MSc Program
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Automated Mobility on Demand – A Transportation Concept for Vienna´s Metropolitan Area

A Master's Thesis submitted for the degree of
“Master of Science”

supervised by
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Affidavit

I, **THOMAS SCHMIDT, BSC**, hereby declare

1. that I am the sole author of the present Master's Thesis, "AUTOMATED MOBILITY ON DEMAND – A TRANSPORTATION CONCEPT FOR VIENNA´S METROPOLITAN AREA", 61 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

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Abstract

In this paper, the impact of intermodal mobility on our current mobility behaviour is analysed. To be more specific, this research will evaluate the effects of an autonomous mobility on demand (AMoD) service with electric vehicles, and whether it would help to decrease overall congestion and emissions by internal combustion vehicles.

At first, the current mobility behaviour of the observed region is analysed together with the demand pattern to understand how a future mobility concept would need to be designed and what requirements it should serve. Adding on, the concept of ride sharing, intermodal mobility, as well as the technological aspects of autonomous vehicles and battery-electric-vehicles are explained to give a better understanding of the underlying principles. Furthermore, the literature review will give an outline of the already existing research regarding this topic. This will demonstrate that there is already some research in this area, however, due to significant differences between the papers, it appears that there is still room for new relevant research.

For the research of this paper, a macroscopic mobility simulation was used as methodology in order to assess the effect of an AMoD ride sharing service. This was done for the district of Mödling in the metropolitan region of Vienna. This region shares borders with Vienna and is one of the regions from where most commuters travel towards and from Vienna. Also, due to its features it would serve as role model for further regions around Vienna or even the city itself.

For the simulation, three different scenarios were created to better analyse the significance of ride sharing. All three simulations show that it would be possible to decrease the current private vehicle fleet to maximum 10% with ride sharing, but still serving full demand. Other positive effects include a lower total mileage of the vehicles, fewer vehicles on the roads at any given time what leads to less congestion, and most importantly, it would lead to lower emission by the vehicles. This would be especially true if the sharing fleet consisted of battery-electric-vehicles only. Therefore, electric autonomous ride sharing can be seen as a future mobility trend that helps to decrease vehicle fleet size, congestion, and emissions. This will help cities to become cleaner, safer, and less congested by vehicles. Not only during rush hours for commuters, but during the whole day as the service can be used at any time for any reason within the given area of operation. Thus, private transportation would get more efficient and sustainable in the future by the introduction of AMoD ride sharing.

Table of Contents

List of abbreviations

ADAS	Advanced Driver Assistance System
ADS	Automated Driving System
AMoD	Autonomous Mobility-on-Demand
AV	Autonomous Vehicles
B2C	Business to Customer
BEV	Battery-Electric Vehicles
CAV	Connected and Autonomous Vehicles
CFCs	Chlorofluorocarbons
CH_4	Methane
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
GHG	Greenhouse Gas
H_2O	Water Vapour
HC	Hydrocarbon
HCFCs	Hydrofluorocarbons
IoT	Internet of Things
LPG	Liquified Petroleum Gas
N_2O	Nitrous Oxide
NOx	Nitrogen Oxides
O_3	Ozone
P2P	Peer to Peer
SAEV	Shared Autonomous Electric Vehicle

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1. Introduction

Transportation plays an important role in the life of almost every person. Not only today, but already decades, even centuries ago it was a central role that determined people´s life. Transportation is not only about driving with a car from point A to point B or taking an airplane, but how to do it in the most efficient, economic and today also in the most sustainable way possible. The basic definition explains it as the "movement of humans, animals and goods from one location to another". Of course, over time the transportation patterns of humans have changed, from walking and running only, to horseback riding and coaches. Then bicycles evolved and not long after, the first trains and cars were introduced. Along with this, airplanes and motorised ships were developed. Today, there are even more means of transportation such as electric scooters, motorbikes, or even personal transporters, such as the Segway or self-balancing unicycles. Besides private transportation, public transport was introduced early in increasing cities in order to manage the traffic and to better cope with the high numbers of peoples. (Lay, 1992) (Bardi, et al., 2006)

Together with the development of the mode of transportation, the type of motorisation changed and developed. Even though electric and hydrogen engines for cars existed already early on, combustion and steam engines prevailed due to their longer range, security and abundance. However, today, due to the increasing awareness of climate change and the push of society, transportation is moving back, or forward, to green technologies. The most notable ones are electric engines and hydrogen fuel cells, as well as alternative fuels such as compressed natural gas (CNG) and liquefied petroleum gas (LPG). (Sturm, 2020)

Thus, it is only natural that officials together with scientists and specialists develop transportation concepts in order to deal with the increasing number of people and their need for transportation, especially within cities. As the modes of transport are constantly changing, such concepts need to be renewed and updated on a regular basis. Over recent years, a new concept has entered this field, which is "Intermodal Mobility". This concept can be described as the transportation combination of two or more different modes in a journey. An example would be to take the bicycle to the station, take the train or underground, and then walk the last meters to the destination. There are several clear advantages to this concept which are:

- Reduced travel time

- Reduced energy demand
- Reduced emissions
- Efficient time management

This concept gets especially effective and sustainable when the motorised modes of transportation are powered by electric instead of combustion or steam engines. (Southern, 2006) (Brauner, 2020)

1.1. Aim of this work

Currently, thousands of people commute from Lower Austria and Burgenland to Vienna every day for work and private reasons. Around 250.000 people commute every day to Vienna, while approximately 90.000 commute from Vienna to Lower Austria or Burgenland. These commutes, as well as the majority of leisure trips of people living outside of Vienna, are mainly done with a private vehicle. This is due to the partly insufficient public transportation network in Lower Austria, but as well to the more comfortable and maybe even cheaper option of driving by car. About half of all transportation in Lower Austria is done by car. This not only causes high congestions on the roads, but additionally, many greenhouse gases (GHG) are emitted especially during rush hours in the morning and afternoon/evening, and the time is wasted unproductively in the car. This poses problems to the society, the city, the environment and to a certain extend to the GDP of Austria.

On the other side, positive trends in statistics are showing that in cities less people use the car for commuting and general transportation. Together with this, less young people take the driving test and the number of car sales were decreasing slightly in 2019, which might be a continuing trend. (Arbeiterkammer, 2019) (Amt der NÖ Landesregierung, 2008)

Thus, this paper aims to provide a solution for these problems (long commuting congestions; high emissions; loss of productivity) by designing and developing an intermodal transportation concept for the year 2040 for Vienna and its surroundings with the special focus on a potential shared autonomous electric vehicle service.

1.2. Research question and hypothesis

Through the problem description above, the following research questions could be formulated:

- *How would such an intermodal transportation concept be designed for the metropolitan region of Vienna?*
- *What would the effect of an intermodal transportation concept with a shared autonomous electric vehicle service be on congestion and emissions?*

Along with these research questions, the following hypothesis was developed:

With the introduction of a shared autonomous electric vehicle service, commuters would switch from private vehicles to public transportation. This would result in a decrease of congestion on main commuting roads and overall emissions by transportation.

In order to facilitate this project, the concept will be designed for the year 2040 as only then the required technology for autonomous driving will be available and fully functionally for efficient and effective usage. Further information about this and other assumptions influencing this concept are described later in chapter 4.2.

2. State of the Art

This chapter will assess the current state of the art of certain topics which are important for this thesis. Furthermore, it will give an overview of current technologies and levels of areas concerning the research topic of this work.

2.1. Efficiency and emission levels

The transport sector is globally seen as one of the biggest contributors to climate change. The following statistics only include the operation of means of transportation and not their construction and decomposition.

