

MASTER'S THESIS

The impact of automated motorized vehicles on urban mobility in Fürstenfeldbruck

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The development of autonomous vehicles (also called self-driving, driverless or robotic) is a rapid process which can be observed nowadays. Be it the vehicles themselves or the infrastructure necessary for a proper functioning of them in the common traffic, the concept of self-driving automobiles as the future of individual mobility introduces a number research questions.

The one I am willing to answer is: how will automated vehicles influence travel demand and traffic flow in Fürstenfeldbruck in the near future?

The thesis will consist of two main parts. The first one will focus on a social research within the whole Munich Metropolitan Area (incl. Fürstenfeldbruck) in order to reach a possibly broad sample size. The idea of this part is to determine the level of awareness of individual commuters about the concept of driverless cars, mainly the knowledge about the technology and to reveal the level of trust to robotic automobiles. This will help estimate realistic scenarios for the future modal split of various vehicles and will forecast travel demand based on predicted commuter behavior. Consequently, in the second part of the thesis, traffic flow calculations will be conducted in order to model the influence of driverless vehicles on urban mobility. The study area for the calculated model will be Fürstenfeldbruck – one of numerous small to middle-sized towns in the Munich Metropolitan Area generating high travel demand due to regular individual daily commuting. The main focus will be put on rush hours, so that the impact of robotic technology on the traffic flow within roads of limited capacity could be observed.

The research conducted in this thesis will help predict the realistic usage share of automated vehicles in the future in the Munich Metropolitan Area and the model calculation results should allow to define if traffic flow optimization is a significant advantage and a true selling point of self-driving automobiles.



The student will present intermediate results to the mentor (Prof. Dr.-Ing. Rolf Moeckel and Dr. Ana Tsui Moreno Chou) in the fifth, tenth, 15th and 20th week.

The student must hold a 20-minute presentation with a subsequent discussion at the most two months after the submission of the thesis. The presentation will be considered in the final grade in cases where the thesis itself cannot be clearly evaluated.

Prof. Dr.-Ing. Rolf Moeckel

Abstract

Today's developed world welcomes great technological revolutions in the field of transportation in an evolutionary manner, as safety and improvements in mobility must go hand in hand with the idea of sustainable development. This thesis focuses on the future use of automated vehicles (AVs) on public roads in the Munich Region and tackles the matter from a sociological and modelling perspective.

To address the society-based aspect of the thesis' topic, a survey was conducted to discover the influential factors on AV-related developments from the opinions of potential future AV users. The question fields included general knowledge on AVs, participants' travel behavior, potential use of AVs and respondents' statistical information. The results of the survey indicated who may be the potential beneficiaries of the technology and how would they use it.

To examine potential influence of automated vehicles on the traffic flow, a computer model (MATSim) was run for the city of Fürstenfeldbruck. With a modal split directly influenced by survey's results and a varying penetration rate of AVs in usage, one can observe a change in volume to capacity ratios, new vehicle kilometers travelled (VKT) rates and differences in average travel and waiting times depending on the number of available AVs that meet the demand.

The results indicate a possible AV technology introduction without significant negative impacts on overall traffic conditions in the study area. Car volume and VKT levels did not impede traffic flow in Fürstenfeldbruck in any of the scenarios, whereas proper adjustment of AV supply allows the individual trips to be kept within attractive time frames.

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1 Introduction to automated vehicles

Automated vehicles (shortly: AVs) are vehicles which incorporate at least partial control functionality critical for cruise safety without the need of direct human input (Zmud, Sener, & Wagner, 2016). Alternative names for AVs are autonomous vehicles, self-driving cars and robot cars (Bassett, 2015). Computer onboard technology with support of various sensors, cameras, light detection and ranging (LIDAR) and the global positioning system (GPS) allows automated vehicles to operate with partial to no human interaction. Automated vehicles are designed in a range of forms: from passenger cars through freight vehicles to public transport units. An autonomous car is a special example of an automated vehicle, where the entire operation is done without any human support (Zmud et al., 2016).

1.1 History of development

The strive to achieve automation in areas of life where systematic and constant human input is necessary has been long part of engineering developments. With self-propelled torpedoes developed as early as in the 1860s and first autopilot systems introduced just around a decade after first Wright brother flights, automated operation implementations are not completely new concepts in the 21st century. Nowadays it is not a surprise to use automated vehicles and devices of various types: driverless harvesters, sailboats with auto-tillers, semi-autonomous military drones or robot vacuum cleaners in our households (Weber, 2014).

The dream of a fully-operational autonomous vehicle emerged practically as soon as the invention of a car entered public roads. Since first combustion engine-operated individual vehicles were developed in times without computers, dreams of automated car operation were mostly associated with science-fiction movies, as the concept was still far from realistic solutions due to lack of corresponding technology and the complexity of road infrastructure environment (Weber, 2014).

Nevertheless, first ideas of cars not needing a driver emerged already in the 1920s and were strongly dependent on external steering inputs. In 1925, Houdina Radio Control demonstrated the potential of radio technology by controlling the movement of a car from a human-driven vehicle going right behind. The project was named “American Wonder” and “Phantom Auto” and was exhibited on the roads of New York and Milwaukee. A second significant development was the implementation of electronic receivers for detector circuits embedded on specifically-designed roadways in the General Motors’ made Firebird II in 1956. Based on the signal from the circuits, the cars were able to detect location and velocity of other cars on the road stretch and receive guiding information to control their movement (U, 2016).

Further automobile developments included function-specific automation. The first cruise control system was introduced in 1958 and allowed vehicles to maintain certain speed without constant human input. The Anti-Lock Braking system was developed in 1971 and allowed brakes intensity to be regulated by the car itself in order to improve its efficiency (U, 2016).

With the emerge of computing, more complex solutions could be implemented to vehicles to make their operation significantly more automated. The first largely successful modern project of a car going on its own on a highway over hundreds of miles was a Mercedes van prepared by an engineering team from the Munich Bundeswehr University under the lead of a pioneer Ernst Dickmann in the years 1986-2003 (Weber, 2014). After a number of complex projects being successful in various university-based research centers, current biggest autonomous car projects tend to be undertaken mostly by automobile and IT companies, such as BMW, Volkswagen, GM Tesla or Google. Thanks to increasing computing power in smaller within more energy-efficient form factors, more precise sensors and successful technology implementations, fully autonomous vehicles are only a step ahead to become a common sight on public roads in the near future (U, 2016).

1.2 Contemporary state of technology

The progress in automated vehicles' design has gone a long way and the modern designs are far from being undeveloped or raw. One of the most well-known AV undertakings is the Google Self-Driving Car project, started in 2009. The vehicles use data from LIDAR (Light Detection and Ranging) and Google Maps for localization and use visual input and radar for detection and identification of other vehicles, pedestrians and objects. Its aim is to emulate ideal behavior of a human driver. Tesla is another big player in the AV development. Introduced in 2015, the "Autopilot" software for Tesla Model S enables the car to follow and switch lanes and to autonomously park on command. This is considered the first publicly available car model with truly automated characteristics. Both Google and Tesla spent a lot of time on their developments, with Google cars having a collective driving experience of 75 years and Tesla cars having driven 47 million kilometers on autopilot (U, 2016).

The National Highway Traffic Safety Administration (in short: NHTSA) has categorized vehicle levels of automation and thus helped clarify policy and technical debate about AVs (Zmud et al., 2016).

Table 1.1 Levels of vehicle automation (U.S. Department of Transportation, 2016)

Level	0	1	2	3	4
Label	No automation	Function-specific automation	Combined function automation	Limited self-driving automation	Full self-driving automation
Description	No automated driving features	Example: cruise control	Example: adaptive cruise control with lane centering	Driver cedes full control of all safety-critical functions under certain traffic conditions	Vehicle performs all driving functions without human intervention

In the NHTSA standard, there are 5 levels of vehicle automation. The scale starts with level 0, where there are no automated functions of the vehicle and the driver is full-control of steering, throttle and braking. Cars with level 1 or 2 automation are currently available on the automobile market and offer various forms of cruise control, lane centering and other equipment options. Cars with level 3 automation allow the driver to engage in other activities than driving with the need of his/her availability to retake steering control in a moment's notice. At level 4, the vehicle is considered fully autonomous and can replace the driver completely (Zmud et al., 2016).

2 Literature review

For the purposes of the thesis I analyzed contemporary scientific work relating to VMT levels / road capacity, surveys and IT security. To broaden the spectrum of this section, general opportunities and threats of AVs and its relevant conclusion is also part of the literature review.

OECD/International Transport Forum (2015) modelled changes caused by a large-scale transport mode share increase of self-driving cars in a mid-sized European city of Lisbon. Two types of vehicles were investigated: AutoVots that pick up and drop off single passengers sequentially and TaxiBots, which are shared autonomous taxis. The goal of the study was to replace all car and bus trips with automated vehicles' trips. The scenarios included 100% shared self-driving fleet or 50% private car use for motorized trips, with or without high-capacity public transport. The factors that also contributed to the scenarios were travelers (potential broad use of the shared mobility system), car routes (dynamically routed to pick up and drop off passengers or designed travel on fixed "A to B" routes) and dispatcher systems (dynamically assigning cars to clients and fleet size).

The results of the study show that a combination of high-capacity public transport with TaxiBots can deliver the same mobility with just 10% of private cars present on the roads. The system would also result in an overall increase of car travel volume by 6%. The use of vehicles would drop by 65% with a 9% increase in overall vehicle-kilometers. The use of AVs will be mostly beneficial when there are no private cars in use, since a 50/50 combination of those increases total vehicle travel between 30% and 90%. No economic factors were investigated while working on that study (International Transport Forum / OECD, 2015).

Suzanne Childress et al. (2014) studied anticipated automated vehicles effects on transportation networks and traveler choices based on advancements in the development of AV technology. Four scenarios were analyzed. The first one assumed a 30% increase in network capacity on freeways and major arteries. The second one included a lower perception of travel time, setting this factor at 65% of the actual travel time for high income households. In the third scenario, all cars owned privately were AVs and all trips had perceived travel time set at 65%. Additionally, parking costs were reduced to 50%. In the last, fourth scenario, all cars are automated and the costs of individual vehicles increase to a fixed \$1.65 per mile as shared solutions prove to be the most efficient ones.

The results show a VMT (Vehicle Miles Travelled) reduction (-35.4%) only in the last scenario, due to a vast per-mile costs increase from \$0.15 to \$1.65. In this case the average trip length is reduced by -7.3% to -19%. All other scenarios indicate a VMT growth (3.6-19.6%) and either no average trip length change or a growth of 1,5% to 61,3% (Childress, Nichols, Charlton, & Coe, 2014).

Texas A&M Transportation Institute (2016) conveyed a survey in Texas about public AV technology acceptance, usage likelihood, potential travel behavior change and the impact of self-driving vehicles on traffic and congestion. The VMT predictions were inconclusive whether

there would be a steady increase or decrease after an AV introduction. A similar VMT level was predicted based on 66% of responses. 25% of them indicated VMT growth and 9% a decrease. The study also discovered that Texas residents are more interested in using AVs as private cars (59%) rather than shared vehicles (41%).

M. Kyriakidis, R. Happee and J.C.F. de Winter Department (2015) conveyed an international survey investigating 5000 users' concern, willingness and acceptance levels for purchasing partially- to fully-automated vehicles. 69% of the respondents estimated that AVs should reach a share of 50% by the year 2050. The biggest concerns about automated vehicles' technology were IT-security related, the next ones that followed were legal issues and general system safety. Participants from more developed countries were more skeptical to the idea of their vehicles' sharing data in contrast to developing countries' populations. The general outlook of the survey was positive and brought optimistic incentives for vehicle developers and other stakeholders (Kyriakidis, Happee, & Winter, 2015).

D. Milakis, B. van Arem and B. van Wee researched policy and society related implications of automated driving. Their study clearly indicates a possible positive short term impact on road capacity. A significant benefit in this field (>10% road capacity increase) requires a critical threshold of 40% penetration rate of vehicles equipped with CACC (cooperative adaptive cruise control). A theoretical double road capacity could be reached with a 100% penetration rate of automated vehicles. VMT levels are expected to increase by 4-26% due to mode and destination choice changes as well as generally increased mobility. A special example of VMT increase is the use of shared automated vehicles which can increase its value by up to 90% thanks to frequent journeys of empty AVs (Milakis, Arem, & Wee, 2015).

In another paper, D. Milakis and M. Snelder researched possible future developments in AVs in the Netherlands between years 2030 and 2050. Fully-automated vehicles penetration grades for 2050 vary greatly between 7-61%. The influencing factors are influenced by long-term pace of technology development and the level of support of officials' policies. Road capacity change is expected to be more significant in motorways than in urban streets. Its rate on motorways in 2050 is estimated to lay between -3% and +25% (Milakis & Snelder, 2017).

The rapid development of automated vehicles and their widespread implementation in the future will cause a great impact on transportation and built environment. The technology offers efficient operation, greater safety, allows users to be engaged in activities they have not been able to do until now and offers mobility to population groups which are not able to drive on their own, such as children or the elderly. The impact on the built environment is also not to be underestimated: with the trend of less private car ownership ratios and the improvements AVs will serve, we can expect future streets in urban areas to offer more space for other traffic users, such as pedestrians and cyclists. The redesign and alternative use of unnecessary parking lots or right of way lanes is also to be expected (Chapin et al., 2016).

There are numerous opportunities connected with the development of automated vehicles which would potentially be beneficial for travelers (Childress et al., 2015):

- Driver stress reduction – no stress necessary since there are no human drivers, all travelers are passengers and can rest or work while commuting.
- Driver costs reduction – reduced expenditure on taxi and PT drivers.
- Non-driver mobility – ensuring independent mobility for non-drivers which also reduces costs caused by PT subsidies and employed chauffeurs/motorists.
- Safety increase – AV technology may reduce crash risks and accident costs, lowering also insurance costs. Autonomous cars may also reduce high-risk driving, for example by impaired drivers.
- Road capacity increase – high level of vehicle interaction may allow commuting in platoons (groups of vehicles travelling close to each other). It also allows usage of narrower lanes, fewer intersection stops, and congestion reduction.
- Parking efficiency increase – the vehicle can park on its own, saving the user's time for parking spot search, increasing convenience and reducing parking costs in general.
- Fuel efficiency increase and pollution reduction – optimized vehicle operation – smooth stretches with few stops and steady velocities may decrease fuel consumption and exhaust fumes emissions.
- Vehicle sharing support – could be a catalyst to promote sharing of vehicles and reduce private car ownership.

AVs are not only about the positives, some threats and potential problems may also be encountered (Childress et al., 2015):

- Costs increase – adjustments to AVs will require additional services, maintenance and vehicle equipment and possibly also roadway infrastructure.
- Additional risks – failures caused by IT systems and safety decrease of human operated vehicles under certain conditions (drivers may take additional risks, i.e. offsetting behavior).
- Privacy and security issues – terrorists may use AVs for explosives delivery, IT systems are exposed to hacking, GPS tracking and sharing of data may be subject to privacy issues.
- Induced travel and an increase in external costs – due to comfort and affordability, AVs may induce more trips and increase people's mobility, increasing therefore external costs, such as parking, accidents and pollution.
- Social equality issues – may reduce convenience and usability of other means of transport, leading to social inequalities.
- Employment and business activity reduction – there should be less driver jobs, smaller demand for car repair services and general lower demand for individual car production is the car sharing model becomes popular.
- Threats to overall transport planning – too much focus on AV mobility may impede the development of conventional but still efficient transport projects, i.e. transit and pedestrian improvements, reforms in pricing and transport strategies.

