
	House wife / husband	60,5%
	Retiree	62,0%
	Pupil < 18	67,1%
	Pupil >= 18	67,6%
	Student	63,2%
	Part-time / Marginally employed	49,8%
	Full-time employed	60,8%

REFERENCES

Axhausen, K. W., & Frick, M. (2004). Nutzungen, Strukturen, Verkehr. Arbeitsbericht Verkehrs- und Raumplanung 205, *Stadtverkehrsplanung. Grundlagen, Methoden, Ziele*. 2., neu bearbeitete und erweiterte Auflage, pp. 61–78. Berlin, Heidelberg: Springer-Verlag Berlin & Heidelberg.

Bagloee, S. A., Tavana, M., Asadi, M., & Oliver, T. (2016). Autonomous vehicles: Challenges, opportunities, and future implications for transportation policies. *Journal of Modern Transportation, 24*(4), 284–303.

Berger, P. (2016). *Studie: Ein Car Sharing-Wagen ersetzt in Köln 18 private Pkw.* Retrieved November 03, 2017, from Kölner Stadt-Anzeiger: https://www.ksta.de/koeln/studie-ein-carsharing-wagen-ersetzt-in-koeln-18-private-pkw-24268714.

Bienzeisler, L. (2017). Verkehrliche Auswirkungen einer autonomen Carsharingflotte. *ATZ - Automobiltechnische Zeitschrift, 119*(7-8), 66–71. Retrieved October 12, 2017, from www.atz-worldwide.com.

Bundesanstalt für Straßenwesen (2016). *BASt - Automatische Straßenverkehrszählung.* Retrieved October 13, 2017, from Bundesanstalt für Straßenwesen: http://www.bast.de/DE/Verkehrstechnik/Fachthemen/v2-verkehrszaehlung/Aktuell/zaehl_aktuell_node.html?nn=624736&cms_detail=8023&cms_map=0.

Bundesministerium für Verkehr und digitale Infrastruktur (2017). *Ethik-Kommission: Automatisiertes und Vernetztes Fahren*. Bericht Juni 2017. Retrieved November 15, 2017, from Bundesministerium für Verkehr und digitale Infrastruktur: https://www.bmvi.de/SharedDocs/DE/Publikationen/G/bericht-der-ethik-kommission.pdf?__blob=publicationFile.

Correia, G. H. d. A., & van Arem, B. (2016). Solving the User Optimum Privately Owned Automated Vehicles Assignment Problem (UO-POAVAP): A model to explore the impacts of self-driving vehicles on urban mobility. *Transportation Research Part B: Methodological, 87*, 64–88. Retrieved September 26, 2016, from http://dx.doi.org/10.1016/j.trb.2016.03.002.

Dolgov, D. (2016). *Google Self-Driving Car Project Monthly Report September 2016: Two Million Miles closer to a Fully Autonomous Future.* Retrieved September 09, 2017, from Google: https://static.googleusercontent.com/media/www.google.com/de//selfdrivingcar/files/reports/report-0916.pdf.

Fagnant, D. J., & Kockelman, K. M. (2014). The travel and environmental implications of shared autonomous vehicles, using agent-based model scenarios. *Transportation Research Part C: Emerging Technologies, 40*, 1–13. Retrieved October 20, 2017, from http://dx.doi.org/10.1016/j.trc.2013.12.001.

Fagnant, D. J., & Kockelman, K. (2015). Preparing a nation for autonomous vehicles: Opportunities, barriers and policy recommendations. *Transportation Research Part A: Policy and Practice, 77*, 167–181. Retrieved October 20, 2017, from http://dx.doi.org/10.1016/j.tra.2015.04.003.

Foresight Horizon Scanning Centre, Government Office for Science (2009). *Scenario Planning: Guidance Note.* Retrieved October 04, 2017, from http://webarchive.nationalarchives.gov.uk/20140108141323/http://www.bis.gov.uk/assets/foresight/docs/horizon-scanning-centre/foresight_scenario_planning.pdf.

Freie Hansestadt Bremen - Senat Für Umwelt, Bau und Verkehr (2012). *Bericht der Verwaltung für die Sitzung der Deputation für Umwelt, Bau, Verkehr, Stadtentwicklung und Energie (Stadt): Umsetzung des Car-Sharing Aktionsplans.* Bremen, from Freie Hansestadt Bremen - Senat Für Umwelt, Bau und Verkehr: https://www.bauumwelt.bremen.de/detail.php?template=20_search_d&search%5Bsend%5D=true&lang=de&search%5Bvt%5D=momo.