In total, road transport contributes 73% to pollutant emissions of all mobility sectors. (European Parliament, 2019) Of all industries, the emissions of road transport sum up to 16.5% of global emissions. The emissions include besides carbon dioxide (CO_2) all other GHGs, which are water vapour (H_2O), methane (CH_4), nitrous oxide (N_2O), ozone (O_3), chlorofluorocarbons (CFCs), hydrofluorocarbons (HCFCs). However, the latter three are hardly ever emitted by any modes of transportation, but are included in the list of GHGs as possible trace gases from other sources such as refrigerants, spray cans, or printers. As denoted, these gases have a positive feedback on climate change and thus, their emissions are sought to be reduced. (WHO, 2011) Besides GHGs, combustion engines for transportation emit other pollutants such as carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), and soot/particles. Such pollutants only have precursory effects on climate change, however, they mainly have negative effects on human health as some are cancerogenic, or cause inflammation of the human respiratory system, or are toxic for the human metabolism. (Sturm, 2020)

In Austria, the transportation sector contributes more than 45% to the total GHG emissions. This is equivalent to approximately 21.7 million tonnes of CO_2 equivalent emissions. For one half of this, the passenger traffic sector is responsible, the other half falls towards the freight transport sector. 2018, for the fifth time in a row, the emissions levels of traffic had increased in Austria. (Umwelt Bundesamt, 2018) This is due to the constantly increasing number of vehicles registered in Austria. In February 2020, a new all-time high was reached with 5,043,230 cars in Austria. That is 0.57 cars per capita. A similar picture can be found in Vienna itself. About 42% of the city´s CO_2 equivalent emissions are emitted by traffic only (passenger and freight transport combined). In Vienna, 709,288 cars were registered in total in 2018, which makes the city´s per capita count of 0.38 cars lower than the country´s. (Statistik Austria, 2020) This places Vienna with 1.23 kg CO_2 with the lowest per capita traffic CO_2 emissions in Austria compared to all other province capitals. However, this is only because of the large population size. On the other side of the chart is Styria with 2.3 kg CO_2/per capita. Lower Austria is placed on sixth place with per capita CO_2 emissions with 2.13 kg. (VCÖ, 2020)

As this paper is trying to design a transportation concept with the focus on a shared autonomous electric vehicle (SAEV), the motorisation of vehicles needs to be addressed. Since the goal is to develop a sustainable transportation option, a battery-electric motorisation is chosen as it represents, as of today, the most reliable and efficient option. Combustion engines would not be a viable option as they are responsible for the current emission levels and their technology is not about to improve drastically within the next years. Thus, introducing a SAEV, there would not be much difference regarding emissions compared to today’s bus services. A hydrogen fuel cell would represent a viable option as this is as well a sustainable way of motorisation. Nevertheless, there is currently no technology for sustainable hydrogen production. Today, the hydrogen production heavily involves the usage of fossil fuels to split hydrogen and oxygen. And as there is currently no outlook of greener technologies in the future, this option is neglected. Additionally, the required infrastructure for a secure hydrogen network is currently underdeveloped in Austria. Similarly, it would be more difficult to build such a network compared of building up a network for battery-electric mobility. Battery-electric motorisation therefore represents the most viable option from today´s perspective. Today, the required technology for battery-electric vehicles (BEV) is already advanced and it will further improve in the next years. This will have positive impacts on the main disadvantages of BEVs, which are the loading-time and the capacity. Thus, in future BEVs can be charged faster and travel a longer distance. Furthermore, the efficiency of BEVs is considerably larger compared to fuel cell vehicles and combustion engine vehicles. BEVs only lose efficiency due to transmission of the electricity and the battery use. Their energy is with 69% the highest. Fuel cell vehicles have an efficiency level of 26% when using renewable energies as they lose valuable efficiency due to the transmission, the electrolysis, the compression/transport of hydrogen, and the electric motor. Combustion engines have with only 13% the lowest efficiency due to loses in the transmission, the power-to-liquid process, the transport, the mechanical processes, and the internal combustion. Of course, the highest efficiency for BEVs is reached when the electricity is produced by renewable energy sources such as hydro, solar, or wind power. (Sturm, 2020) (Agora Verkehrswende, 2019)

2.2. Transportation

To better understand why the concept of intermodal mobility together with a SAEV is discussed and evaluated in this thesis, the current forms and statistics of transportation in and around Vienna need to be analysed. Also, the statistics of commuting to and from Vienna need to be assessed to better understand the ways and patterns of commuters as well as their respective starting points and destinations.

2.2.1. General journey patterns

In Austria, a total of 98 million kilometres are travelled every single day. This includes all means of transport, except planes and ships. An immense share of more than 71% of these passenger kilometres are done with a car, either driving or as passenger. This amounts to 70 million kilometres car travel per day only in Austria. However, this does not include any commercial or freight transport. The rest of the passenger kilometres is covered by motorbikes, public transport, cycling, walking, and further means of transport. Of the passenger kilometres travelled by car every day, 39% are for work commutes to and from the working place. This sums up to about 27 million kilometres driven every day with the car to reach work. Additionally, 14%, or almost 10 million kilometres of all passenger kilometres travelled each day are due to business trips. Together, work related travels account for more than 37 million kilometres driven by car every day in Austria. Combined, all work commutes and business trips travelled by car in Austria account for 3 million tons of CO_2 per year emitted to the ambient air. Reasons for the other 47% of journeys made every day are school/education, pick-ups and drop-offs, shopping, leisure, visiting trips and errands. They account in total for almost 33 million kilometres per day. Furthermore, according to this statistics, more than 224.000 people commute from Lower Austria and Burgenland to Vienna and vice versa for business reasons every day. 73% of them use the car every day for the work commute, while the other 27% travel by public transport. (VCÖ, 2020)

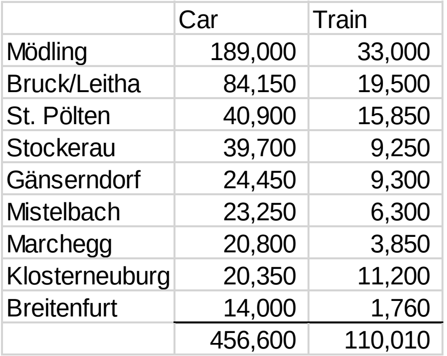
A study in Lower Austria in 2008 about the travelling habits of households partly confirms these statistics. The study was trying to analyse the travelling behaviour of households during their everyday lives and by this it should showcase how future transportation concepts can be adapted to the evaluated travel patterns. In Lower Austria, every household owns 1.5 cars, only 5% of all households do not have their own car. When considering that

Lower Austria has a population of 1.68 million people and about 730,500 households, only about 36525 households do not have their own vehicle. (Statistik Austria, 2019)

This is surprising as more than 90% of people living in Lower Austria stated that they live in walking distance from a bus station. Similarly, more than 70% stated that they would live in walking distance to a train station. However, even though people have these opportunities for travelling, the schedules and the network of buses and trains is limited and, to most people, is unsatisfying, which is why the car is preferred. This is underlined by the fact that for more than 60% of all daily journeys in Lower Austria a car is used. Reasons for journeys during the week in Lower Austria are work with 25%, leisure with 50%, education with 15%, and pick-ups and drop-offs with 10%. There is a big shift on the weekend, as leisure journeys amount to 75% and work journeys to only 7%. For the remaining 18%, other reasons are stated for the journeys. (Amt der NÖ Landesregierung, 2008)

2.2.2. Commutes to Vienna

In recent years, the commuting patterns of workers travelling to and from Vienna every day were analysed in order to better see potentials and bottlenecks of the current transportation system. The statistics were used to know which streams and directions to focus on and for example, to know which roads and which public transport network to improve. Therefore, it was analysed how many people commute to and from Vienna every day and where they start their travels and which routes they take.