From all of the characteristics described above, the road capacity- and safety-related ones are the most important for the study. Ideally, road capacity increase with its coordinated platoon driving, narrower lanes and fewer stops at intersections will outperform the potential induced travel caused by comfort and affordability.

Since safety and reliability of AV systems is focused mostly on IT solutions, it is essential, apart from perfecting their programmed codes, to protect them from hacker attacks which could be a cyber risk affecting people in a very physical way. A well-protected IT solution could virtually eliminate driver errors which are responsible for 80% of crashes (Pendyala & Bhat, 2014).

2.1 Objectives

The goal of this thesis is to estimate traffic flow change in Fürstenfeldbruck after the popularization of automated vehicles in around 2050.

In order to analyze the topic, a questionnaire addressed to the residents of Munich and its surroundings was conducted to study the awareness about the subject, as well as to measure levels of trust and willingness of use of the rapidly developing technology. With the survey's data available there will be a possibility to forecast percentage of AVs in use, define new modal splits and calculate a traffic flow computer model to be able to confirm traffic flow influence that automated vehicles could provide in the future.

2.2 Hypotheses

Automatic vehicles are undoubtedly a big chance for significant traffic flow improvements, especially taking into consideration numerous short- and long-term assumptions about road capacity and volume-delay functions, which are based only on human-operated vehicles. Coordination between AVs allows shorter headways, which makes higher vehicle volumes possible at high speeds. With the capability of collision rate reductions, AVs would be an important factor in reducing non-recurrent congestion. Shared automated vehicles have a high potential of becoming popular, since they would introduce per-km fee rates corresponding to already existing rideshare services and would reduce the necessity of car ownership and its storage. Parking issues would also be solved to a great extent, since autonomous cars are capable of self-parking at less central locations. (Childress et al., 2014)

The opportunities introduced by autonomous vehicles are a big chance for people depending on individual mobility in their daily travel. With the constant development of the technology, people are likely to become more open towards it and contribute to the trend of lower car ownership, acceptance of slightly higher travel times in favor of convenience and ultimately also accept the idea of car sharing in self-driving cars. In the context of a Munich's satellite town Fürstenfeldbruck which is strongly dependent on the center of the metro region, it is a

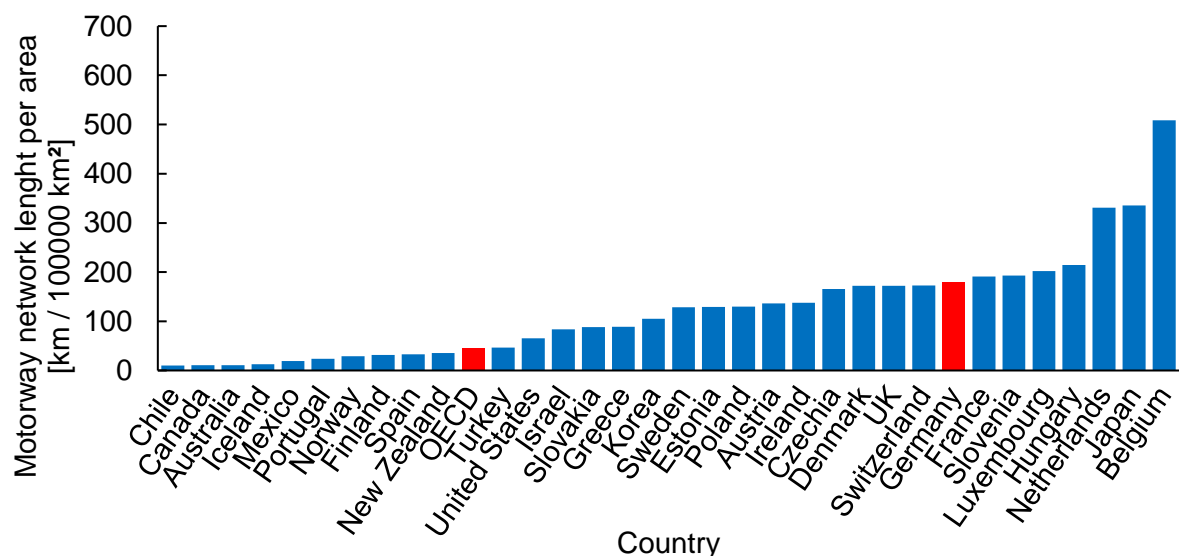
great opportunity to reduce traffic jams, improve urban esthetics (for example by reducing the number of parking places) and to improve the overall quality of life.

2.3 Problem statement

Previous AV studies indicate an overall high impact of future AV developments on mobility. There several significantly varying factors, such as VMT change, car volume developments or legislative measures that will have an impact on the future shape of individual/shared transportation. A lot of those factors are influenced by local characteristics of the study areas: the infrastructure, current modal split and population mobility behavior. Existing research suggests further social research to determine the approach towards AVs from different social groups and types of people. To accomplish that I conducted a survey as it is a tool that allows me to collect current and local data which is specifically tailored to the purposes of the study. A computer model which handles data collected in the social research part is a modern means of working with data and allows me to extract exactly those values, which are relevant to the thesis' research question.

With the conclusions drawn from the previous studies, I will attempt to fill in the local context gap in the topic of automated vehicles and study its influence on traffic flow in a long-term. The survey will allow me to take into consideration long German history of the autobahn and independent individual travel. High density of the national motorway network is also to be considered. (OECD, 2013).

Figure 2.1 Motorway network density in 2011 (OECD, 2013)



My innovation in the research is the coverage of 2 main survey respondent groups. One of them are the German speaking respondents, covering a versatile range of age, gender, income

levels and car ownership ratios. The second respondent group are English speaking commuters of Greater Munich, who tend to be young, very dependent on public transport and are likely to stay in the Bavarian's capital metro region permanently, since Munich has a steady high ratio of growth of the immigrant population. (Munich Statistical Office, 2016). This diversity of respondents should shed new light on how demographic change may also be a factor in modelling of transport of an urban region.

3 Data and methodology

The thesis consists of two parts: (1) online survey, (2) case study.

In order to be able to address subjective perception of citizens and estimate changes on mode choice due to autonomous vehicles in the near future, a social survey was conducted in the planning region Munich. The attitude and trust levels are used as a base to estimate future implementation developments in this field and to form scenarios in the case study. Additional survey-based interviews were conducted to enlarge the sample of Fürstenfeldbruck citizens and enrich the results.

The case study constitutes the second part of the thesis and its function is to quantify the effects of the inclusion of autonomous vehicles on congestion and mobility in Fürstenfeldbruck.

3.1 Study area description

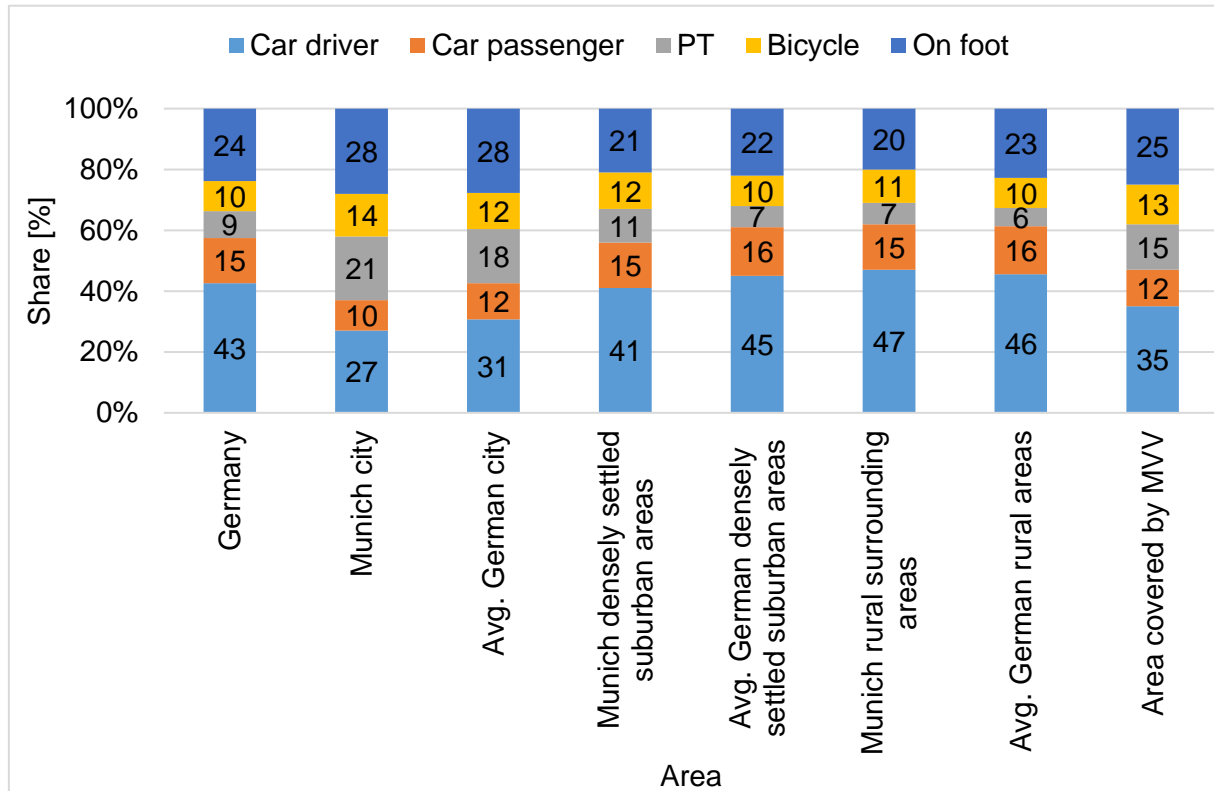
The planning region Munich (also called Greater Munich) is a region in the state development scheme located in the center of the Upper Bavaria governmental district and aside from Munich City it incorporates also Dachau, Ebersberg, Erding, Freising, Fürstenfeldbruck, Landsberg at the Lech, Munich and Starnberg districts (Lkr. – Landkreise). Its surface covers around 5,504 km² and it is home to approximately 2.4 million inhabitants (Planning Association of Greater Munich, 2017)

Figure 3.1 MVV delineation of Greater Munich Area



The vast majority of Greater Munich is served by MVV (Münchner Verkehrs- und Tarifverbund – Munich Transport and Tariff Association). Its users are served by 434 km of suburban train lines (S-Bahn), 95 km of metro lines (U-Bahn), 79 km of tramway lines (Tram) and 482 km of urban and 4840,9 km of suburban buses (Bus) (Munich Transport and Tariff Association, 2015).

Figure 3.2 Modal split of transportation modes in various places in Germany (Munich Transport and Tariff Association & Landeshauptstadt München, 2010)



The modal split of Munich (city) and its densely settled surrounding areas indicates a lower than average use of individual vehicles, whereas Bavarian rural areas are very dependent on individual motorized mobility. Urban and suburban areas in Greater Munich also represent a higher than average reliability on public transport, cycling and reaching places on foot.

3.2 Online survey description

Between the 7th of March and the 30th of April 2017, a Google Forms online survey was undertaken. After a brief introduction to automated vehicles, participants were asked questions in four categories. The first one was about AV awareness, to research the general state of knowledge about the technology. Second question group contained travel behavior statistics, like the number of journeys per day, preferred modes of transports, average daily time spent on travelling and the subjective safety perception of vehicles. In the third part, participants were asked about the future of AVs, their possible use, purchase and willingness of adaptation to its characteristics, compared to traditional transport modes. The fourth part contained statistical information, i.e. age, gender, household size, monthly income, car ownership and place of living.

The survey was offered in both English and German language, to address a possibly broad range of respondents, including German-speaking, mostly local people and also people with

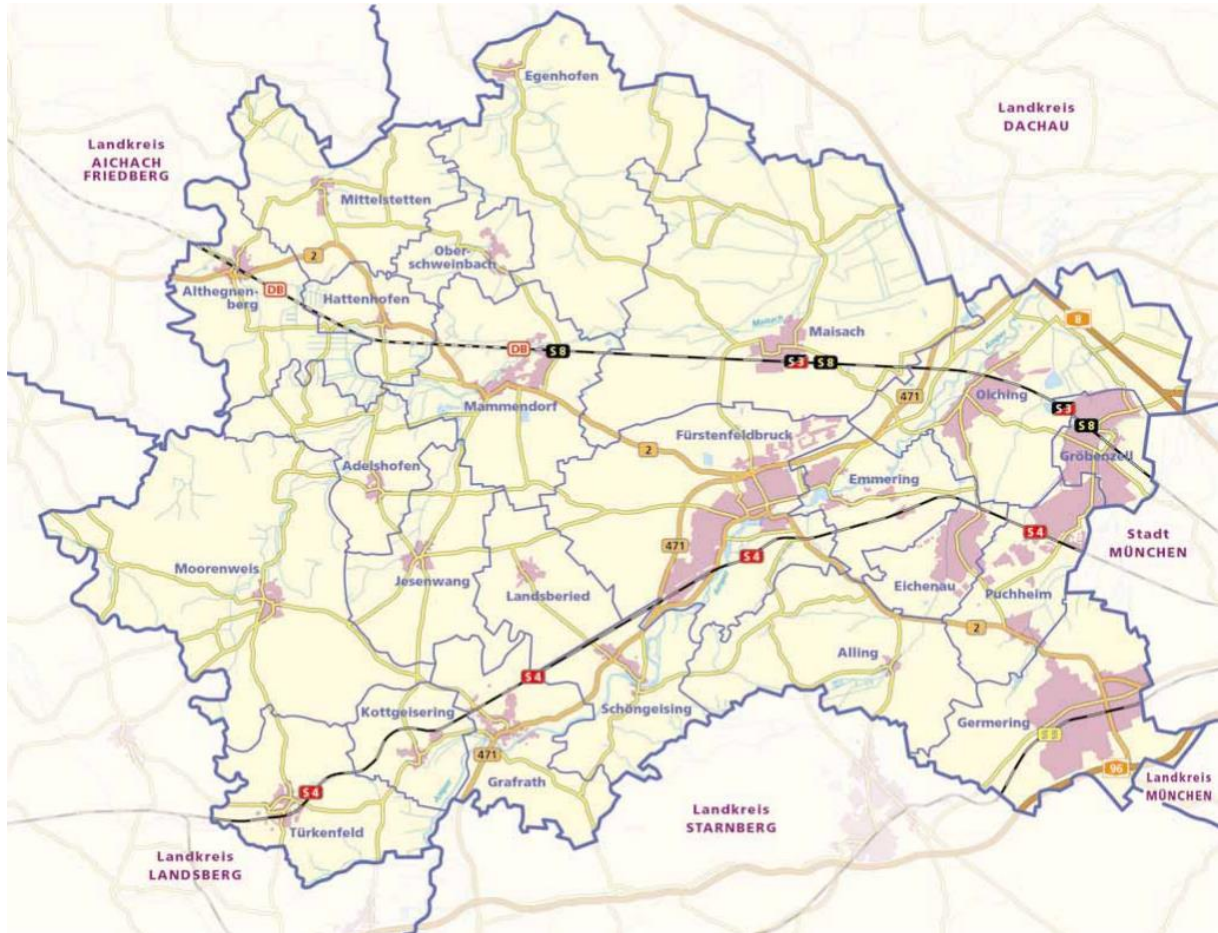
immigrant background. There were 44 answers in English and 42 in German. The study has a broad spectrum of questions which will not all be relevant for the model calculation in the second part of the thesis but may help with further research which could cover more social-oriented areas.