Friedrich, B. (2015). Verkehrliche Wirkung autonomer Fahrzeuge. In M. Maurer, J. C. Gerdes, B. Lenz, & H. Winner (Eds.), *Autonomes Fahren. Technische, rechtliche und gesellschaftliche Aspekte* (1st ed., pp. 331–350). Berlin, Heidelberg: Springer Berlin Heidelberg.

Friedrich, M. & Hartl, M. (2016). *MEGAFON: Modellergebnisse geteilter autonomer Fahrzeugflotten des oeffentlichen Nahverkehrs.* Retrieved October 08, 2017, from Universität Stuttgart - Institut für Straßen- und Verkehrswesen: http://www.isv.uni-stuttgart.de/vuv/news/Downloads/MEGAFON_Abschlussbericht_V028_20161212.pdf.

Fulton, L., Mason, J., & Meroux, D. (2017). *Three Revolutions in Urban Transportation: How to achieve the full potential of vehicle electrification, automation and shared mobility in urban transportation systems around the world by 2050,* from University of California Davis; Institute for Transportation & Development Policy: https://www.itdp.org/wp-content/uploads/2017/04/UCD-ITDP-3R-Report-FINAL.pdf.

Golowko, K., Zimmermann, V., & Zimmer, D. (2017). Automatisiertes Fahren Einflüsse auf die Rückhaltesysteme. *ATZ - Automobiltechnische Zeitschrift, 119*(7), 26–33.

Guerra, E. (2016). Planning for Cars That Drive Themselves: Metropolitan Planning Organizations, Regional Transportation Plans, and Autonomous Vehicles. *Journal of Planning Education and Research, 36*(2), 210–224.

Heilig, M., Hilgert, T., Mallig, N., Kagerbauer, M., & Vortisch, P. (2017). Potentials of Autonomous Vehicles in a Changing Private Transportation System – a Case Study in the Stuttgart Region. *Transportation Research Procedia, 26*, 13–21.

Herold, K., Ringler, H., & Wagner, U. (2013). *Radverkehr - 20-Punkte-Programm: Zwischenstand und Fortschreibung des 20-Punkte-Programms zur Förderung des Radverkehrs in Karlsruhe,* from Stadt Karlsruhe, Stadtplanungsamt: https://www.karlsruhe.de/b3/verkehr/radverkehr/massnahmen/HF_sections/content/ZZkRU2CZAtsvPA/ZZl4jA7xgdAQNo/Brosch%C3%BCre_Internetversion_klein.pdf.

Institut für angewandte Sozialwissenschaften (infas), & Deutsches Zentrum für Luft- und Raumfahrt e.V. (2008). *MiD 2008: Mobilität in Deutschland 2008*. Ergebnisbericht: Struktur – Aufkommen – Emissionen – Trends. Bundesministerium für Verkehr, Bau und Stadtentwicklung, from http://www.mobilitaet-in-deutschland.de/mid2008-publikationen.html.

Isaac, L. (2016). *Driving towards Driverless: A Guide for Government Agencies,* from WSP | Parsons Brinckerhoff: http://www.wsp-pb.com/Globaln/USA/Transportation%20and%20Infrastructure/driving-towards-driverless-WBP-Fellow-monograph-lauren-isaac-feb-24-2016.pdf.

Kennedy, C. A. (2002). A comparison of the sustainability of public and private transportation systems: Study of the Greater Toronto Area: A comparison of the sustainability of public and private transportation systems: Study of the Greater Toronto Area. *Transportation, 29*, 459–493.

Kesteloo, H. (2017). *Elon Musk on Boring Company, Semi-Truck, Mars: TED Talk [transcript].* Retrieved November 09, 2017, from https://electrek.co/2017/05/01/elon-musk-on-boring-company-semi-truck-mars-ted-talk-transcript/.

Klumpp, D. (2016). *DIVSI Studie - digitalisierte urbane Mobilität: Datengelenkter Verkehr zwischen Erwartung und Realität,* from DIVSI - Deutsches Institut für Vertrauen und Sicherheit im Internet: https://www.divsi.de/wp-content/uploads/2016/09/DIVSI-Studie-Digitalisierte-Urbane-Mobilitaet.pdf.