	Car	Train
Mödling	189,000	33,000
Bruck/Leitha	84,150	19,500
St. Pölten	40,900	15,850
Stockerau	39,700	9,250
Gänserndorf	24,450	9,300
Mistelbach	23,250	6,300
Marchegg	20,800	3,850
Klosterneuburg	20,350	11,200
Breitenfurt	14,000	1,760
	456,600	110,010

Figure 1 – Total Commutes

When considering all routes towards Vienna, it can clearly be seen that most commuters arrive from the areas south of Vienna. This takes all reasons for commuting into account and not only business-related journeys. Mödling and Bruck/Leitha have the largest share of people commuting to Vienna every day between 5 am and midnight. Besides that, the northern and western regions Stockerau and St. Pölten, respectively, represent large origins for commuters in the same time frame. At the same time, both Mödling and Bruck/Leitha also have the largest number of people commuting by train. For all origins it can be stated that approximately a third of the total commutes are performed within the morning rush hour between 5 am and 9 am. The other two thirds are spread over the whole day, while it can be assumed that equally as many as in the morning also commute back during the afternoon/evening rush hour between 4 pm and 8 pm. During these times, the southern routes to Vienna are especially highly frequented.

	Car	Train
Breitenfurt	89%	11%
Marchegg	85%	15%
Mödling	84%	16%
Stockerau	81%	19%
Mistelbach	79%	21%
Bruck/Leitha	77%	23%
Gänserndorf	72%	28%
St. Pölten	72%	28%
Klosterneuburg	64%	36%

Figure 2 – Modal split of commutes

While most commuters in general come from the southern regions of Vienna, the studies also clearly show from which areas most people are commuting by car and by train. Whereas most people from Breitenfurt and surroundings commute by car, the largest share of commuters taking the train to Vienna come from Klosterneuburg and the regions surrounding it. Nevertheless, the majority of commuters of all regions still uses the car for commuting. The two tables clearly indicate in which regions most infrastructure investment is needed and where the public transportation network should be improved and extended. (Planungsgemeinschaft-Ost, 2016) (AK Wien, 2015)

2.2.3. Modal split

The study “Österreich unterwegs 2013/2014” conducted by the Austrian ministry for traffic, innovation, and technology assessed the mobility patterns and behaviours for all of Austria. With this data, the modal splits for the most important regions were analysed. Furthermore, it gave insight in the reasons and the durations of the majority of journeys undertaken. (2016) A modal split shows the usage of means of transport by share for certain regions. In this study, the regions are Austria in total, Vienna, major cities besides Vienna, central regions, and peripheral regions.

It can be clearly seen that the share of public transport is highest in Vienna and lowest in peripheral regions of Austria. The opposite goes for using the car, while Vienna has the lowest value, it is the highest in peripheral regions. This factor would either indicate that the public transportation network in peripheral region is too underdeveloped to further increase the share, that public transportation is too expensive, or simply that people prefer to commute by car. In Vienna the share of cars has constantly been decreasing over the past years, while public transport, walking, and cycling have been steadily increasing as mode of transport.

Modal split	Walking	Cycling	Car (driving)	Car (as passenger)	Public Transport
Austria	18%	7%	47%	12%	17%
Vienna	26%	7%	23%	6%	38%
Cities (except Vienna)	20%	13%	39%	11%	17%
Central regions	14%	8%	51%	13%	13%
Peripheral regions	15%	6%	56%	13%	8%

Figure 3 - Modal Split

The modal split share of public transportation can be further divided into the different modes of public transportation as can be seen in Figure 4. This way it can be analysed what modes are mostly used and as well indicated what modes are offered to commuters. While Vienna has a high share for tram and underground, the other regions have a higher share of city and regional busses, as well as trains. This is because in only a few cities and regions of Austria trams or an underground are available.

Share of public transport of all journeys	City/regional bus	Tram, Underground	Train
Austria	5%	8%	4%
Vienna	4%	30%	4%
Cities (except Vienna)	9%	7%	1%
Central regions	6%	2%	5%
Peripheral regions	5%	1%	3%

Figure 4 - Share of public transportation

Furthermore, the report shows the duration of each commuting journey for the respective regions. Through this it can be analysed how the duration and length of the journey influences the chosen mode of transport. Even though the duration and length are quite similar across all regions with an average duration of 25.4 minutes and an average length of 12.16 kilometres, the modes used are widely differing within the regions.

	Duration per journey in minutes	Length per journey in km
Austria	25	12.9
Vienna	28	9.9
Cities (except Vienna)	24	10.3
Central regions	25	12.7
Peripheral regions	25	15
Average	25.40	12.16

Figure 5 - Commute duration and length

Even though the duration of each commute is on average longer than in all other regions, public transportation is still the mode used most often. This is likely because it would even take longer when a car would be used instead. It would take longer to drive with a car through a city like Vienna than using public transport, a bicycle, or in some cases walking.

Furthermore, the average daily journey time could be calculated and assessed for specific days as can be seen in Figure 6.

	All working days	Saturdays	Sundays and public holidays	Average weekday
Average daily journey duration in minutes	70	66	58	67

Figure 6 - Average journey duration

It is shown that on normal working days (Monday to Friday) the journey duration is the longest, while on weekends it is shorter, even though more visits and leisure trips are done on the weekend. However, journeys on working days not only include the commutes to and from the working place, but also pick-ups and drop-offs, education, and shopping trips. This accumulates to about 70 minutes journey time per working day. The exact shares of journey reasons can be seen in Figure 7 below.

Reasons for all journeys	Workplace	Businesstravel	Education	Pick-up/drop-off	Shopping	Errands	Leisure	Visits
Austria	26%	5%	8%	7%	16%	13%	15%	8%
Vienna	24%	6%	10%	7%	18%	13%	15%	7%
Cities (except Vienna)	25%	5%	8%	7%	15%	14%	17%	9%
Central regions	28%	5%	9%	8%	16%	12%	15%	8%
Peripheral regions	27%	6%	8%	7%	15%	13%	15%	8%

Figure 7 - Reasons for all journeys

This helps to understand the journey pattern of households, which can be used in the design of a transportation concept in order to better include the most frequented destinations.

The last analysis presented from the “Österreich unterwegs 2013/2014” report is the modal split for each weekday. This furthers knowledge of at what days which mode of transport is used on what days, where the preferences lie and how this would influence a transportation concept. Figure 8 shows the modal split per weekday.

Modal split per weekday	All working days	Saturdays	Sundays and public holidays	Average weekday
Walking	2%	2%	2%	2%
Cycling	2%	2%	2%	2%
Car (driving)	57%	47%	41%	53%
Car (as passenger)	15%	32%	37%	21%
Public Transport	22%	15%	14%	20%

Figure 8 - Modal split per weekday

It can be seen that on any day the preferred mode of transport is the car used by a single person. Car sharing by two or more people, however, only has a larger share on the weekends when leisure trips and visits are done. This is opposite to public transportation, which is mainly used on working days and less on weekends. Walking and cycling on the other side, have a constant share of 2% on all weekdays.

2.2.4. Concept of car sharing

The principle of the sharing economy has evolved over the past decades. First, the commonly used term was access-based consumption before it switched to sharing. Even though, the principle of sharing has received proliferation and wide acceptance in the past decades, it has already been centuries ago that it was established in our society. Sharing resources is well established in industries and in society for machinery or other resources. But new technologies and electronic services have helped to develop new business models, which increased the use and participation in the sharing economy. (Bardhi & Eckhardt, 2012) (Puschmann & Alt, 2016)

The history of car sharing started in Switzerland in 1948 with the world´s first system called “Sefage”, which operated until 1998. Today, car sharing can be defined as “a service which includes access to shared vehicles 24 hours, seven days a week at unattended self-service locations, among other social environmental criteria”. Today, there are two different operation models of car sharing – business to customer (B2C) and peer to peer (P2P) sharing. (Shaheen & Cohen, 2012). P2P sharing is the classic sharing model where one individual provides a vehicle for sharing to other individuals or to a group. Also, a whole group can own and share a vehicle amongst each other or share it to others. For B2C sharing, there are different models such as round-trip and point-to-point. Round-trip concepts only offer a station-based sharing, which means that a vehicle would need to be picked up at a certain location and brought back again. This would be a typical model of a car rental service. Point-to-point concepts offer station-based and free-floating sharing. Station-based sharing means that the vehicle can be picked up at a fixed station and brought back at the same or a different station. These stations are usually distributed over various locations. Free-floating sharing means that a vehicle can be used between any two locations within a certain area, for example the borders of a city. (Le Vine, et al., 2014) However, both concepts of B2C sharing do not fully apply to the scope of this paper because both do not fully apply to an autonomous sharing concept as it will be designed for the transportation concept. Nevertheless, they will be relevant as the transportation concept will try to include other modes of transportations as well, including sharing providers in Vienna and Lower Austria.