In order to become a satisfactory amount of answers directly from the main study area (only 8% of the online responses came from FFB), I additionally conducted survey-based interviews on the 6th of May 2017 between 11:00 and 14:00 o'clock in the center of Fürstenfeldbruck. I managed to become 20 more responses from its citizens and will include them to the interpretation of the social research. The street interviews covered all of the questions placed in the online survey but excluded household monthly net income questions as they may have intimidated the respondents when asked personally.

3.3 Case study: application to Fürstenfeldbruck

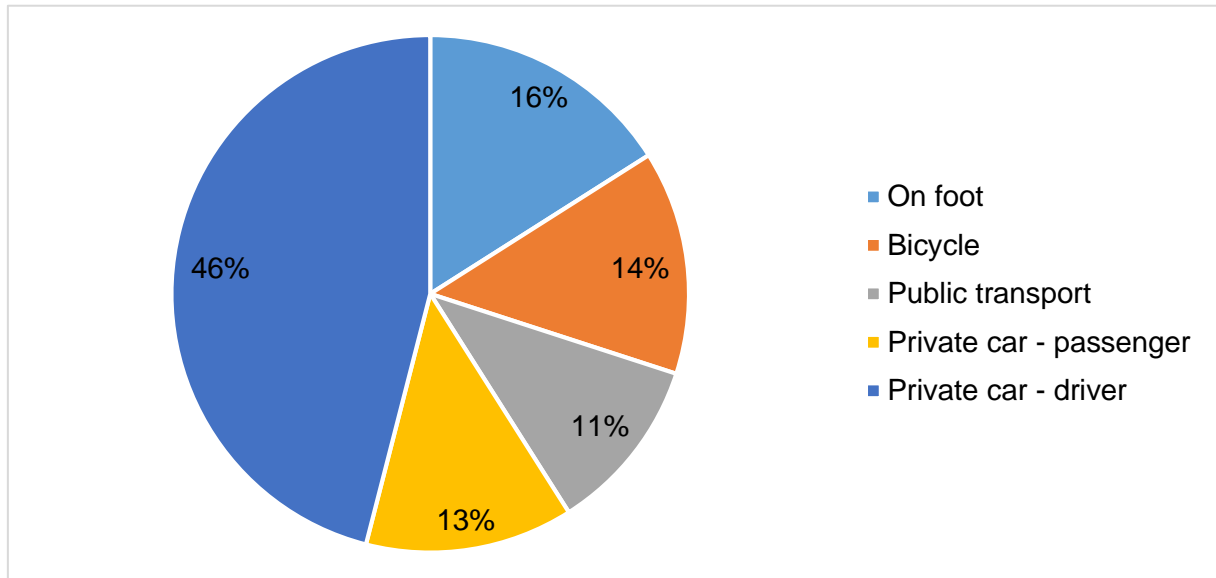
Fürstenfeldbruck is the capital of an administrative Bavarian district (Landkreis in German) of the same name. It borders the city of Munich and Munich district in the East, in the south and south-west the regions of Starnberg and Landsberg am Lech. In the north and north east there is Region Dachau and in north-west there is Aichach-Friedberg. Landkreis Fürstenfeldbruck covers around 435 km² of land surface and it is home to approximately 210 thousand inhabitants. From all Bavarian planning regions, FFB's population density is second in Bavaria, being lower only than Munich Landkreis. (Fürstenfeldbruck Administrative District Office, 2017)

Figure 3.3 Map of Fürstenfeldbruck region (Fürstenfeldbruck Administrative District Office, 2017)



Fürstenfeldbruck is covered by MVV (Munich Transport and Tariff Association). Its users are served by 3 suburban train lines (S-Bahn) with 16 stations. Furthermore, there are 2 long-distance train lines and 32 bus lines. Additionally, there are 2 motorways crossing the area of the region (Munich Transport and Tariff Association, 2010).

Figure 3.4 Modal split of transportation modes in Fürstenfeldbruck (Munich Transport and Tariff Association, 2010)



The modal split of Fürstenfeldbruck indicates high usage of individual vehicles (combined 59% for automobile drivers and passengers). Further used modes of transport are on foot (16%), by bike (14%) and by PT (11%).

To simulate the influence of AVs on the traffic flow of FFB, a microscopic simulator MATSim was used. The program simulates use of automated taxis to partially substitute travel demand for home-based trips to work in the Fürstenfeldbruck area. In order to accomplish this, different scenarios with an AV penetration rate based on the survey's results and a range of different AV fleets and will be compared.

The results will demonstrate volume to capacity level changes in each scenario. The model analysis will also include change of vehicle kilometers travelled (VKT) and the performance indicators of AVs themselves – average travel and waiting times.

4 Survey results and analysis

This chapter presents the results of the online and street surveys with an interpretation in the end. All of the survey's questions and answers are attached as an appendix to this thesis in order to allow the reader further specified use of the data.

4.1 Online survey results

The survey's respondents were mostly men (~70%) with a quite even distribution of monthly net income (≤ 500 to > 5000 €) and the number of persons living in the household (1-4+). The age of English-speaking respondents ranged mostly (98%) between 18 and 35 years and owned mostly (81,8%) no private car, whereas the German-speaking participants covered a wider spectrum of age (18-55 years) with 93% replies and mostly did own an automobile (61,9%). In both respondent groups, the place of residence was mostly Munich City (59,5%-77,3%). There were 7 responses from Fürstenfeldbruck (8% of all responses).

Figure 4.1 Age groups of German-speaking respondents (in years)

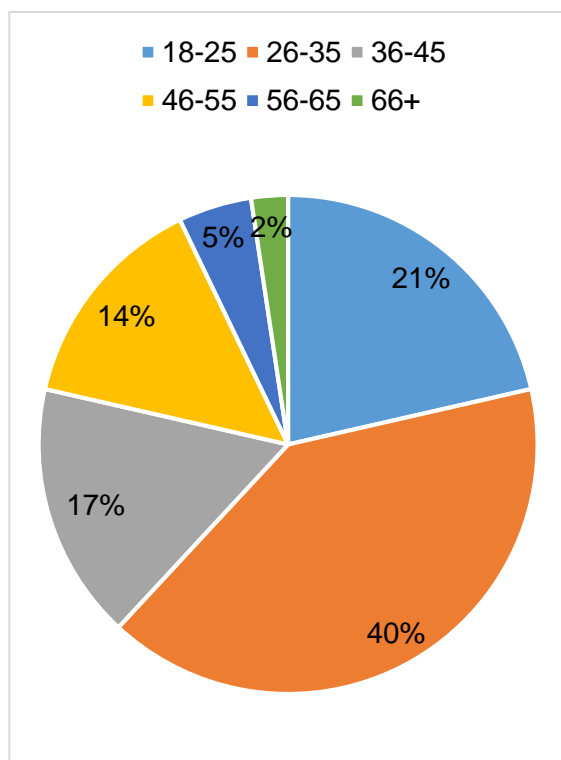
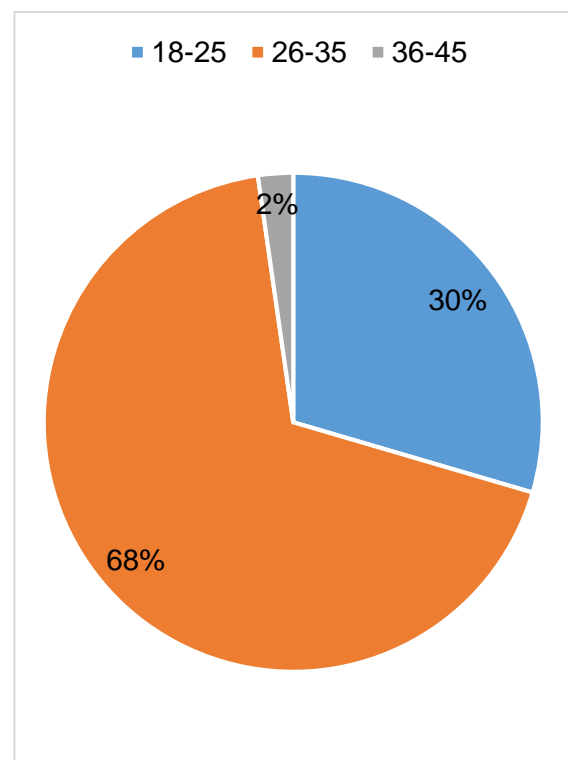


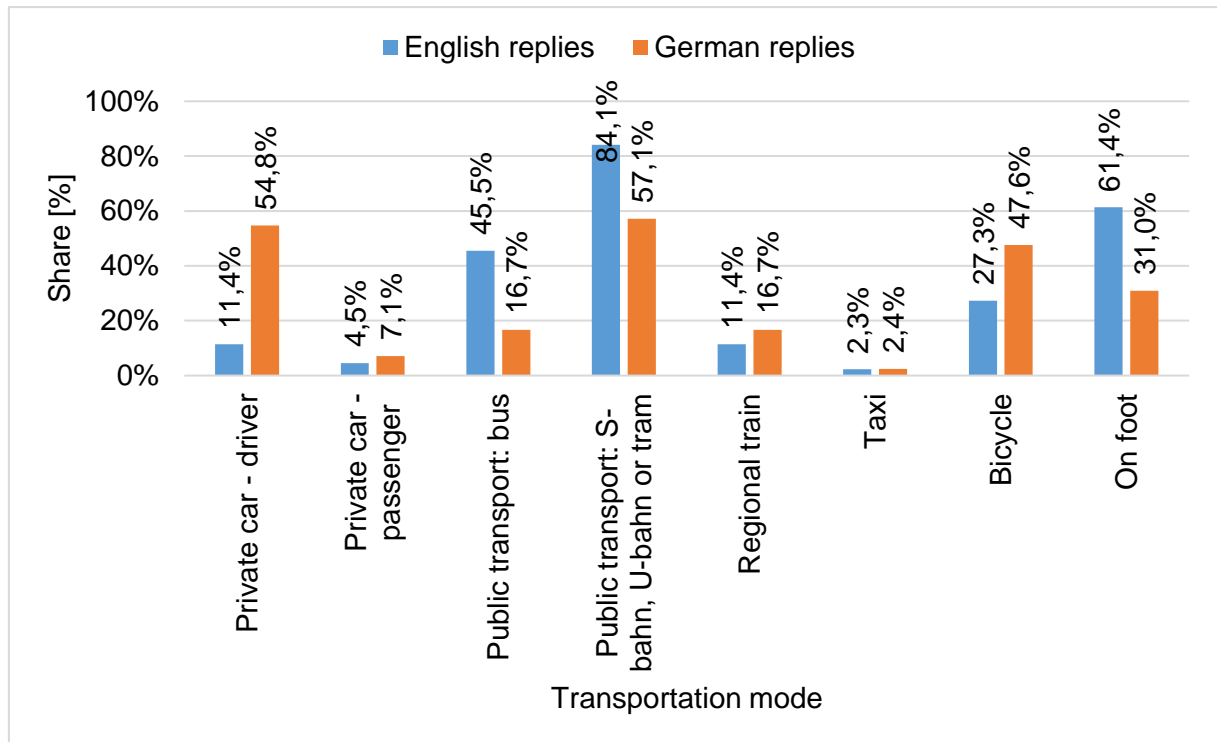
Figure 4.2 Age groups of English-speaking respondents (in years)



Both English and German-speaking respondents declared moderate to high levels of being informed about the development of automated vehicles with 91% of answers ranging from 3-5 on a scale of 1-5, with 5 being the highest. Using the same scale the declared observation of

the spreading of information about AVs was rated mostly between 2 and 4, covering 94% of the responses.

Figure 4.3 Modes of transport used regularly for daily commuting to regular activity places (in percentage of replies)



English-speaking survey participants rely mostly on rail-based public transport (PT) - U-Bahn, S-Bahn and Tram - with the percentage of 84,1%. The next most commonly selected transportation modes are on foot (61,4%) and PT-Bus (45,5%). The natives rely also strongly on Rail-PT (57,1%), but their second 2 choices are private car (as a driver) with 54,8% and cycling (47,6%).

In a question that followed, English respondents selected PT in general to be the most important in daily commuting (70,5%). The choice of the key transportation mode for German speakers was not as clear with 42,9% of respondents declaring it to be PT, and 38,1% selecting the private car.

Both participant groups rated private cars to be safe, with most responses (~55%) being level 4 in a 1-to-5 scale, with 5 being the safest. The safety of automated cars, on the other hand, gave no clear results with all respondents assigning various safety grades, from 1 to 5, with no clear tendency. Both English- and German-speaking participants saw most potential use of AVs as private (50-61,9%) and shared (54,5%-66,7%) cars, with native Germans also seeing an opportunity for them to be used as taxis (54,8%).

Most of the participants were open for potential 10-20% detours caused by AV- technology (positive responses ranging from 79,5-81%). There was no clear tendency with the willingness

of an AV purchase with replies ranging quite evenly from “not at all” to “certainly”. A competitive price or a max. 20% premium – that was the cost-based willingness to purchase an AV (responses ranging from 90,9 to 92,8%). The most commonly declared ways of using AVs were on the Autobahn - for long journeys and in traffic jams (61,4-97,6%) The next popular options were PT driverless buses (50-57,1%) and city traffic (42,9-52,3%).

4.2 Street survey results

Generally, the results of street interviews in Fürstenfeldbruck correlated quite well with average online answers on German-speaking respondents.