Kocherscheid, K., Rietz, C., Poppelreuter, S., Riestock, N., Müller, A., Rudinger, G., & Engin, T. (2007). Verkehrssicherheitsbotschaften für Senioren: Nutzung der Kommunikationspotenziale im allgemeinmedizinischen Behandlungsalltag. *Berichte der Bundesanstalt für Straßenwesen, Mensch und Sicherheit*(Heft M 184), 1–124, from http://bast.opus.hbz-nrw.de/frontdoor.php?source_opus=216&la=de.

Kromkamp, B. A. (2009). *Scenario planning.* Retrieved October 04, 2017, from http://www.quesucede.com/page/show/id/scenario-planning.

Lang, N., Ruessmann, M., Mei-Pochtler, A., Dauner, T., Komiya, S., Mosquet, X. et al. (2016). *Self-Driving Vehicles: Robo-Taxis and the Urban Mobility Revolution,* from Boston Consulting Group: http://www.auto-mat.ch/wAssets/docs/BCG-Self-Driving-Vehicles-Robo-Taxis-and-the-Urban-Mobility-Revolution.pdf.

Lindner, R., Armbruster, A., & Preuß, S. (2017). *Künstliche Intelligenz : Das ist der nächste Schritt zum ganz alleine fahrenden Auto.* Retrieved November 09, 2017, from Frankfurter Allgemeine Zeitung: http://www.faz.net/aktuell/wirtschaft/kuenstliche-intelligenz/alphabet-zeigt-naechsten-schrittzum-allein-fahrenden-auto-15283468.html?printPagedArticle=true#pageIndex_0.

McGuckin, N., & Nakamoto, Y. (Eds.). 2005. *Differences in Trip Chaining by Men and Women: Technical Papers. Research on Women's Issues in Transportation: Vol. 2.* Washington, DC: Transportation Research Board.

Millard-Ball, A. (2016). Pedestrians, Autonomous Vehicles, and Cities. *Journal of Planning Education and Research, 38*(1), 6-12. Retrieved October 28, 2016, from https://doi.org/10.1177/0739456X16675674.

National Highway Traffic Safety Administration and U.S. Department of Transportation (2015). *Crash Stats: Critical Reasons for Crashes Investigated in the National Motor Vehicle Crash Causation Survey: A Brief Statistical Summary.* Washington, DC. Retrieved October 01, 2017, from National Highway Traffic Safety Administration and U.S. Department of Transportation: https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812115.

OECD - International Transport Forum (2015). *Urban Mobility System Upgrade: How shared self-driving cars could change city traffic.* Paris, from OECD - International Transport Forum: https://www.itf-oecd.org/sites/default/files/docs/15cpb_self-drivingcars.pdf.

Oetting, A. (2002). *„Angebotsabhängige Modellierung der reisezweckspezifischen Verkehrserzeugung und ihre Anwendung auf den städtischen Freizeitverkehr“.* Dissertation, Rheinisch-Westfälische Technische Hochschule Aachen, Aachen.

Omniphon GmbH (2012). *Mobilitätsverhalten 2012 - Stadt Karlsruhe: Im Auftrag der Stadt Karlsruhe und des Nachbarschaftsverbandes Karlsruhe.* Karlsruhe, from Omniphon GmbH: https://www.karlsruhe.de/b3/verkehr/HF_sections/rightColumn/ZZmQwxTjX53atE/ZZkKWz4rgDh1Fh/Ergebnisbericht_Karlsruhe_Endversion.pdf.

Presse- und Informationsamt der Bundesregierung (2017). *Klare Ethik-Regeln für Fahrcomputer.* Retrieved September 29, 2017, from https://www.bundesregierung.de/Content/DE/Artikel/2017/08/2017-08-23-ethik-kommission-regeln-fahrcomputer.html.

Rigole, P.-J. (2014). *Study of a Shared Autonomous Vehicles Based: Mobility Solution in Stockholm.* Master of Science Thesis, Royal Institue of Technology, Stockholm, from www.ima.kth.se.

SAE International (2014). *SAE J3016: Automated Driving - Levels of Driving automation SAE international Standard J3016,* from SAE International: https://www.sae.org/misc/pdfs/automated_driving.pdf.

Sieg, U. (2017). Special "Autonomes Fahren". *Nahverkehr…Praxis, Ausgabe 9/10*, 5–6.