In both regions countless sharing providers were established already. But besides car sharing, there are also many other sharing models for mobility purposes, such as bike sharing, e-scooter sharing, or similar. It is estimated that already more than 100,000 households in Austria are using one or more mobility sharing concepts. The potential would be even larger as there are many households in Austria owning a car but only using it several times a year or a month. Also, the carless households can be seen as potential customers. Furthermore, households with a second or even a third car would be another target group as they could use mobility sharing instead of the additional cars as only 10% of all cars are used at any given time. Thus, 90% of cars stand idle during most of the time. Through this, it was projected that a successful car sharing system can replace up to 3.6 private vehicles with each shared vehicle. Positive side effects of this would be a reduction of off-gasses and an increase in the usage of public transport, bicycles and walking. However, it is also estimated that mobility sharing concepts, especially free-floating and micro concepts such as e-scooter sharing, would reduce the usage of public transport or bicycles, as many people use sharing concepts instead of public transportation or walking. This would be especially true for the first/last-mile transportation which lies between the household and the next public transport station. Therefore, the sustainability of micro sharing concepts is still disputable as people are now able to use mobility concepts, and thus, emit off-gasses, instead of simply walking and public transportation. However, mobility sharing concepts are not only booming in large cities. In Lower Austria, more than 70 towns have already established their own sharing concepts which mainly rely on e-mobility and bike sharing. Nevertheless, to proficiently establish a sustainable mobility sharing concept in cites and especially in peripheral regions, additional offers are required, such as community busses and collective on-demand taxi (in German the “Anrufsammeltaxi”). (VCÖ, 2018)

2.3. Automation technology

Since this paper will try to design a transportation concept with the focus of an autonomous shared bus service, automation of vehicles is an important aspect. Therefore, this topic is necessary to be discussed and analysed.

The term “connected and autonomous vehicles” (CAV – only AV for “autonomous vehicles” will be used from here on) is comprised of the two different aspects “connected” and “autonomous”. Both have various levels of effectiveness and implementations. At first, one needs to differentiate between autonomous and automated driving, and connected and cooperative driving. Autonomous driving means, that a vehicle is able and allowed to make decisions independently and without command of any driver. In the case of autonomous driving, a single vehicle can make its own decisions independently. Automated driving on the other hand is the execution of processes and procedures without the intervention of a human driver. This means that autonomous driving would not necessarily lead to an improvement of traffic because if everybody decides on their own, without cooperative coordination with other traffic participants, then chaos and traffic collapses may be a consequence. Usually, autonomy is only appropriate in cases of low traffic density. However, automated driving can lead to significant traffic improvements, as cooperative behaviour can be enforced much easier for robots than humans as they follow their instructions more precisely. Connected driving is the exchange of driving information between automated as well as non-automated vehicles and other traffic participants and/or infrastructure in an automated way. Cooperative driving means that single vehicles and drivers act cooperatively within traffic. This implies that single traffic participants are coordinating their aims and actions in the light of improved overall effects. Combined, this leads to automated traffic. It not only deals with the automation of single traffic participants but with the overall automation of traffic as a holistic system. Thus, it encompasses the automation of traffic control, infrastructure and vehicles and the connection and cooperation between all traffic participants. (Kuhn, 2018)

The U.S. Department of Transportation´s National Highway Traffic Safety Administration (NHTSA) has created a definition of automation which divides vehicles into levels based on the degree of automation (who does what, when). Here, level 0 is the lowest and level 5 the highest degree of automation. This classification is widely accepted across the globe. (NHTSA, 2019)

The levels of automation and their definitions are (NHTSA, 2019):

Level 0: the human driver does all the driving.

Level 1: An advanced driver assistance system (ADAS) on the vehicle can sometimes assist the human driver with either steering or braking/accelerating, but not both simultaneously.

Level 2: An ADAS on the vehicle can itself actually control both steering and braking/accelerating simultaneously under some circumstances. The human driver must continue to pay full attention (“monitor the driving environment”) at all times and perform the rest of the driving task.

Level 3: An Automated Driving System (ADS) on the vehicle can itself perform all aspects of the driving task under some circumstances. In those circumstances, the human driver must be ready to take back control at any time when the ADS requests the human driver to do so. In all other circumstances, the human driver performs the driving task.

Level 4: An ADS on the vehicle can itself perform all driving tasks and monitor the driving environment – essentially, do all the driving – in certain circumstances. The human need not pay attention in those circumstances.

Level 5: An ADS on the vehicle can do all the driving in all circumstances. The human occupants are just passengers and need never be involved in driving.

Similarly to the levels of automation, there are different degrees of connectivity which define the connected systems which communicate with the vehicle. Again, there are five levels (CAAT, 2019):

- V2I: Vehicle to Infrastructure
- V2V: Vehicle to Vehicle
- V2C: Vehicle to Cloud
- V2P: Vehicle to Pedestrian
- V2X: Vehicle to Everything/Environment

The ultimate goal is the combination of level 5 automation with V2X connectivity, meaning that automated vehicles are communicating and exchanging information with their environment. Through this, the vehicle becomes a receiver and transmitter of data and is connected in real time. Today, there are already fully autonomous vehicles with level 5 automation being tested. However, they only operate on specific testing areas under specific circumstances. They are still far away from being able to operate on real life streets. As for now, many newly registered vehicles are already equipped with level 2 and maybe even level 3 automation. The technologies include for example a lane-keeping assistant or an adaptive cruise control. These vehicles can drive and park already somewhat on their own, but a driver is always required in the car ready to take over the wheal in case needed. (BMVIT, 2018)

2.3.1. Required technology

In order to achieve V2X connectivity with level 5 automation for real life driving situations, however, further technology advances are required and essential.

Infrastructure

Changes and updates to the infrastructure will be vital in order to fully facilitate autonomous driving. This will help V2X connectivity to reach full capacity. Without an infrastructure upgrade, fully AVs would not be able to operate efficiently and thus, the proposed transportation concept with the ASBS would not be feasible. Such upgrades would mainly include the ability of traffic lights, symbols, signs, and other traffic relevant infrastructure to have a wireless connection to the internet in order to transfer and share relevant data with other parties. By this, AVs can have the ability to better calculate the upcoming traffic and be aware of their environment. Additionally, for a battery electric powered autonomous mobility-on-demand (AMoD) service to seemingly work, the infrastructure and network for charging stations are necessary. If a charging station network has not the right size and capacity, BEVs would not be able to provide continuous and efficient service. (Al Barghuthi, et al., 2018)

IoT and Machine Learning

In order for the above to fully work, the Internet of Things (IoT) and machine learning need further development. This will further advance the collaborative environment. By this, technologies can “communicate” with each other and by this, automation will be further enhanced. Also, machine learning together with artificial intelligence will play a major role in software development. This will make the software processes of designing, coding, and testing faster and automated. It is projected with a 50% chance that a human-level machine intelligence will be developed by 2050. (Al Barghuthi, et al., 2018)

Faster communication technology

Currently, we have the 4G communication standard for wireless network connection. However, this technology will not be able to improve data communication due to the limitation in connecting many devices together at a certain speed. 4G was suitable to handle the mobility of smart devices at a short range but will fail to connect many devices and make them operable around us. Thus, machine learning and the IoT would not work as required with 4G. Therefore, the development and implementation of the 5G standard are pivotal. It is designed to connect virtually everyone and everything together including devices, objects, and machines. It is meant to have high data speed, ultra-low latency, more reliability, massive network capacity, and an increased availability. Also, better data security is guaranteed with this connection standard. This will have a large impact of the development of AV as it allows the connection between the vehicle and the infrastructure. (Al Barghuthi, et al., 2018) (Qualcomm, 2020)