Figure 4.4 Age distribution among street survey responses (in years)

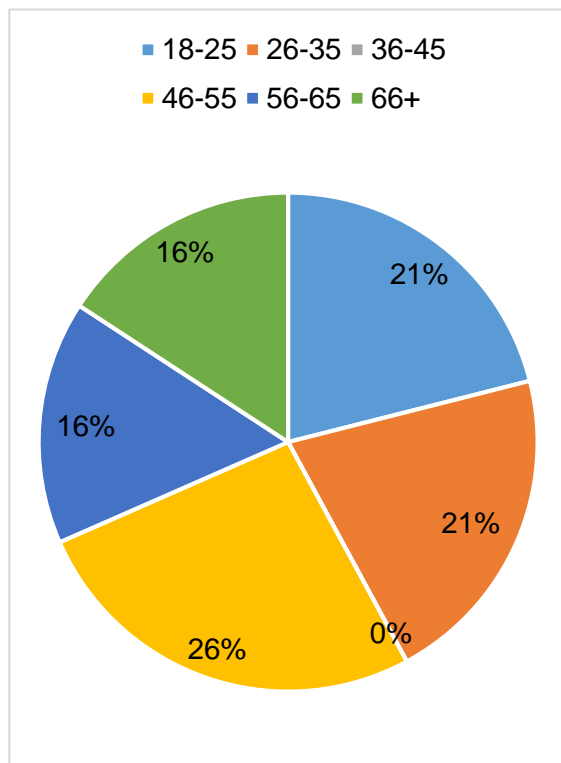
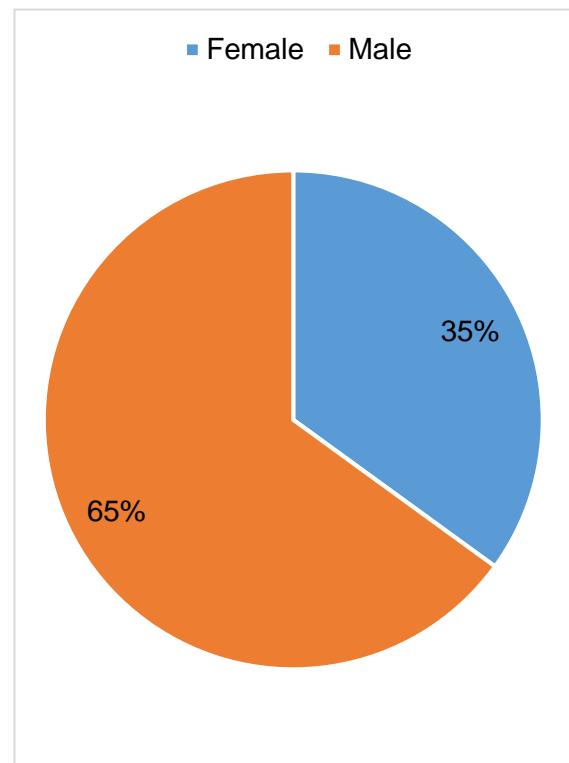


Figure 4.5 Gender distribution among street survey responses



The noticeable differences included lower awareness about AV technology (70% of answers declared no to moderate knowledge on the topic) and a low perception of spreading of information about AVs (80% indicated low information availability levels). Citizens of Fürstenfeldbruck declare high dependency on moving on foot (85%), value private cars more than PT as a main mode of transport in daily commuting (50% vs 35%). They would mostly see AVs used as private individual cars (70%) or taxis (40%). They are mostly not ready to accept detours (60%), a declared maximum is +10% of the way (40% of the replies). 80% of participants would not pay an extra for an AV. The majority sees AVs as a means of transport in urban traffic. Statistical personal data covered the one from the online German survey, with a slightly lower car ownership ratio of 55%.

The relatively small sample of 20 respondents and the characteristics of a street survey (small amount of time to ask all questions thoroughly) may have influenced the outcomes, especially in multiple-choice questions. This will be considered when evaluating results.

4.3 Analysis of both surveys

There is overall high awareness of automated vehicles' developments in Greater Munich. There is a proportionally low level of promotion of AVs which seem to influence the inconclusive perception of AV safety and a rather low willingness of purchasing such vehicles. Respondents do imagine AVs being in use in the future, especially as private and shared cars, as well as taxis.

Figure 4.6 Most important transportation mode in all respondent groups based on age (in percentage of replies)

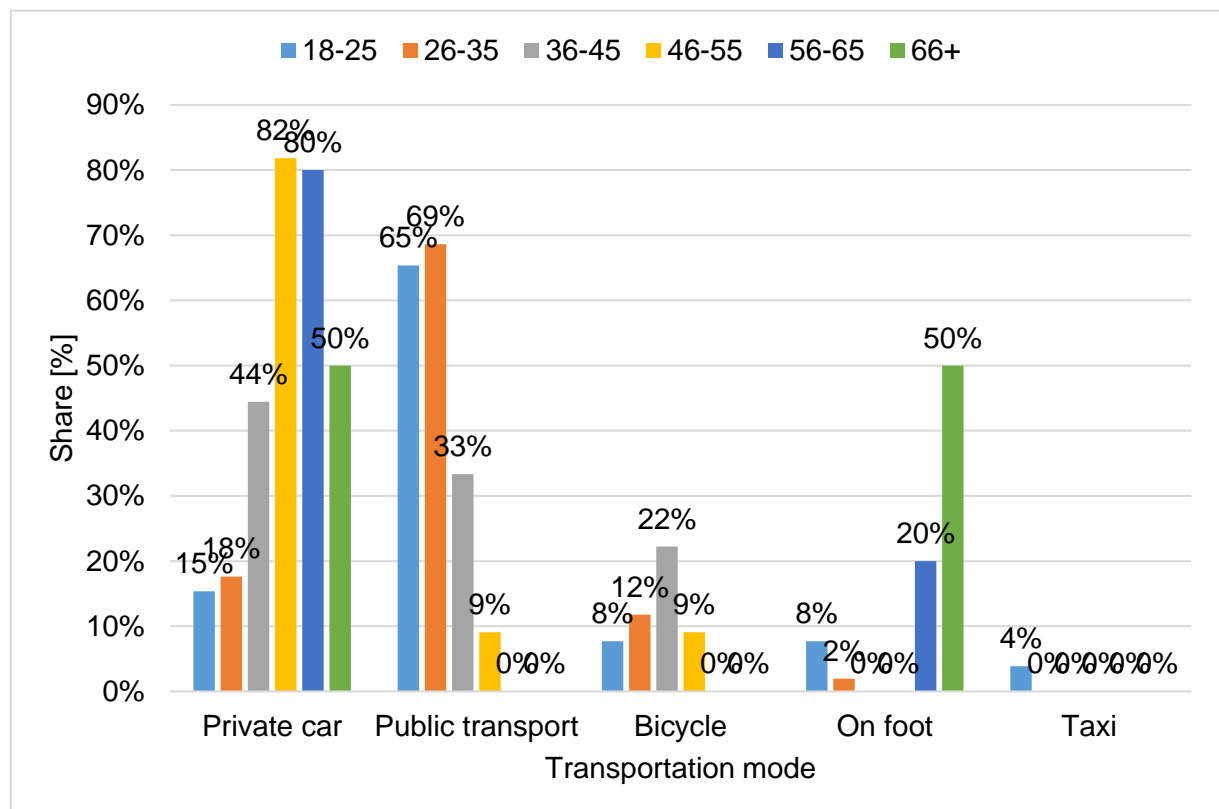
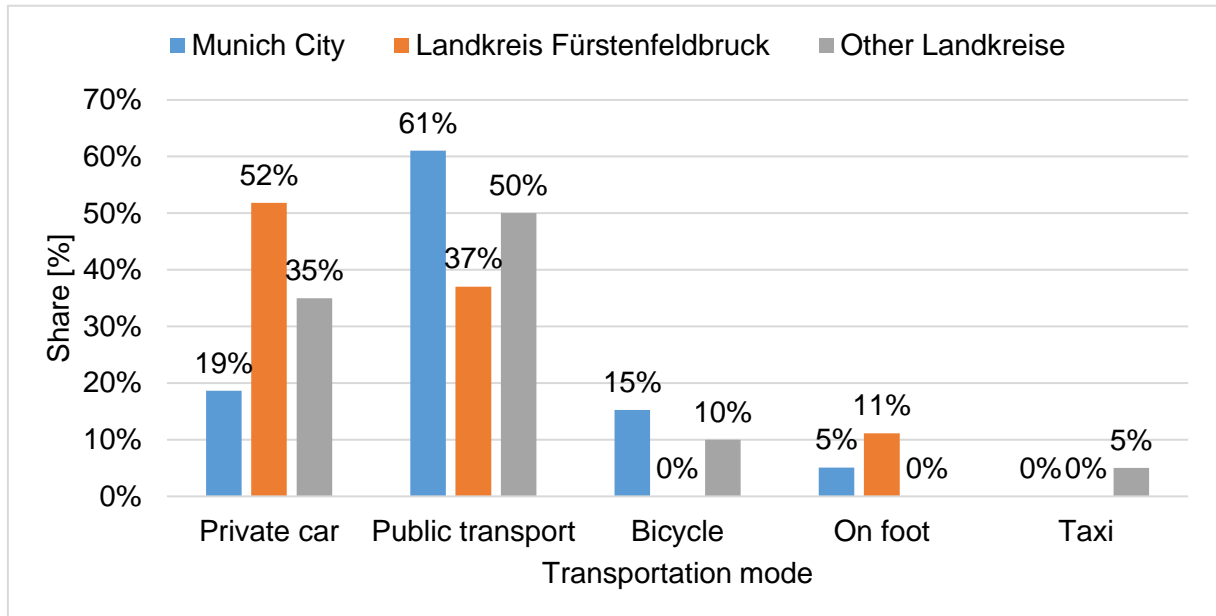


Figure 4.7 Most important transportation mode in all respondent groups based on place of residency (in percentage of replies)



Reliability on different modes of transport is based on the place of residency as well as the age of survey's participants (Figures 4.2. – 4.3.). Respondents up to 35 years of age report high dependency on public transport (65-69%, weighted mean 68%), whereas people older than 36 years rely mostly on private cars (44-82%, weighted mean 66%). Transportation mode results in the age group of 66+ are not very representative due to a small sample size (4 respondents). From all locations researched in the surveys, Munich showed the highest PT-usage ratio (61%). Compared to other regions, Fürstentfeldbruck has an above-average automobile dependency reaching 52% of respondents. Since it is a rather small city located remotely from the metropolitan capital, its citizens rely on individual transport (private cars) and are potential future beneficiaries of AV technology.

Figure 4.8 Average daily travel time of respondents willing to accept 10-30% detours caused by AV technology

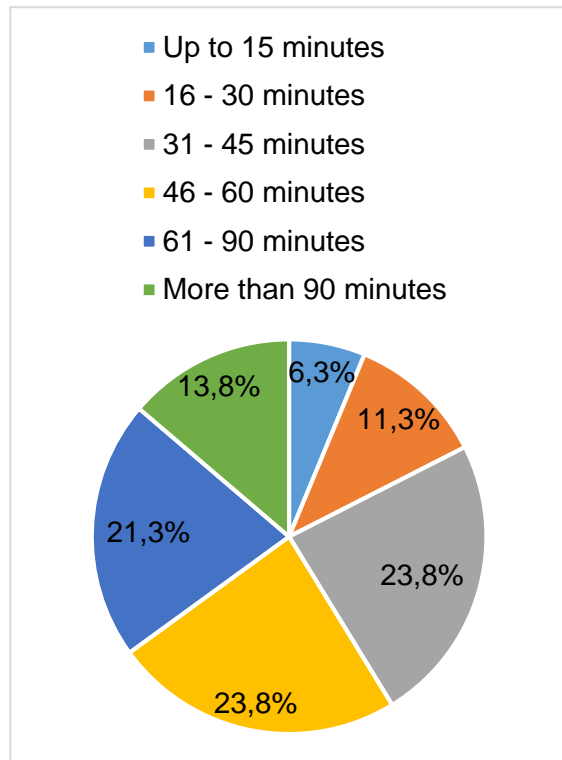
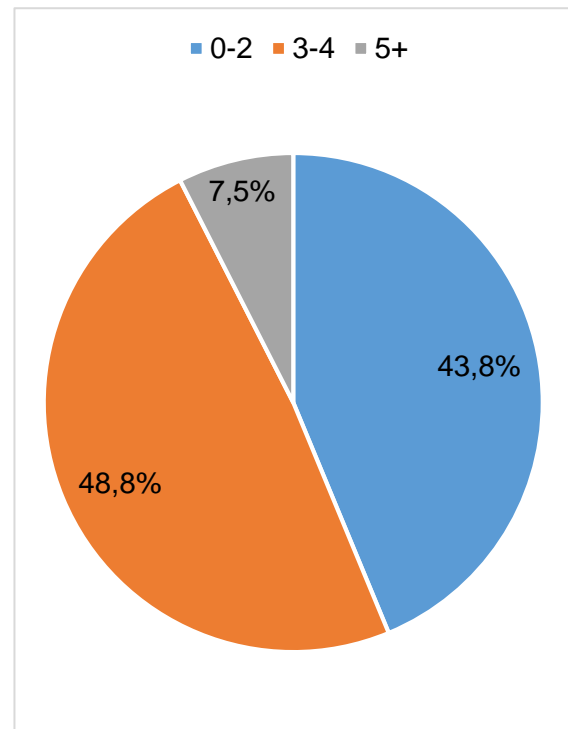


Figure 4.9 Average daily number of trips done by respondents willing to accept 10-30% detours caused by AV technology



80 respondents (75,5%) declared readiness for detours in their daily commuting when using automated vehicles. This group represents various average daily times but does not tend to have more than 4 trips daily (92,6% of answers).

With a more intensive promotion and a regular and steady introduction of automated vehicles to the common traffic, there is a potential for widespread awareness, acceptance and willingness towards AVs. This long-term process has a good chance for a change of the modal split in the Greater Munich by 2050.

4.4 Estimation of model scenarios based on the survey

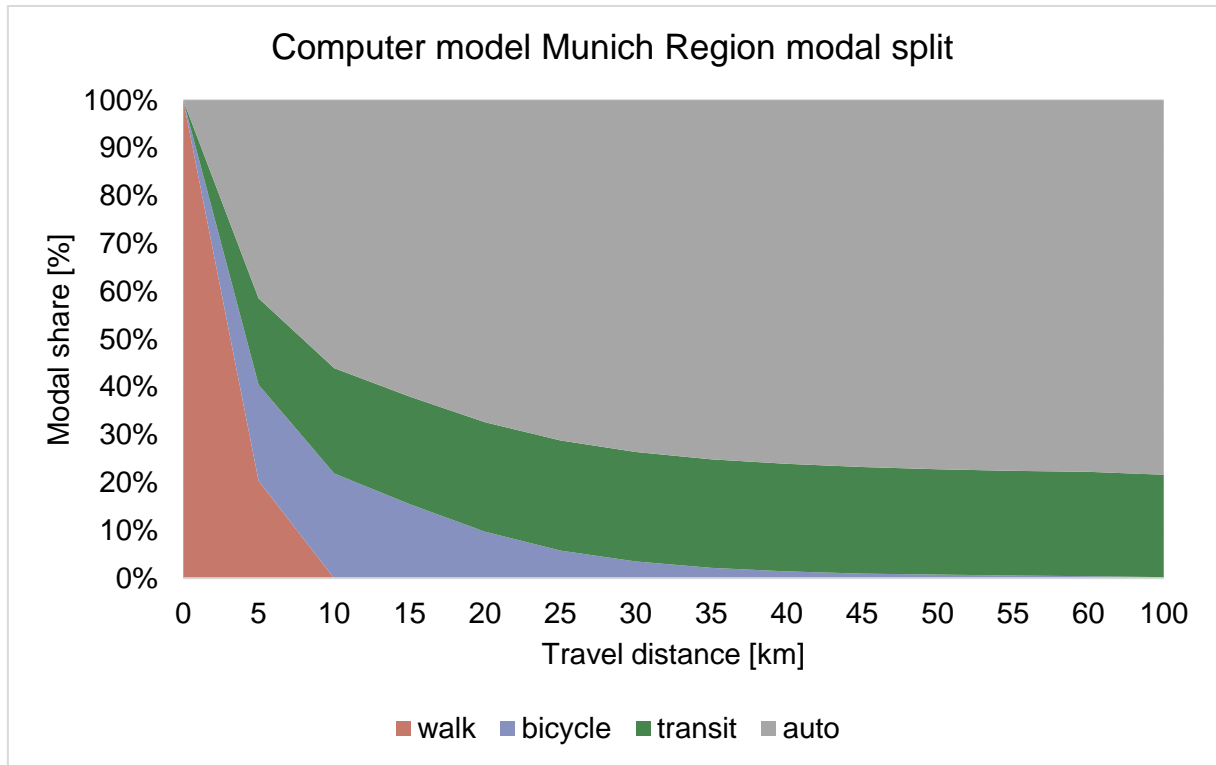
A regression analysis was conducted to look for a correlation between declared future use of shared AVs in a private way and the demographics of the respondents (age, gender).