Stadt Karlsruhe - Amt für Stadtentwicklung (2016). *Kleinräumige Bevölkerungsprognose 2035*. Heft Nr. 50. Karlsruhe. Retrieved October 02, 2017, from Stadt Karlsruhe - Amt für Stadtentwicklung: https://web3.karlsruhe.de/Stadtentwicklung/afsta/Stadtentwicklung/download/afsta-heft_50_bevprognose_2035.pdf.

Stadt Karlsruhe - Amt für Stadtentwicklung - Statistikstelle (2016). Daten und Fakten 2016. Retrieved September 13, 2017, from https://web3.karlsruhe.de/Stadtentwicklung/statistik/pdf/2016/2016-daten-und-fakten.pdf.

Stadt Karlsruhe - Amt für Stadtentwicklung - Statistikstelle (2017a). Statistik Aktuell: Bevölkerung. Retrieved September 13, 2017, from https://web3.karlsruhe.de/Stadtentwicklung/statistik/pdf/2017/2017-06-bevoelkerung.pdf.

Stadt Karlsruhe, Amt für Stadtentwicklung - Statistikstelle (2017b). *Karlsruher Statistikatlas.* Retrieved October 05, 2017, from https://web3.karlsruhe.de/Stadtentwicklung/statistik/atlas/.

Stadtplanungsamt Karlsruhe (2013). *Verkehrsentwicklungsplan Karlsruhe: 6: Wirkung des Handlungskonzepts.* Karlsruhe, from Stadtplanungsamt Karlsruhe: www.karlsruhe.de.

Statistisches Bundesamt (2017). *Erwerbstätigkeit: Atypische Beschäftigung.* Retrieved November 22, 2017, from Statistisches Bundesamt (Destatis): https://www.destatis.de/DE/ZahlenFakten/GesamtwirtschaftUmwelt/Arbeitsmarkt/Erwerbstaetigkeit/TabellenArbeitskraefteerhebung/AtypKernerwerbErwerbsformZR.html.

Taylor, C. W. (1990). *Creating Strategic Visions.* Thesis, U.S. Army War College, Pennsylvania.

Thill, J.-C., & Thomas, I. (1987). Toward Conceptualizing Trip-Chaining Behaviour: A Review. *Geographical Analysis, 19*(1), 1–17.

Thomas Winkle (2015). Sicherheitspotenzial automatisierter Fahrzeuge: Erkenntnisse aus der Unfallforschung. In M. Maurer, J. C. Gerdes, B. Lenz, & H. Winner (Eds.), *Autonomes Fahren. Technische, rechtliche und gesellschaftliche Aspekte* (1st ed., pp. 351–376). Berlin, Heidelberg: Springer Berlin Heidelberg.

Trommer, S., Kolarova, V., Fraedrich, E., Kröger, L., Kickhöfer, B., Kuhnimhofer, T., et al. (2016). *Autonomous Driving: The Impact of Vehicle Automation on Mobility Behaviour.* Munich: Institute for Mobility Research (ifmo), from www.imfo.de.

Tsantilas, S. (2016). *Motorcycle rear-ending raises questions on Tesla vehicle type approval in Europe.* Retrieved November 09, 2017, from New Atlas: https://newatlas.com/tesla-autopilot-fema/46045/.

Victoria Transport Policy Institute (2017). *Evaluating Public Transit Benefits and Costs: Best Practices Guidebook.* Victoria, from Victoria Transport Policy Institute: www.vtpi.org.

Vincent, W., & Callaghan Jerram, L. (2006). The Potential for Bus Rapid Transit to Reduce Transportation-Related CO2 Emissions. *Journal of Public Transportation, BRT Special Edition*, 219–237.

Weinert, J., Ma, C., Yang, X., & Cherry, C. (2007). Electric Two-Wheelers in China: Effect on Travel Behaviour, Mode Shift, and User Safety Perceptions in a Medium-Sized City. *Transportation Research Record: Journal of the Transportation Research Board, 2038*, 62–68.

Westhoff, J. (2014). *Radiolexikon Gesundheit - Fahruntüchtigkeit durch Medikamente.* Retrieved October 09, 2017, from Deutschlandfunk: http://www.deutschlandfunk.de/radiolexikon-gesundheit-fahruntuechtigkeit-durch-medikamente.709.de.html?dram:article_id=285214.