Energy storage and transfer

Today, lithium batteries are widely used in small devices, such as mobile phones and other portable electronic devices. They are also used for battery-electric-vehicles for storage. However, the battery storage there is limited and thus, limits the mileage of the vehicle which makes it to a major disadvantage for battery-electric vehicles. Additionally, it requires a relatively long time recharge the energy storage of the vehicles. Even with today´s quick charging it still takes longer than fuelling a combustion-driven vehicle and in addition, this method leads to a faster abrasion of the battery. Therefore, for an efficient and successful battery-electric-vehicle both, the energy storage and the charging time need to be improved to increase the market share of such vehicles and to become more competitive to other technologies. Many researchers are already dedicated to these topics today to develop the technology for the future. (Agora Verkehrswende, 2019)

2.3.2. Acceptance of autonomous public transport

Scientists have been trying to assess people´s acceptance of autonomous public transport through various studies. Pakusch and Bossauer (2017) have found in their study that 91% of the study participants in their survey have heard of autonomous driving before. 37% of the respondents have even already tested at least one AV themselves, while the rest of the respondents have at least experienced autonomous transportation, such as an autonomous train, tram, or metro, before. A majority of more than 77% can generally imagine using autonomous public transport regularly in the future. There are no significant influences by characteristics like age, gender, or social status. But the study shows, that the previous experience with autonomous transportation has an influence on the willingness to use it in the future. People without experience with autonomous transportation are less likely to use it in the future. Also, the experience with autonomous driving itself influences the willingness of using autonomous transportation in the same way as previous experience. This confirms, that autonomous driving and autonomous transportation has reached a high degree of familiarity and acceptance amongst today´s population. Other studies have found a similar picture with more or less the same degree of acceptance. (Schoettle & Sivak, 2014) Nevertheless, this proves to be a good foundation for this paper as the acceptance of the users is an important factor for the transportation concept to successfully work.

Another claim that is often stated as a problem for autonomous driving is that people would be reluctant to use the technology, as they would give up their independence and freedom of driving themselves. Also, many people would prefer to have their own vehicle which not only serves as a status symbol but is also preferable for independent travelling. Certainly, for many people such claims are true, however, it can be observed that the younger generation does not identify itself with the statements made above as much as people from older generations. Still, the statements hold true for many young people as well, but statistics show that newly registered vehicles are mainly purchased by older people and that car ownership is generally lower amongst the younger generations. Furthermore, it can be observed that adolescents are less likely to take their driving test than previous generations. This, combined with the rise in awareness for sustainability and climate change, are good precursors for autonomous vehicles and especially for autonomous public transport. (Pakusch & Bossauer, 2017) (Adam, 2015)

2.3.3. Mobility behaviour

Of course, only predictions can be made about the influence of autonomous vehicles on people´s mobility behaviour as the rate of acceptance and the market share are unclear. However, there are some main predictions (Trommer, et al., 2016) (Fraedrich, et al., 2015):

1. Certain groups, disabled people, elderly people, and teenagers will highly benefit from autonomous driving for a variety of reasons. They will be granted

an independence in their mobility what will lead to easier access to essential services and a reduced likelihood of social isolation. Thus, more people among these groups will turn to autonomous mobility and might do more trips than they currently do, as they do not have to rely on other people for travelling assistance anymore. Another group that might benefit is people with high annual mileages, such as long-distance commuters. By autonomous driving, they would be enabled to use the commuting time in a more productive or pleasurable way since many of them today spend much of their time in dense traffic or find long routine road trips both exhausting and tedious. As a result, more people could be willing to commute longer distances, and existing long-distance commuters might switch to AVs.

2. Due to autonomous driving, different and new use cases and business models will develop over time as they are strongly linked to the different levels of automation. Usage cases with a lower level of autonomy, where the driver still has to pay attention to intervene if required, are not expected to have a high impact on mobility behaviour. However, higher levels, especially level 5 autonomy, have the chance to change it significantly. It will likely lead to new business models offering similar services as a taxi today, such as AMoD – which is partly the topic of this work – at costs much lower than today´s car-sharing services. This might therefore have the greatest impact on mobility behaviour.

3. Autonomous driving is likely to change the generalised costs of driving and thus, make it overall less expensive than today. Especially the value of travel time will change the users´ mobility behaviour, because monetary and time costs are the two most determining factors regarding mobility behaviour. AVs can increase the value of time spent during travels as it can be used for more useful purposes such as work or socialising. This is already a strong advantage for public transport today. Furthermore, as no driver is needed in AVs the operational costs would be drastically reduced as this is today a major cost factor.

4. It is predicted that the advanced driving technology will be more reliable than human drivers could ever be, because the system can make and objective decision within milliseconds and without any distractions. Thus, AVs should

reduce the amount of road accidents, especially since more than 90% of them are caused by human error. Adding on, even if accidents would happen, an AVs can mitigate the severity of a crash which could otherwise not be avoided.

5. The higher the level of automation the higher the energy efficiency and the lower the emissions. The technology can improve fuel consumption by optimising the operation of the vehicle. The system can accelerate and brake more smoothly than a human driver what improves efficiency. This would be even more improved with an electric engine, however, in any case it would reduce fuel costs and increase mileage. And as energy efficiency is improved with electric engines, the emission pollution is reduced. This factor is even more enhanced due to the possibility of building lighter vehicles as crashes are reduced by the automation technology.

2.3.4. Challenges

As with most innovations and developments, there are also challenges to it. The two most important challenges to be considered for autonomous driving are the legislation behind it as well as the liability, and the aspect of cyber and data security. Both will be briefly analysed, however, it is not the scope of this thesis to describe solutions to them.

Legislation and liability

With AVs, new situations and cases will come up that cannot be compared to today´s. Also, liability and insurance policies will need to be updated in order to fit AVs. Therefore, the legal basis for autonomous driving will need to be re-evaluated for this purpose as the current international legislation does not cover for this technology. The main international legal document currently applied for road traffic is the Vienna Convention on Road Traffic. It entered into force in 1977 with 36 signatories and 79 parties. (United Nations, 2019) Under this agreement, autonomous driving would not be possible/allowed as such because of Art. 8. Art. 8.1 states that “every moving vehicle or combination of vehicles shall have a driver” and Art. 8.5 states “every driver shall at all times be able to control his vehicle ...”. Both paragraphs contradict the technology of autonomous driving as they always require a driver present in the vehicle and that the driver should always be in full control. This, however, would not be the case with an AV as it does not require the driver to be in control at any time. In practice, this would illegalise partial and fully autonomous systems. (Economic Commission for Europe, 1968) Therefore, this treaty together with its additions and updates would need to be reviewed and adapted to the new circumstances regarding autonomous driving.

Similarly, current insurance policies would not cover incidences with AVs as they are not included. However, with AVs completely new situations would arise that demand new regulations. For example, who is liable if a fully autonomous vehicle is involved in an accident and causes casualties? Is the vehicle owner, the vehicle passenger, the vehicle constructer, the software developer to be held liable for this? And what would this look like if more than one AV is involved? This and similar issues are still to be discussed by policy makers and insurances, together with the general ethics an AV should follow. (Maurer, et al., 2016)

Cyber and data security

Due to the constant connection of AVs with its environment via internet, large amounts of data will be created in the process. This data needs to be processed, handled, and stored. In this chain, many problems may arise due to privacy issues. Data about the vehicle, the vehicle owner, the driving patterns and possibly the onboard conversations and entertainment will be created and collected. This is only natural to fully access all benefits of an AV and to have it at its maximum efficiency. However, this creates problems as well as this personal data is viable information. Therefore, stringent cyber and data security laws are needed in order to protect the vehicle owner and passengers. Additionally, strong cyber and data security is needed to protect the data from outside intrusion and inappropriate use and disclosure to third parties. This will be a large issue for vehicle manufacturers, communication companies and the infrastructure providers to ensure maximum cyber and data security. (Maurer, et al., 2016)

3. Literature review

This chapter analyses already existing literature and reports which deal with the implementation of an autonomous shared mobility into a city´s transportation concept. Also, the current urban development plan of Vienna will be assessed regarding autonomous and sustainable mobility. To conclude, it is tried to define the differences between the existing literature and this work.