Table 4.1 Regression analysis of respondents willing to use AVs as shared cars (means of public transport) - individual use

<i>Regression Statistics</i>					
Multiple R	0,263611754				
R square	0,069491157				
Adjusted R square	0,051423024				
Standard Error	0,487105825				
Observations	106				
<i>ANOVA</i>					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	2	1,825126235	0,912563117	3,84606187	0,024496611
Residual	103	24,43902471	0,237272085		
Total	105	26,26415094			
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-values</i>	
Intercept	0,68292605	0,147005736	4,645574175	0,000010058	
Age	-0,007656107	0,003554112	-2,15415488	0,033559791	
Gender	0,179387177	0,102178943	1,755617864	0,082126542	

Due to a low answer sample (106 responses) I accepted a relatively high P-value threshold of 0,1. The results indicate statistical significance of the input variables (age, gender) on the output ones (usage of AVs privately).

Due to the inability to gather a minimum of 4 strata's (30 answers per strata recommended), a further analysis with more correlations among variables was foregone.

Figure 4.10 Progressive modal split used in the MATSim model

MATSim uses a progressive modal split which is based dependent on the length of a trip. In this case, the longer the trip, the lower the probability of walking and cycling but a higher one for public transport and private cars.

The results of the regression analysis will be used to change the progressive modal split of the studied area used in the model for scenarios 1 to 4.

$$\text{Penetration Rate} = \text{Intercept} + \text{Age}_{\text{coef}} * \text{Age} + \text{Gender}_{\text{coef}} * \text{Gender}$$

$$\text{Penetration Rate} = 0,68292605 - 0,007656107 * \text{Age} + 0,179387177 * \text{Gender}$$

The Penetration Rate of AV usage of each combination of age and gender is calculated using the age and gender coefficients established in the regression analysis. This is executed by a Monte Carlo deterministic numerical integration. If the iterated random value is lower than the modelled Penetration Rate, the transportation mode choice is changed from car to an automated vehicle.

5 Case study

The calculation of the model is done for the study area described in chapter 3.3 (Case study: application to Fürstenfeldbruck) and is based on the modal split change calculation from chapter 4.4 (Estimation of model scenarios based on the survey). The population of modelled travelers will stay the same in all scenarios and represents the current size and structure of society in Greater Munich. The AV fleet will be the manipulated factor in scenarios 1 to 4.

Figure 5.1 Simulation scenarios

	Scenario 0 – base (no AVs)	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Traffic demand	Given by the model				
Transportation modes	On foot, bicycle, PT, private car	Scenario 0 + AVs for individual use			
Analyzed area with AVs	-	FFB study area only			
AV fleet	-	200	400	600	1000
AV occupancy	-	1			
Number of iterations	10				
Calculated time of simulation	One whole day – 24 hours				

Figure 5.2 Area of links and nodes for model calculation (used for modelling of all vehicles but AVs in all scenarios) with a blue-marked FFB area

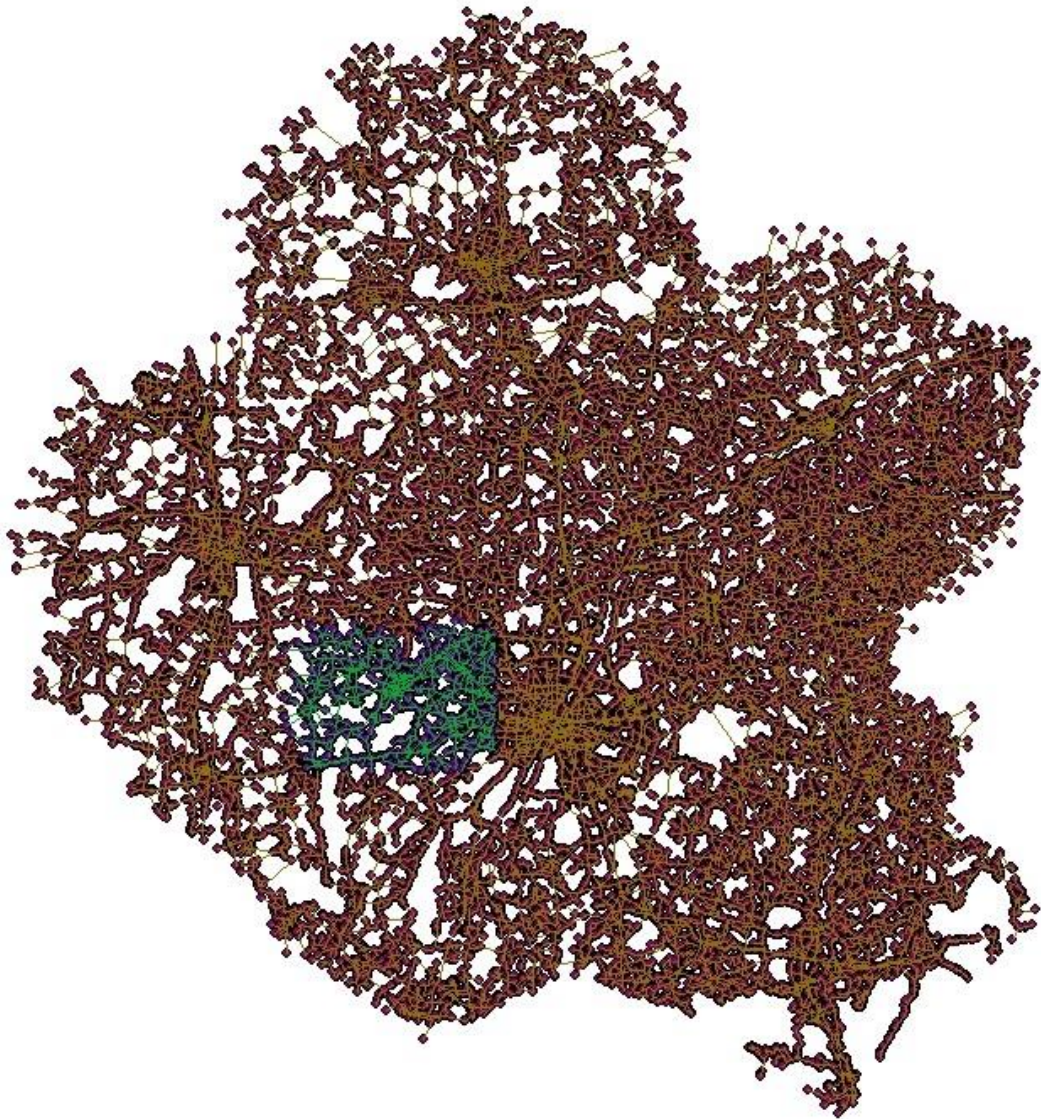
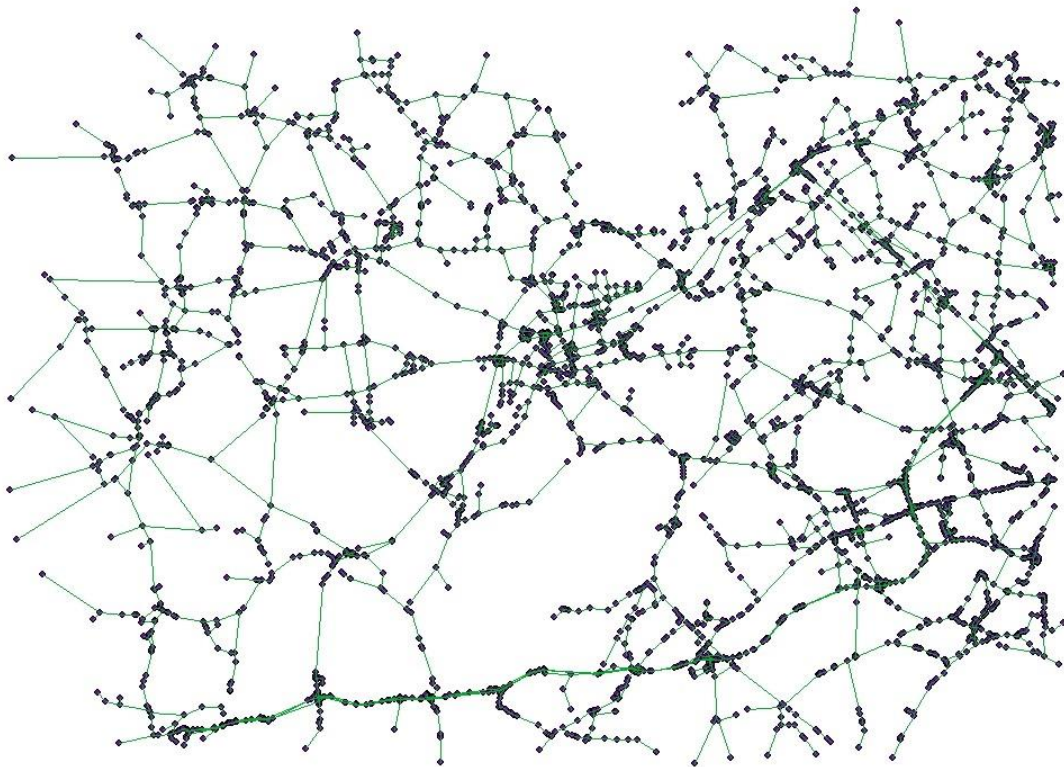


Figure 5.2 shows the entire calculation area used in the MATSim model. It consists of nodes and links representing intersections and streets of the Munich region. The map includes main streets, arteries and some middle-sized streets; smaller, less relevant links are excluded in the calculation. The red area is where transportation modes on foot, bicycle, PT and private car are modelled. The blue area also includes automated vehicles and is focused on Fürstenfeldbruck. It can be seen more in detail in Figure 5.3.

Figure 5.3 FFB-based area of links and nodes for model calculation (used for modelling of all vehicles - including AVs – in scenarios 1-4)



To generate the automated vehicles trips in scenarios 1-4, MATSim executes the following two applications:

- If the trip origin is within the FFB county, destination within the Munich City county and the initial mode is public transport, destination is changed either to Buchenau or Fürstenfeldbruck S-Bahn stations (in a 50/50% proportion) and the transport mode to car. (The AV share is consequently extracted from it based on 4.4.) This operation allowed the increase of observed AV-based trips in the whole study.
- If the trip origin and destination is within 15 km radius from FFB center and the transport mode is car, it will be switched to automated vehicles (this time in all applying cases). The 15 km radius is illustrated in Figure 5.4.

**Figure 5.4 FFB-based centroid area, where trip origins and destinations are located
(Source: Google Maps)**

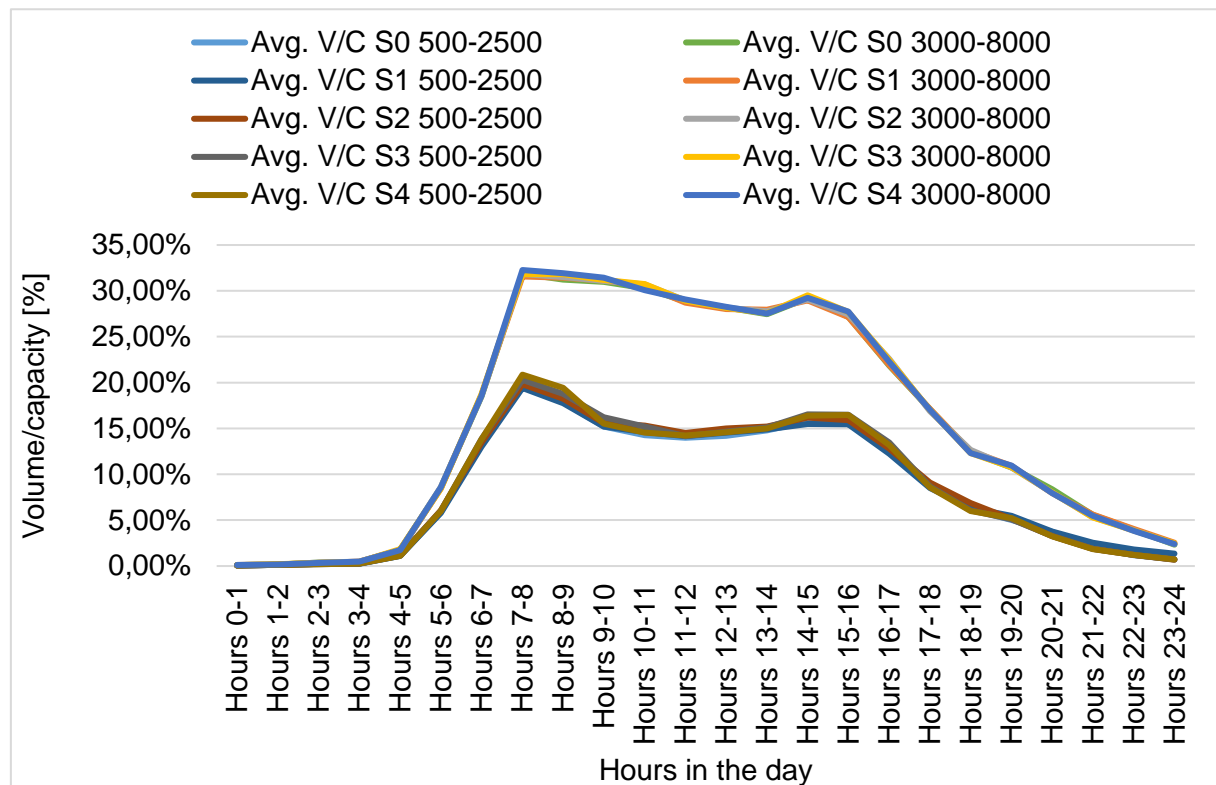


For the purposes of the study, I sorted study area's links (streets) according to capacity and divided them into 2 groups: local to middle sized ones with capacity between 500-2500 vehicles per hour and large/arterial ones with capacity between 3000-8000 vehicles per hour.

The 24-hour modelled volume to capacity ratios illustrated in Figure 5.5 show two value peaks. The first one is caused by home to work trips taken in the morning and has a higher value. The second one combines trips from work to home with trips to other activities and its value is slightly lower. One can also observe a much faster growth of the first peak than the regression of the second one.

In the scenarios analyses, I will concentrate on links with capacity values of 3000-8000 vehicles per hour since those were also the ones with the highest car volume levels. Additionally, I will only focus the study on the first peak, between 7:00 and 11:00.