3.1. STEP 2025 Vienna

STEP 2025 is the official urban development plan of the city Vienna until the year 2025. The plan was submitted and presented already in the year 2014. The STEP 2025 report is an instrument that provides timely answers to questions of the present, but also tries to answer future mobility questions. However, the report does not include concrete examples or indications of what projects will be done, or where, but mainly offers a vision of a future Vienna. It includes strategies for the sectors infrastructure and construction, usage of centres and community areas, business, science, and research, the metropolitan region, green & urban planning, social infrastructure, as well as mobility, which will be in the focus of this analysis. (Municipal Department 18 of Vienna, 2014)

The key point in the mobility section of the report is to shift the modal split of the Viennese population towards public transportation, cycling, and walking and away from the usage of private vehicles. There will be large investments in mainly eco-friendly means of transport together with intermodal mobility to increase their share, connectivity, and reach. The goal is to have a share of 80-20. Thus, by 2025, Vienna´s population should do 80% of all trips with public transport, bicycle or on foot, while the share of motorised individual traffic is to be reduced to 20%. The infrastructure system of eco-friendly transport modes will be preserved and improved to make it fit for upcoming years and adjust for the increasing usage of the increasing population. Moreover, car and bike sharing services shall be increased and upgraded by means of active co-operation between the City of Vienna, the public transport operator (Wiener Linien), and with potential operators. This is all to be done in close consultation and co-operation on traffic and regional planning issues with Lower Austria and Burgenland as well as with Vienna´s neighbouring municipalities. This will improve the overall mobility situation of Vienna´s metropolitan region and its population. (Municipal Department 18 of Vienna, 2014)

3.1.1. STEP 2025 e-mobility strategy

The city of Vienna is fully aware of the problems arising by individual motorised traffic. Besides the imminent space and traffic problems caused by vehicles, the emissions are a serious problem for the city and the citizens. Individual motorised traffic is the source of roughly 40% of the city´s CO_2 emissions. Therefore, jointly with the STEP 2025 plan, the city has released a report solely dedicated to e-mobility. However, the report mainly focuses on non-rail bound electric vehicles as rail-bound traffic is already to almost a 100% electric and eco-friendly within the city of Vienna. Therefore, it aims on the electrification of the public and private vehicle and bus fleet. As many vehicles as possible should be either electrified or a hybrid variation in order to decrease emissions. Additionally, to promote the electrification of vehicles, the network of charging stations and the respective infrastructure shall be improved and increased over the next years. Furthermore, the city wants to position itself as "the city of short distances" to shift the usage from motorised vehicles to eco-mobility. By this, the usage of vehicles (both motorised and electrified) shall decrease what would lead to a reduction of noise, traffic, and exhaust emissions. This would overall make Vienna a cleaner, more sustainable and better city according to the report. (Municipal Department 18 Vienna, 2016)

Nevertheless, the STEP 2025 strategy of the city of Vienna does not include plans regarding autonomous transportation and vehicles for public transport. But this is acceptable as in 2014 there was no clear outlook for automotive mobility yet. However, it can be assumed that Vienna will consider it in the next development strategy.

3.2. Relevant work dealing with AMoD concepts

A growing body of literature over the past few years have addressed the issues of disruptive technologies and their future potential. In this section of the paper, a number of international studies which have attempted to evaluate the impact of AMoD technology on public transportation are reviewed.

Bischoff and Maciejewski (2016) describe in their work an autonomous taxicab service for Berlin that is supposed to replace the entire private transit with motorised vehicles. Their simulation comprises two different models. The first includes the whole area of Berlin, while the second only includes the inner city, thus a much smaller area than the first. With their simulation, they calculated for the first model that a taxicab system would need to consist of 100,000 vehicles to serve the demand of the Berlin citizens accordingly, while keeping waiting times at a minimum. Obviously, for the second model, the fleet would be drastically smaller. The second scenario is assumed to be the more efficient one, however, it would not be the goal to only cover such a small area in a mobility concept as for this, additionally, very complicated measures need to be taken in order for it to work. The smaller area scenario could only work with mobility hubs at its boarders where people travel to by public transport or private vehicle, as otherwise, travelling to and away from the inner city would not be possible. However, this would probably not decrease the private vehicle fleet, as people would increasingly use it to travel to the mobility hubs. The simulation of the taxicab system in the research of Bischoff and Maciejewski (2016) only uses usual taxi vehicles for one to 3 persons sharing, and does not assume ride sharing or larger vehicles which might be more efficient. Also, the simulation does not include the metropolitan region of Berlin from where many commuters are originating. However, it would be important to include this into the simulation as most traffic problems inside the city are caused by the additional people commuting from outside the city. This would be the major difference to this work as it tries to identify the advantages of intermodal mobility in the metropolitan region of Vienna.

Similar to the work of Bischoff and Maciejewski is the research of Heilig et al. (2017). They developed a microscopic travel demand model to simulate the mode choice behaviour for the city of Stuttgart. For this, they assumed a world without private vehicles but with the presence of a large AMoD service instead. Assuming that up to four people can share a ride, they calculated that not all trips previously made by private vehicles can be substituted by an AMoD service, but the majority. Additionally, the share of walking, public transportation, and cycling is increasing extensively. Their results show that about 45% of vehicle movements and 20% of all vehicle kilometres travelled could be saved with the introduction of an AMoD service.

The work of Owczarzak and Zak (2015) develops several passengers´ transportation solutions based on autonomous vehicles and compares them with traditional forms of passenger transportation (tram, bus, taxi, and individual car). A multi-criteria decision aiding method to evaluate and rank the different variants of transportation from one to another location. In their assumption they only account for AVs for single person usage and not for ride sharing purposes. This would additionally improve efficiency. Nevertheless, the authors claim that the variations including AVs may belong to the best urban transportation solutions, even though they might be more expensive for the users than normal transportation solutions without AVs. Furthermore, the authors claim that the implementation of AVs in passenger transportation can be useful and increase efficiency and effectiveness of the operation of a public transportation system in a metropolitan region.

Burghout et al. (2015) provide in their work an analysis of potential benefits of a fleet of share autonomous taxis when replacing private car commuter trips in a metropolitan area. They developed a dynamic framework with a multi-criteria evaluation to model the simulation. Different scenarios were created to compare the effectiveness of the proposed service with the results indicating that an AMoD service has the potential to be efficient with using only 5% of today´s private cars and parking places used in Stockholm. In this work, ride sharing is assumed with cars for up to four people, to increase efficiency and to decrease costs for users and emissions. Additionally, the authors assumed an ideal case for which the whole demand of transportation is pre-ordered by users and thus, perfect knowledge of demand over time is given. However, this is unlikely to be the case in practice as most users are likely to use the service randomly without pre-ordering.

Dia and Javanshour (2017) present in their paper the results from an agent-based simulation that demonstrates the impacts of an AMoD service in the city of Melbourne, Australia. Three scenarios are defined in this work. The first, a base case scenario, represents the current situation of traditional privately-owned vehicles as primary mean of transportation. In the second scenario it is assumed that AVs are immediately available to passengers without any waiting time, while in the third scenario this constraint was relaxed by increasing the maximum waiting for passengers to 5 minutes. The two scenarios including an AMoD service show distinctive differences to the base scenario. The main indicators, number of vehicles required and required on-street parking space, are in the second and third scenario significantly lower than in the base case scenario without AMoD service. In the second scenario, the indicators reduced by 43% and 58% respectively, and in the third scenario by 88% and 83% respectively with AMoD ride sharing service, when compared to the base case scenario. However, this is achieved at the expensive of an increase in total vehicle kilometres travelled.

The International Transportation Forum examined the potential impacts resulting from the implementation of a shared fully AV fleet in a study (2015). An agent-based model was developed to simulate all entities´ behaviour connected to the system (travellers, cars, …) The simulation was based on the real urban setting of the city of Lisbon, Portugal. The study modelled two different scenarios, one with an autonomous vehicle shared by several passengers simultaneously (ride sharing), and one for AVs that pick-up and drop-off single passengers sequentially (car-sharing). For both scenarios, the number of cars, kilometres travelled, impacts on congestion and impacts on parking-space was measured. The results show, that both scenarios drastically decrease the number of cars individually used, the parking-space needed, and total congestion. The ride sharing scenario would reduce the number of cars by at least 90%, while the car-sharing scenario would remove about 50% of all vehicles. The researchers measured, that both is even true for peak-hours when demand is highest. The reduction rate would not be as high for this time of the day, but still significant. Similar to the previous studies, mainly inner-city travelling was considered for the simulations.

A comparable research was conducted by Spieser et al. (2014) explores the effect of a complete removal of the entire private vehicle fleet in Singapore, and its replacement by an AV fleet. The results suggest that such an AV fleet could remove more than two thirds of the vehicles currently operating in Singapore while still meeting the demand. Further on, the authors note several benefits of AV fleets, such as better environmental standards, better safety performance, decrease of congestions, lower overall costs, and lower required parking-space. Adding on, it is noted that the findings could be extended to more general situations, such as shared vehicles with human drivers. However, it is concluded that most environmental, safety, and economic benefits are reached with an AV fleet.

The research of Zachariah et al. (2013) is about the implementation of an autonomous taxi fleet in New Jersey, USA based on origin-destination trips derived from travel surveys to approximate the trips made by people in New Jersey every day. The system would work like a normal taxi system, whereas passengers walk to a station and take a taxi which brings them to the station nearest to their destination. Other passengers have the possibility to join the ride, provided their destination is not too far away from the first passenger´s destination. The results of this research show significant ride sharing potential in the region.

Similar to this is the study of Santi et al. (2014) that looks at the potential impact that taxi ride sharing could have on the taxi fleet operation in New York City, USA. However, in this case, the taxi fleet is not autonomous. The results suggest that the total number of kilometres driven by a taxi in New York City could be reduced by 40% with a shared taxi system. This would lead to large decreases in service costs, traffic congestion and emissions, and additionally reduce the fares paid by travellers. In conclusion, the authors note that such a system would be possible and highly efficient for New York City and easily to implement.

4. Research

This chapter will describe the modelling of an AV system, with focus on an AMoD service with ridesharing. This modelling framework will then be applied to the Vienna metropolitan region with the results and scenarios being analysed and put in context with this study. In conclusion, the limitations of this study are discussed, and future research directions are pointed out.

4.1. Methodology

In order to fully understand the impact an AMoD service would have on a region, it was decided to do a macroscopic traffic simulation in the course of this project.

A macroscopic traffic flow model is a mathematical model that defines the connection among traffic flow characteristics such as speed, flow, density, or traffic stream. Such models are usually formed by integrating microscopic traffic flow models and converting the single-entity level characteristics to comparable system level characteristics. Therefore, it describes the intersections at a rather low level of detail compared to microscopic modelling. However, a macroscopic model can give a realistic overview of traffic simulation for a broader environment. (Nasuha & Rohani, 2018) (Härri, et al., 2007)

4.1.1. Modelling

For modelling the simulation, the free software “PTV Visum” was chosen to create a realistic scenario. This is a macroscopic travel-demand modelling software. The software can include all relevant data of all necessary traffic stakeholders, as well as the function to include and simulate autonomous traffic. Furthermore, it is possible to assess different strategies and multiple “what-if” scenarios for different modes of transport such as private, public, shared and even autonomous. (PTV Group, 2020)

4.1.2. Ride sharing schemes

An important part of the AMoD trip scheduling is the ride sharing. As mentioned before, ride sharing is promoted as way to find the optimal equilibrium between passenger number with fuel usage, congestion and transport cost. Thus, it is an efficient and effortless real-time alternative compared to traditional individual traffic, as well as an addition to public transportation. The problem resulting from this optimisation is known as the Dial-A-Ride

Problem involving choice of vehicle, and choice of route with constraints on time windows, detours, number of stops and capacity. (Cordeau & Laporte, 2007)

Of course, in a real time implementation the ride sharing optimisation would need to be solved based on real time demand. Thus, all service requests are handed in by passengers right before their departure, there are no advance bookings. This would not only best represent today´s mobility service market, but also correlates to other forms of demand-responsive transport, such as free-floating car sharing, which usually does not allow longer pre-bookings. After dropping-off all passengers and having no more requests, the AV would either return to a charging station for recharging or park at the drop-off position until the next service. However, in the morning, the initial fleet distribution could be in accordance with the population density of the respective area or city. The service would be available during the whole day, seven days a week. (Bischoff & Maciejewski, 2016)

4.1.3. Theoretical concept of AMoD service

Similar to today´s mobility or ride sharing applications for smartphones, there would be such an application that combines public transportation and ride sharing features. Through this application it would be possible to configure the best route from the trip starting point to the desired location. After calculation, the software would then offer several different optimal routes with which are defined by several different modes of transport or single transport options. Thus, routes can be either:

- single modal (only one mode of transport), or
- intermodal (combination of two or more different modes of transport).

The routes can be listed by trip duration (time), price, sustainability, or length (distance). The user can choose the desired route accordingly. The software will then show the possibility to order or reserve the desired mode of transport if needed, such as an AMoD service, or a shared car. And finally, the application is able to process the payment. An example for such a software would be the application “Trafi” which originated from Vilnius, Lithuania. There, all urban mobility consumption and offers are fed into a single multimodal city mobility app. By this, the user is enabled to book and pay for any services used for transportation in the city. The transportation modes offered are by nature multimodal and based on public transport. (Trafi, 2020) However, it is not in the scope of this project to define an application for intermodal transportation. Thus, the concept is only briefly presented.

The AMoD service itself can be somewhat compared to a traditional public transport bus system. The main differences are however, that the vehicle has no fixed but dynamic stops, and that the driver is replaced by the automation software. It would also be possible with a human driver, however, the human factor is usually the most expensive one and therefore, for the successful and efficient operation of such a system, it is crucial that there is no driver. Through this, the service can run without interruption during the whole day and night. The only stop needed, would be to recharge the battery as it is a BEV. To have the highest efficiency, regions and boundaries need to be defined for each AMoD service. Hence, a vehicle cannot drive from a starting point to a destination which is 200 km away, but it has a certain radius of mobility which overlaps with other regions in order to have optimal efficiency and to allow transfers between vehicles. Figure 9 shows a depiction of such an operational network. (Brauner, 2020)

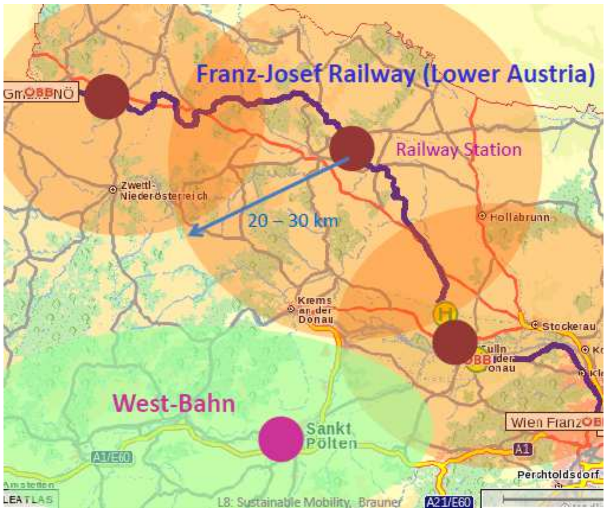


Figure 9 - Regional sections

As this is an AMoD ride sharing service, the vehicle is able to constantly pick-up and drop-off passengers along the way if their starting points and destinations are on the route. The software would then constantly and efficiently recalculate an optimal route. However, this will only work to a certain extend in order to keep maximum travelling time low. Therefore, multiple vehicles would operate within one region. The number of vehicles needed with the right capacity will be presented later on in this paper.