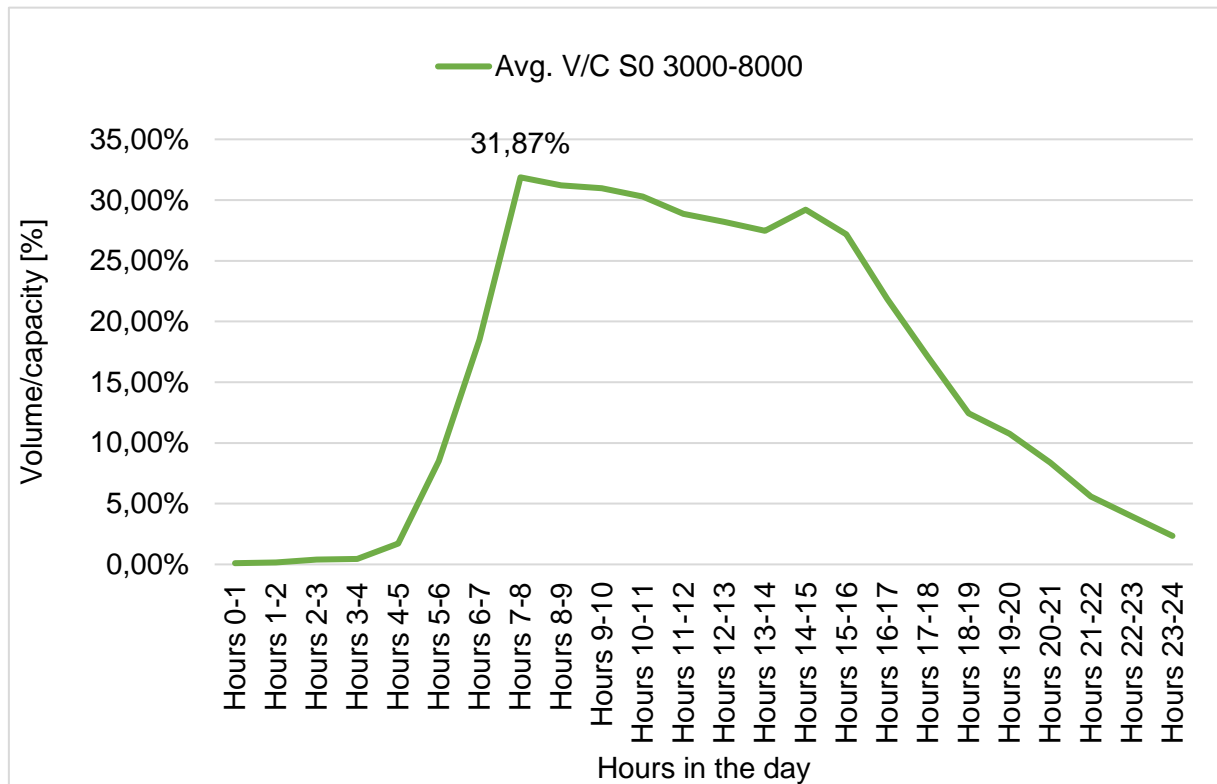
Figure 5.5 Vehicle to capacity ratio on links with capacity values of 500-2500 and 3000-8000 vehicles per hour (Scenarios 0-4)



5.1 Scenario 0

Scenario 0 was run without automated vehicles, with default modal split (see 4.4).

Figure 5.6 Vehicle to capacity ratio on links with capacity values of 3000-8000 vehicles per hour (Scenario 0)

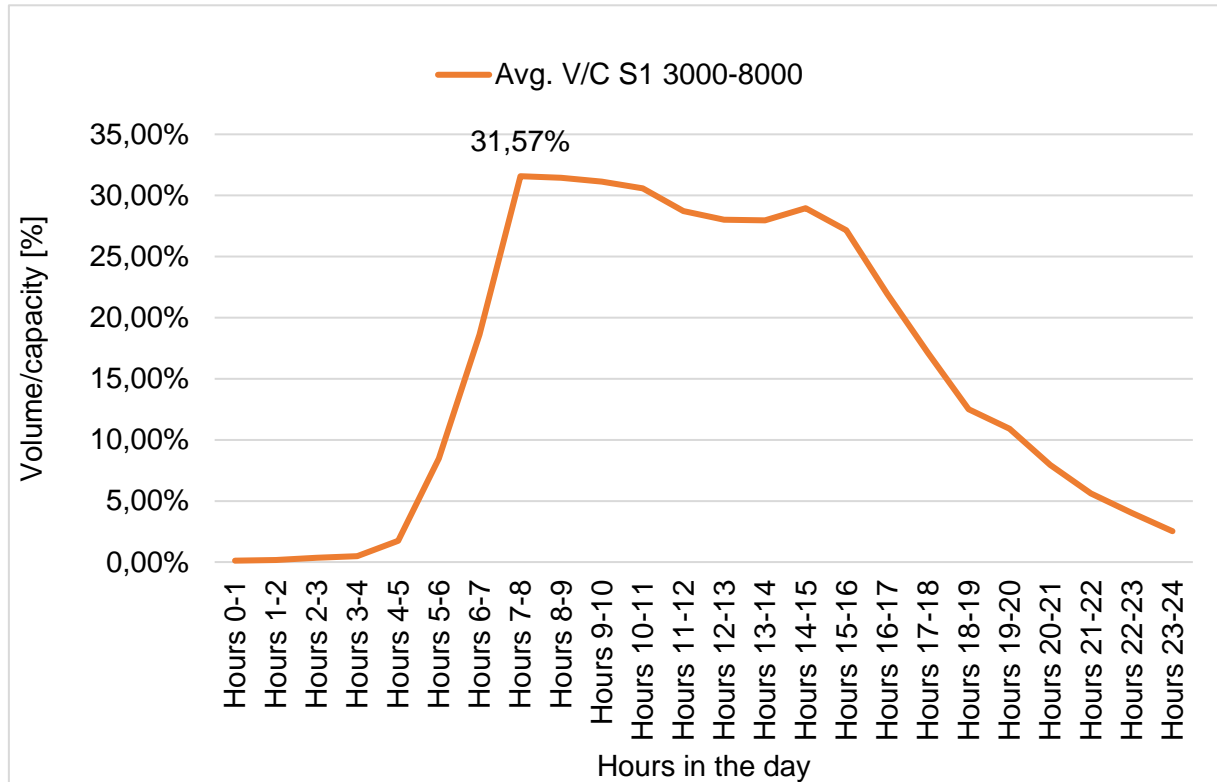


The vehicle to capacity ratio depicted in Figure 5.6 shows a peak of 31,87% on all links with a capacity between 3000-8000 vehicles per hour.

5.2 Scenario 1

Scenario 1 was run with 200 automated vehicles in the study area, with the accordingly changed modal split (see 4.4).

Figure 5.7 Vehicle to capacity ratio on links with capacity values of 3000-8000 vehicles per hour (Scenario 1)



The vehicle to capacity ratio depicted in Figure 5.7 shows a peak of 31,57% on all links with a capacity between 3000-8000 vehicles per hour. This value is slightly lower than in scenario 0 but the change is too low to make a real-life difference.

The low number of available AVs in this scenario is a cause of a very long average waiting time (223 min.) for a vehicle. Therefore, the average trip duration is also rendered high (240 min.).

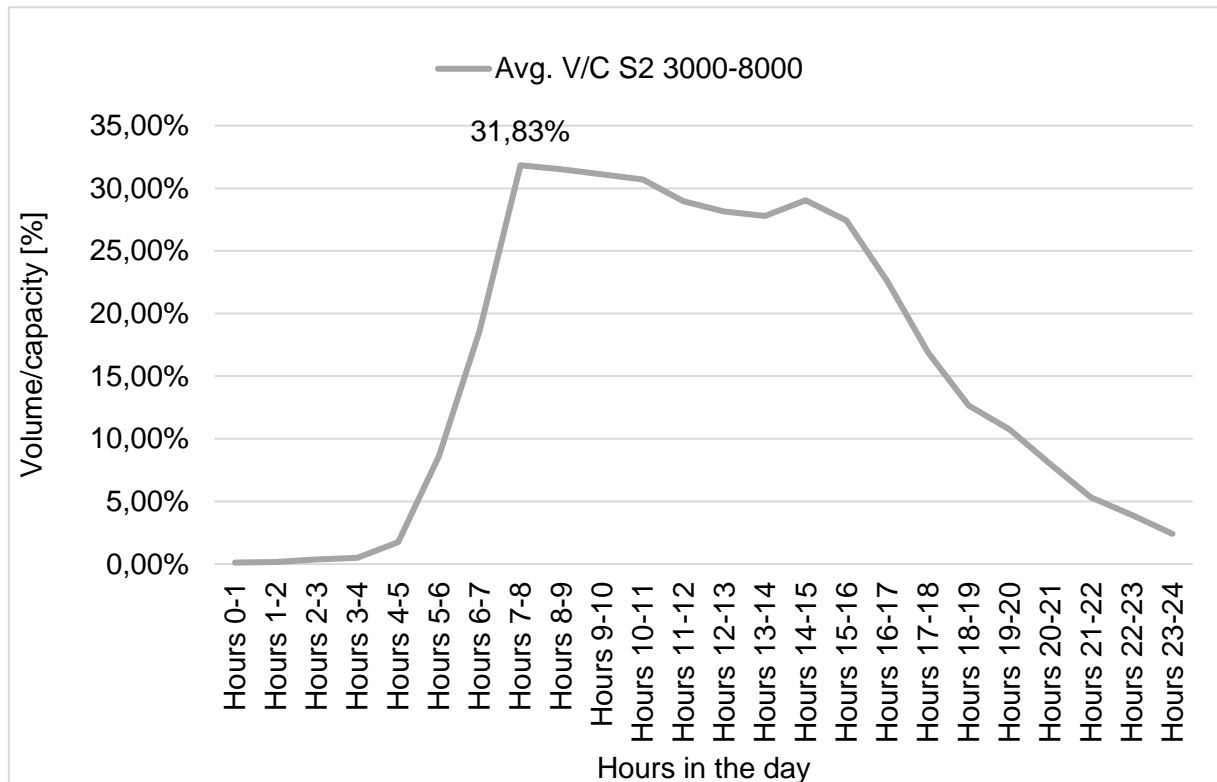
Table 5.1 Average AV trip duration and waiting time (Scenario 1)

Average AV trip duration	239,8	[min]
Average AV waiting time	223,1	[min]

5.3 Scenario 2

Scenario 2 was run with 400 automated vehicles in the study area, with the accordingly changed modal split (see 4.4).

Figure 5.8 Vehicle to capacity ratio on links with capacity values of 3000-8000 vehicles per hour (Scenario 2)



The vehicle to capacity ratio depicted in Figure 5.8 shows a peak of 31,83% on all links with a capacity between 3000-8000 vehicles per hour. This value is slightly lower than in scenario 0 but the change is too low to make a real-life difference.

The still-low number of available AVs in this scenario is a cause of a long average waiting time (66 min.) for a vehicle. Therefore, the average trip duration is also rendered high (84,6 min.).

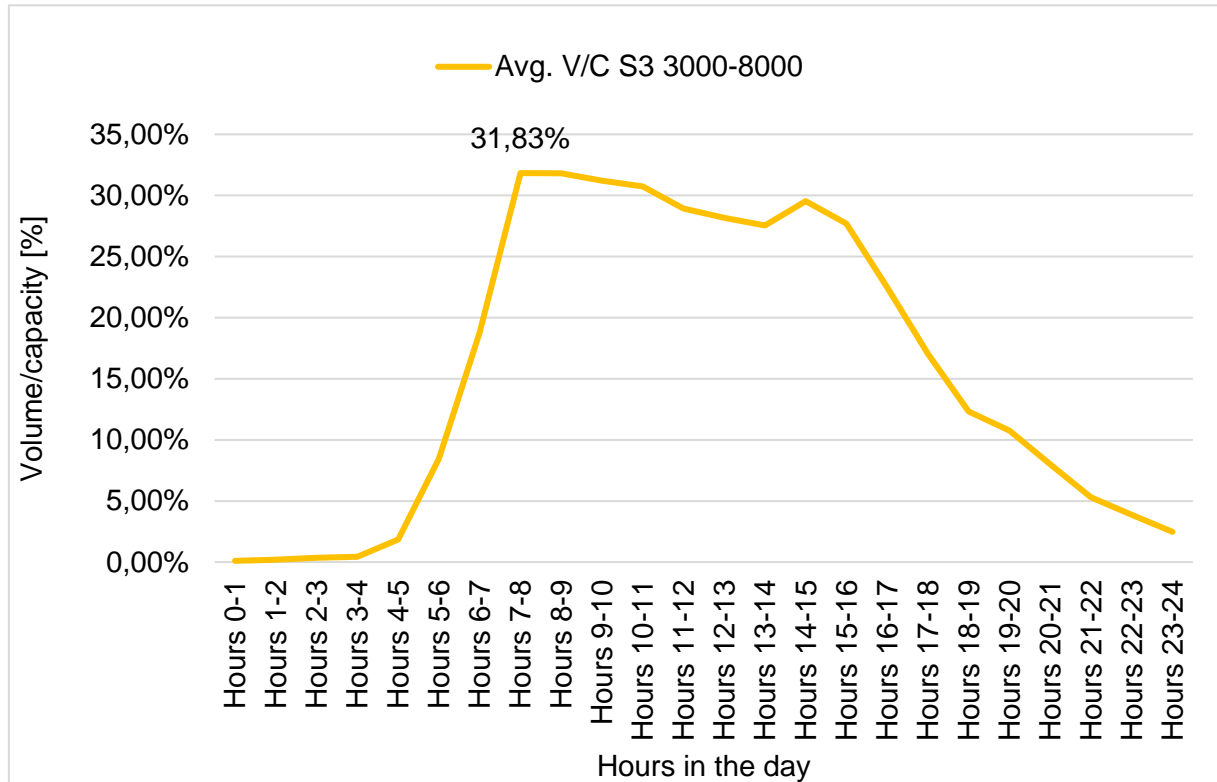
Table 5.2 Average AV trip duration and waiting time (Scenario 2)

Average AV trip duration	84,6 [min]
Average AV waiting time	66,0 [min]

5.4 Scenario 3

Scenario 3 was run with 600 automated vehicles in the study area, with the accordingly changed modal split (see 4.4)

Figure 5.9 Vehicle to capacity ratio on links with capacity values of 3000-8000 vehicles per hour (Scenario 3)



The vehicle to capacity ratio depicted in Figure 5.9 shows a peak of 31,83% on all links with a capacity between 3000-8000 vehicles per hour. This value is slightly lower than in scenario 0 but the change is too low to make a real-life difference. Interestingly, the peak is the same as in scenario 2.

The moderate number of available AVs in this scenario still does not provide a desirable average waiting time (28 min.) for a vehicle. Therefore, the average trip duration is also rendered high (46,6 min.).

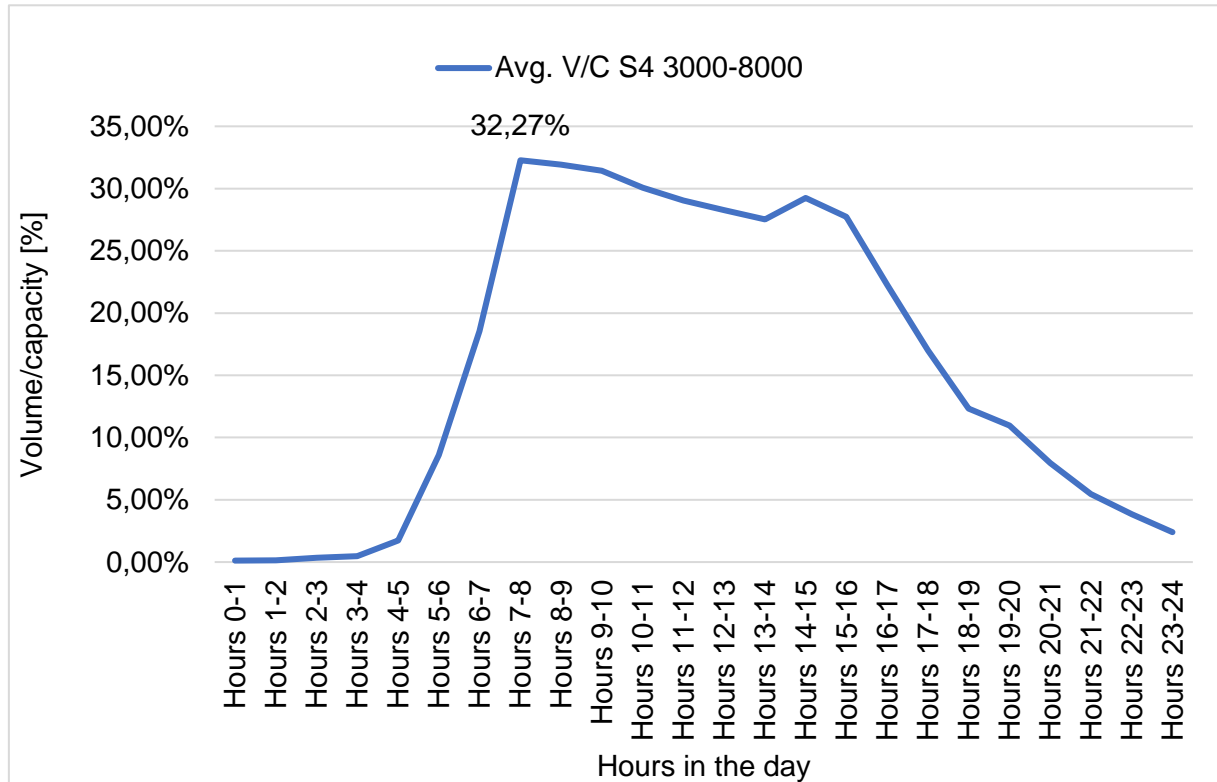
Table 5.3 Average AV trip duration and waiting time (Scenario 3)

Average AV trip duration	46,6	[min]
Average AV waiting time	28,3	[min]

5.5 Scenario 4

Scenario 4 was run with 1000 automated vehicles in the study area, with the accordingly changed modal split (see 4.4)

Figure 5.10 Vehicle to capacity ratio on links with capacity values of 3000-8000 vehicles per hour (Scenario 4)



The vehicle to capacity ratio depicted in Figure 5.10 shows a peak of 32,27% on all links with a capacity between 3000-8000 vehicles per hour. This value is the highest among all scenarios but the change between all of them is too low to make a real-life difference.

The high number of available AVs in this scenario does provide a desirable average waiting time (10 min.) for a vehicle. Therefore, the average trip duration should be acceptable to some (30 min.).

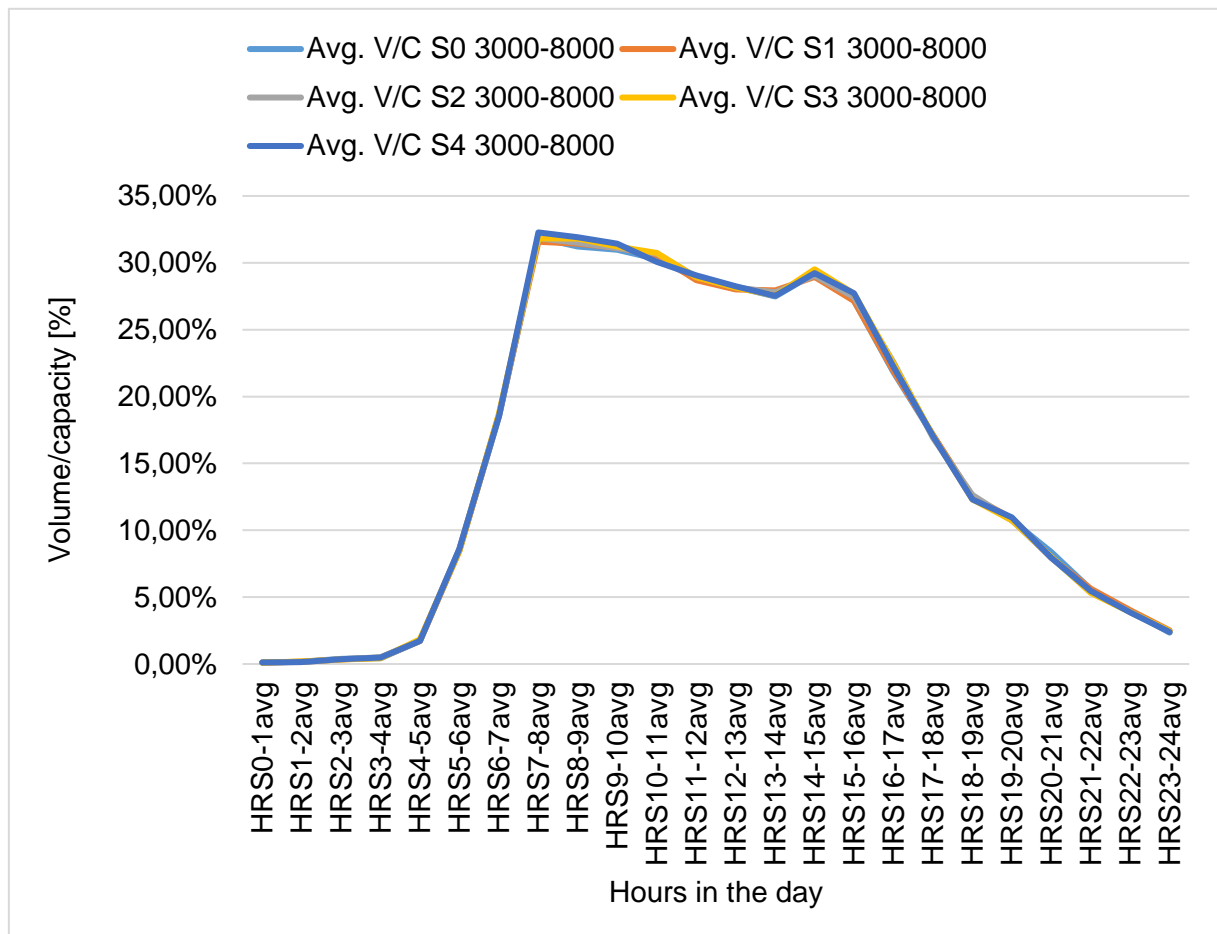
Table 5.4 Average AV trip duration and waiting time (Scenario 4)

Average AV trip duration	30,1	[min]
Average AV waiting time	10,3	[min]

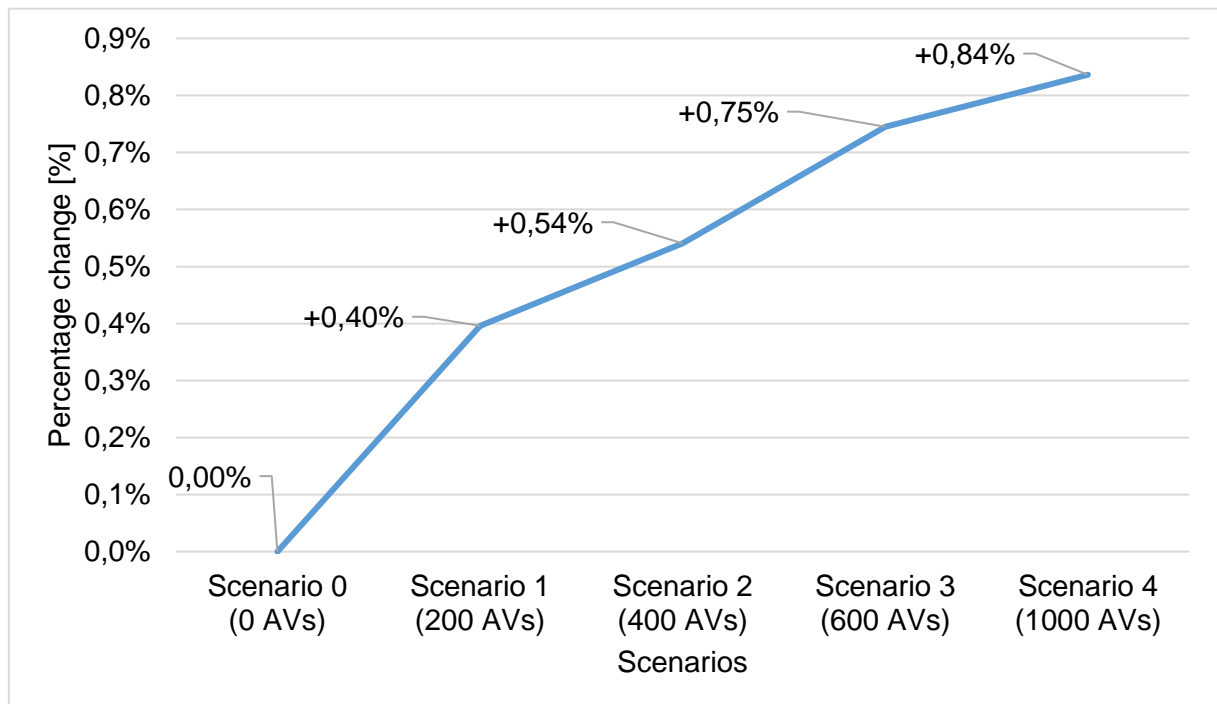
5.6 Results interpretation

In all of the scenarios, the introduction of automated vehicles in the study area changed the volume to capacity ratio development throughout the modelled time of 24 hours to a very low extent (Figure 5.11). Compared to Scenario 0, the volume/capacity morning peak difference was within a range of -0.3% to +0.4%. Therefore, the presence of up to 1000 AVs does not impede traffic flow in Fürstenfeldbruck.

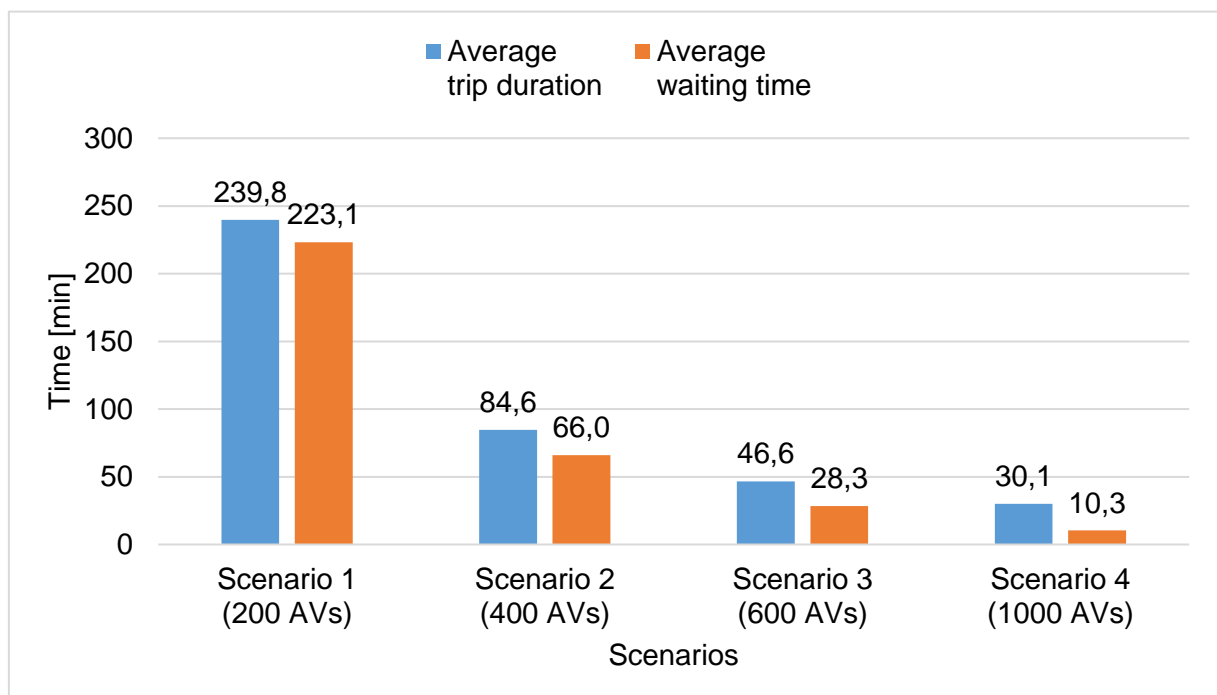
Figure 5.11 Vehicle to capacity ratio on links with capacity values of 3000-8000 vehicles per hour (Scenarios 0-4)



In the peak hours, between 7:00 and 11:00, the overall levels of vehicle kilometers travelled (VKT) raised gradually with the growth of the number of AVs in the network (Figure 5.12). This is caused by additional AV traffic from destinations to origins of modelled trips. A maximal growth of 0.84% VKT is not a significant factor to negatively influence traffic flow in Fürstenfeldbruck in real-life conditions, but the growing trend of Figure 5.12 is a confirmation of many previous AV studies, that the use of automated vehicles does indeed cause induced travel.

Figure 5.12 Vehicle Kilometers Travelled growth between 7:00 and 11:00 (scenarios 0-4)

A strong correlation between AV availability and AV travel demand can be observed in Figure 5.13. A steady and significant decrease in average waiting and travel times in following scenarios implicates a need of a relatively high number of AVs to offer an attractive transport mode to potential travelers.

Figure 5.13 Average AV trip duration and waiting time (Scenarios 1-4)

6 Conclusions and recommendations

This section provides a final summary of the two integral parts of the research: the survey and the model. Furthermore, study limitations, recommendations and future work ideas are provided to put a long-term perspective on the possibilities in the research area.

6.1 Survey results summary

Social surveys are a valid method of research for upcoming technological advancements in various fields. In the case of this master thesis, I found out that the respondents from the Munich Region do have an idea about the developments in the field of automated vehicles. The low purchase readiness and an inconclusive safety perception may be interpreted as an approach to a virtual product, which performance has not yet been experienced by a broader target audience.

Nevertheless, the applicability of automated vehicles in real-world urban environments should be very possible, based on the survey results. Responses indicate high readiness for potential detours and the answers include multiple ideas on how to use the AV technology. One may see a greater chance of AV success in areas with high public transport dependency, as transit users are already used to waiting time as an integral part of daily commuting.

6.2 Model results summary

An introduction of a new means of transport does not have to negatively influence the mobility experience in a study area. Fürstenfeldbruck case study results show little to no influence on congestion-related variables in the study area. Volume to capacity ratios and vehicle kilometers travelled levels are close to the ones in the 0 scenario (without automated vehicles). Induced travel, although kept at relatively low levels, could be observed and grows systematically along with the number growth of extra AVs travelling in the study area.

While considering an introduction of shared automated vehicles to a transport network, one should thoroughly plan a proper supply of available units. A deficit of them impedes strongly average travel and waiting times for each trip, rendering the automated vehicles' technology unattractive for commuters, despite its other advantages.

6.3 Limitations of the study

Scope constraints include mostly the limitation of the modelled area to Fürstenfeldbruck only. The survey's amount of replies has also influenced the flow of the study due to a low quantitative amount of replies (106) and a consequent inability of a complex, statistically relevant interpretation of results using advanced statistical utilities. Given the low number of changed

model factors (size of AV fleet only), one could introduce a higher number of model scenarios for a wider spectrum of results, it was foregone due to time constraints (Future work).

6.4 Recommendations

To confirm any modelled traffic scenarios in real life, it is essential to put them in practice in a controlled, manageable environment. Once it is legally possible to introduce automated vehicles into public roads, after having undertaken additional modelling studies, it would be suitable to test the idea in a city like Fürstenfeldbruck. Its size and geographical location should be a very good testing ground for future pilot projects, which would be implemented in larger urban areas, for example in the city of Munich.

6.5 Future work

In similar studies undertaken in the future, better promotion of social surveys would help increase the overall number of replies. An organization of discussion groups for concerned/active citizens would also contribute to the qualitative input for this kind of research and may also introduce factors not foreseen when forming questions on its own in a related survey. As a further step, one could organize a discussion with a group of professional/academic experts and city officials responsible for transportation.

Scenarios that include the analysis of automated vehicles used in a shared way (with occupancy levels above one) would be a useful factor in assessing the potential benefits of AVs on traffic flow. To include this in the studied model, one could do the following:

- Generate trips in the program within the study area,
- Identify trips assigned to shared AVs,
- Check for trips with origins/destinations close to each other,
- Drop overlapping trips and interpret them as ones with a higher occupancy rate.

A second natural step to extend the scope of the study would be to model the traffic flow in the whole Greater Munich area or in all other small municipalities from the Munich Region to increase the sample number and confirm results from Fürstenfeldbruck in other locations and at a macroscale.

List of References

- Bassett, A. (2015). The Emergence of Driverless Cars: Year In Review 2015 | autonomous car | Britannica.com. Retrieved March 21, 2017, from <https://www.britannica.com/topic/Emergence-of-Driverless-Cars-The-2045163>
- Chapin, T., Stevens, L., Crute, J., Jordan, C., Rokyta, A., & Washington, A. (2016). Envisioning Florida ' s Future : Transportation and Land Use in an Automated Vehicle World, (April).
- Childress, S., Nichols, B., Charlton, B., & Coe, S. (2014). Using an Activity-Based Model to Explore the Potential Impacts of Automated Vehicles. *Transportation Research Record: Journal of the Transportation Research Board*, 2493(2493), 99–106. <https://doi.org/10.3141/2493-11>
- Childress, S., Nichols, B., Charlton, B., Coe, S., Daimler AG, Hong, J., ... Wagner. (2015). Autonomous Vehicle Implementation Predictions: Implications for Transport Planning. *94th Annual Meeting of the Transportation Research Board*, 44(April), 34. <https://doi.org/10.1613/jair.301>
- Fürstenfeldbruck Administrative District Office. (2017). The Administrative District Office presents itself. Retrieved May 18, 2017, from <http://www.lra-ffb.de/lkr/lkrlage.shtml>
- International Transport Forum / OECD. (2015). Urban Mobility System Upgrade Urban Mobility System Upgrade. *Oecd*, 34. Retrieved from https://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0CCEQFjAA&url=http://www.internationaltransportforum.org/Pub/pdf/15CPB_Self-drivingcars.pdf&ei=W4ZLVcKzGIX2UsOsgYAL&usg=AFQjCNFKBn2GepTYHaVHEy_1D_8rMyJTGg&sig2=7fVZvuCP-b
- Kyriakidis, M., Happee, R., & Winter, J. C. F. De. (2015). Public opinion on automated driving : Results of an international questionnaire among 5000 respondents. *Transportation Research Part F: Psychology and Behaviour*, 32, 127–140. <https://doi.org/10.1016/j.trf.2015.04.014>
- Milakis, D., Arem, B. van, & Wee, B. van. (2015). Policy and society related implications of automated driving : a review of literature and directions for future research Policy and society related implications of automated driving : a review of literature and directions for future research.
- Milakis, D., & Snelder, M. (2017). Development and transport implications of automated vehicles in the Netherlands: scenarios for 2030 and 2050. *European Journal of Transport and Infrastructure Research*, 1(17), 63–85.
- Munich Statistical Office. (2016). *The immigrant population in the city districts by chosen nationalities on 31.12.2016*.
- Munich Transport and Tariff Association. (2010). *Mobility in Fürstenfeldbruck Region*. Retrieved from <http://www.lra-ffb.de/pdf/oepnv/MVV-Broschuere-Mobilitaet.pdf>
- Munich Transport and Tariff Association. (2015). MVV - MVV in numbers. Retrieved May 11, 2017, from <http://www.mvv-muenchen.de/de/der-mvv/mvv-in-zahlen/index.html>
- Munich Transport and Tariff Association, & Landeshauptstadt München. (2010). Mobility in Germany. Retrieved from http://www.mvv-muenchen.de/fileadmin/media/download/downloadbereich/Publikationen/documents/IN_FAS_Kurzbericht_MiD_20101124.pdf
- OECD. (2013). Road traffic, vehicles and networks. *Environment at a Glance 2013: OECD Indicators*. Retrieved from http://www.oecd-ilibrary.org/environment/environment-at-a-glance-2013/motor-vehicle-ownership-2011-or-latest-available_9789264208919-graph58-en
- Pendyala, R. M., & Bhat, C. R. (2014). Activity-Travel Behavior Impacts of Driverless Cars.

- 93rd Annual Meeting of the Transportation Research Board.*
- Planning Association of Greater Munich. (2017). Short information. Retrieved May 11, 2017, from http://www.region-muenchen.com/themen/info_en/info_en.htm
- U.S. Department of Transportation. (2016). Federal Automated Vehicles Policy, (September), 116. <https://doi.org/12507-091216-v9>
- U, J. (2016). The Road to Driverless Cars: 1925 - 2025 > ENGINEERING.com. Retrieved March 30, 2017, from <http://www.engineering.com/DesignerEdge/DesignerEdgeArticles/ArticleID/12665/The-Road-to-Driverless-Cars-1925--2025.aspx>
- Weber, M. (2014). Where to? A History of Autonomous Vehicles | Computer History Museum. Retrieved March 21, 2017, from <http://www.computerhistory.org/atchm/where-to-a-history-of-autonomous-vehicles/>
- Zmud, J., Sener, I. N., & Wagner, J. (2016). Consumer Acceptance and Travel Behavior Impacts of Automated Vehicles Final Report, Texas A&M Transportation Institute PRC 15-49 F. Retrieved from <http://tti.tamu.edu/documents/PRC-15-49-F.pdf%5Cnhttp://tti.tamu.edu/2016/03/11/ttis-zmud-talks-consumer-acceptance-of-automated-vehicles-at-sxsw/>

List of Abbreviations

AV	Automated Vehicle
CACC	Cooperative Adaptive Cruise Control
FFB	Fürstenfeldbruck
LIDAR	Light Detection and Ranging
MVV	Munich Transport and Tariff Association
NHTSA	National Highway Traffic Safety Administration
PT	Public Transport
VKT	Vehicle Kilometers Travelled
VMT	Vehicle Miles Travelled

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Appendix A: Full version of the questionnaire (English)

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* Required

Wählen Sie Ihre Sprache - choose your language *

☐ Deutsch

☐ English

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Automated Vehicles Survey

You are invited to take part in a research survey about automated vehicles and their possible future influence on your daily mobility. Your participation will take approximately 10 min. and is completed online at your computer.

The purpose of the survey is a TU Munich scientific study focused on improving traffic flow in peak hours in Fürstenfeldbruck for individual vehicles (<https://www.msm.bgu.tum.de/lehre/masterarbeit>). The survey is addressed to the commuters of the Munich Metropolitan Area and is anonymous.

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What are Automated Vehicles?

Please take a moment and read a brief definition of the survey's subject.

An automated vehicle is capable of partial to full-automated operation. Synonymous names for the subject are driverless cars, autonomous cars, self-driving cars and robot cars.

First driverless car concepts were created and tested as early as in the 1920s but only recently has IT technology advanced enough to allow modern cars to achieve high levels of precision in vehicle control. The technology is still in rapid development and there are numerous functioning models from a variety of manufacturers. The automated car concept faces legal challenges in order to allow it to be used on public roads.

(Source: Encyclopedia Britannica)

Sample illustration: an automated car in use



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Knowledge on Automated Vehicles

Question page 1 of 4

How informed are you about the development of automated vehicles? *

	1	2	3	4	5	
Not at all (I hear of them for the first time)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Very well (I am an expert on the subject)

Subjectively, how do you perceive the spread of information about automated vehicles in public life? (eg. news, ads) *

	1	2	3	4	5	
Almost non-existent / I don't know	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Practically everywhere

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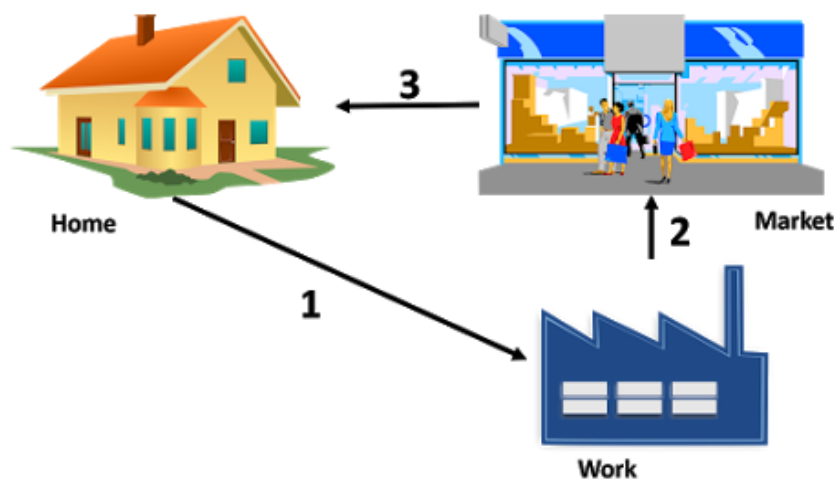
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Travel Behavior

Question page 2 of 4

How many journeys per workday do you usually do? (One journey is a whole movement from point A to B) *



- ☐ 0-2
- ☐ 3-4
- ☐ 5+

Which modes of transport do you regularly use for daily commuting to your regular activity places, i.e. work, school? (you can choose more than one answer) *

- ☐ Private car - driver
- ☐ Private car - passenger
- ☐ Public transport: bus
- ☐ Public transport: S-bahn, U-bahn or tram
- ☐ Regional train
- ☐ Taxi
- ☐ Bicycle
- ☐ On foot

How much time do you spend traveling during an average day? *

- ☐ Up to 15 minutes
- ☐ 16 - 30 minutes
- ☐ 31 - 45 minutes
- ☐ 46 - 60 minutes
- ☐ 61 - 90 minutes
- ☐ More than 90 minutes

Which mode of transport is the most important one in your daily commuting? *

Choose ▼

The possible answers to the question above were:

- Private car,
- Public transport,
- Taxi,
- Bicycle,
- On foot.

How safe do you perceive private cars? (From a driver/passenger perspective) *

	1	2	3	4	5	
Not safe	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Very safe

How safe do you perceive automated vehicles? (From a driver/passenger perspective) *

	1	2	3	4	5	
Not safe	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Very safe

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Future Use of Autonomous Cars

Question page 3 of 4

How would you consider using automated cars? (you can choose more than one answer) *

- ☐ as an own private car
- ☐ as a shared car (means of public transport) - individual use
- ☐ as a shared car (means of public transport) - shared use with other/foreign passengers
- ☐ as a rental car (for long journeys)
- ☐ as a taxi
- ☐ as a delivery service
- ☐ I won't use them
- ☐ Other: _____

Automated vehicles introduce advantages, that traditional cars don't have

Since there is no human driver in a robotic vehicle, all passengers can engage in activities which are not related to the travel.

A shared autonomous vehicle chooses an optimal route, on which passengers can hop on and off in various places and can still travel possibly direct.

Compared to direct routes, how much of a detour (extra distance) in your daily travel in an automated vehicle would you be willing to accept, given the extra comfort you become as a non-driver? *

- ☐ None at all
- ☐ Max 10% longer way
- ☐ Max 20% longer way
- ☐ Max 30% longer way

Would you consider purchasing a private automated car? *

	1	2	3	4	5	
Not at all	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Definitely

How much more would you be ready to pay for an automated vehicle, compared to a traditional one? *

- ☐ I wouldn't pay more than a conventional car
- ☐ max. +20% of the price
- ☐ max. +40% of the price
- ☐ max. +60% of the price

For which of the following situations could you imagine using automated vehicles? (you can choose more than one answer) *

- ☐ On long freeway journeys
- ☐ In traffic jams on the freeway
- ☐ On rural roads
- ☐ In city traffic
- ☐ On my everyday journeys
- ☐ For public transport buses

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Statistical information

Question page 4 of 4

How old are you? *

- ☐ 17 or younger
- ☐ 18-25
- ☐ 26-35
- ☐ 36-45
- ☐ 46-55
- ☐ 56-65
- ☐ 66+
- ☐ I prefer not to answer.

What is your gender? *

- ☐ Male
- ☐ Female
- ☐ I prefer not to answer / other

Including yourself, how many persons live in your household? *

- ☐ One
- ☐ Two
- ☐ Three
- ☐ Four or more
- ☐ I prefer not to answer.

What is your household monthly net income? *

- ☐ ≤500€
- ☐ 501-1000€
- ☐ 1001-1500€
- ☐ 1501-2000€
- ☐ 2001-3000€
- ☐ 3001€ - 4000€
- ☐ 4001€ - 5000€
- ☐ > 5000€
- ☐ I prefer not to answer.

Do you own a private car? *

- ☐ Yes
- ☐ No
- ☐ I prefer not to answer.

Munich metropolitan area districts



Where do you live? *

- ☐ Munich city (München Stadt)
- ☐ Landkreis Dachau
- ☐ Landkreis Freising
- ☐ Landkreis Erding
- ☐ Landkreis Ebersberg
- ☐ Landkreis München
- ☐ Landkreis Starnberg
- ☐ Landkreis Landsberg am Lech
- ☐ Landkreis Fürstenfeldbruck
- ☐ Other: _____

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Umfrage über autonome Fahrzeuge - Automated vehicles survey

Thank you!

Thank you for participating in the survey. You can optionally add your comments in the section below - I appreciate your feedback!

If you have any questions regarding the survey, please contact me per e-mail.
andrzej.michalski@tum.de

Feedback, comments?

Your answer

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Appendix B: Results of the online questionnaire and street survey

The complete results of the online questionnaire and the street survey are located on the CD attached to the thesis, as their entire content proved to unproportionally voluminous to be part of this document's text.

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Declaration concerning the Master's Thesis

I hereby confirm that the presented thesis work has been done independently and using only the sources and resources as are listed. This thesis has not previously been submitted elsewhere for purposes of assessment.

Munich, July 14th, 2017



Andrzej Michalski