In order to make the ride sharing procedure plausible and realistic, three schemes are implied sequentially to better deal with the number of passengers. Their operation is explained below. (Burghout, et al., 2015)

Ride sharing scheme 1: Co-passengers with the same origin and destination

1. Pick-up the first passenger with origin at location A and destination B and allocate passenger to AV.
2. If available, find list of further passengers with origin at location A to destination B, fulfilling the conditions for start and travel time.
3. If list of further passengers is empty, the second ride sharing scheme applies. If not, continue with this scheme.
4. Among all passengers, select the one with closest location and earliest booking.
5. Allocate the additional passengers to the AV in a sequential order.
6. If the AV is not full, this procedure can be repeated from step 2 onwards to find further potential passengers.

Thus, the possible AV trip itineraries would look like the following: A-B, AA-BB, AAA-BBB, AAAA-BBBB, and so on.

Ride sharing scheme 2: Co-passengers with same origin but different destinations

1. Pick list of passengers from origin A to any destination different from B, called destination C, fulfilling the conditions for start and travel time.
2. If list of further passengers is empty, the third ride sharing scheme applies. If not, continue with this scheme.
3. The itineraries AA-BC and AA-CB are evaluated for all passengers. The one with shortest travel time for all passengers is selected.
4. Among all passengers, select the one with closest location and earliest booking.
5. If the AV is not full, the procedure will be repeated with BC/CB as unbreakable itinerary. This would mean that lists of passengers with same origin, but new different destinations will be evaluated as long as they are within the parameters and the maximum travel time is not exceeded.

Thus, the possible AV trip itineraries would look like the following: AA-BC, CB, AAA-BCE, EBC, CBE, ECB, CBB, BBC, and so on.

Ride sharing scheme 3: Co-passengers with different origin but same destination

1. Pick passenger list with any origin different to A, called D, to destination B fulfilling the conditions for start and travel time. AD-BB is the only possible itinerary as A must be before D.

2. If list of further passengers is empty, the fourth ride sharing scheme applies. If not, continue with this scheme.
3. If the itinerary AD-BB has multiple passengers, the one with the earliest starting time and shortest travel time is selected.
4. The other passengers are allocated to the AV.
5. If the AV is not full, the procedure will be repeated with evaluating the itineraries ADE-BBB and so on.

Thus, the possible AV trip itineraries would look like the following: AD-BB, ADE-BBB, ADEF-BBBB, and so on.

Ride sharing scheme 4: Co-passengers with different origin and different destination

1. Pick passenger list with any origin different to A, called D, to any destination different from B, called destination C, fulfilling the conditions for start and travel time. AD-BC is the only possible itinerary as A must be before D and B before C.
2. If list of further passengers is empty, then stop. If not, continue with this scheme.
3. If the itinerary AD-BC has multiple passengers, the one with the earliest starting time and shortest travel time is selected.
4. The other passengers are sequentially allocated to the AV.
5. If the AV is not full, the procedure will be repeated with evaluating the itineraries for further origins and destinations which are in the within the boundaries and which would not exceed the maximum travel time.

Thus, the possible AV trip itineraries would look like the following: AD-BC, ADE-BCF, and so on.

Whereas the first scheme is rather simple, the complexity with scheduling the pick-ups and drop-offs sequentially increases drastically with schemes 2, 3, and 4.

Additionally, the following rules are needed to be applied to the AMoD ride sharing scheme to better facilitate the service:

- The drop-off of passengers is done in the same order as they were picked-up.
- If several different itineraries are possible, for example the AV has different alternatives implying different routes/itineraries, then the itinerary with the shortest drive time is chosen. Therefore, the above rule can be neglected.
- If multiple co-passengers are possible for a given itinerary, then the one with the closest start time is chosen.

4.2. Assumptions and calculations

This part of the chapter deals with the description of the simulation of ride sharing to be applied to the Vienna metropolitan area. The general assumptions made regarding the AMoD service are as following:

- The maximum number of passengers per AV varies between 4, 6, and 8. The optimal number will be identified by the simulation.
- The maximum waiting time each passenger is accepting to be picked up is assumed to be either 5, 10, or 15 minutes.
- The relative increase in travel time a passenger is accepting, which is allowed for additional passengers to be picked-up, dropped-off, and further detours.
- The time for each passenger to board the AV after it has arrived at the pick-up station is considered to be 2 minutes.
- The time for each passenger to get off the AV after it has arrived at the destination is considered to be 1 minute.
- The pick-up and drop-off times include any delays that might occur with the picking up and dropping off procedure, as well as driving manoeuvres such as slowing down, merging into traffic, passing obstacles, getting into or out possible bays, etc.).
- The maximum speed of the AV in all areas is assumed to be 30 km/h.

4.2.1. Simulated area

In order to better facilitate the simulation, it is only done for a certain area of the Vienna metropolitan region. This can consequently be used as an example and be scaled up for the whole metropolitan region of Vienna. However, this will not be done in the course of this paper. The focus will lie on the southern metropolitan region of Vienna, namely the district of Mödling. This is one of the higher populated regions around Vienna. Also, most people that commute towards Vienna come from the southern direction towards the city. Additionally, a significant number of people commute to Mödling from Vienna. This is only natural, as it is the only district in Austria through which four motorways flow, namely the highways A2, A3, and A21 and the freeway S1 as well as the main road B17. This is complemented by the highly frequented train route “Südbahn”. (Land Niederösterreich, 2020)

4.2.2. Public transportation

The district of Mödling offers multiple modes of public transport to the citizens. It features several train stations with direct connection to Vienna, the most important ones are Mödling, Traiskirchen, and Perchtoldsdorf. Additionally, the “Badner Bahn”, which is a tram-train service for the Vienna metropolitan region, runs directly from the centre of Vienna through the district of Mödling towards Baden. Furthermore, there are several bus lines within the district of Mödling, some collective on-demand taxi services, and a few private carsharing platforms which are limited to the respective towns where they are located. However, the latter two are not being included in this simulation as it is assumed that they could be replaced by the AMoD service. The same assumption holds true for the bus lines, as they are likely to be either replaced or newly routed by the appearance of an AMoD service. However, this will not be discussed in the course of this work. (Land Niederösterreich, 2020) (Stadtgemeinde Mödling, 2020)

4.2.3. Automation and battery technology

Even though the simulation is done based on current statistics regarding traffic, population, and behaviour, the assumptions made for the automation and battery technology are made based on technological standards from the years 2040-2050. This is because the current state of technology of AV and BEV is available and working, however, not on a level which is needed for the efficient operation of an AMoD service. Therefore, the following are assumptions are made regarding the technology standards:

- The charging of the BEV is possible without human assistance
- The charging of the battery to 100% takes maximum 1 hour
- All necessary technology advancements for V2X infrastructure are available
- The necessary infrastructure upgrades for V2X are available

4.3. Case study: Mödling

This section will present the information which was used as input data for the simulation to evaluate the effectiveness of an AMoD service in combination with intermodal mobility in the metropolitan region of Vienna. As explained before, the district of Mödling is used as an example case to calculate the effectiveness. The district Mödling lies at the borders to the south, south-west of Vienna. Figure 10 shows the exact geographical location (OpenStreetMap Österreich, 2020).

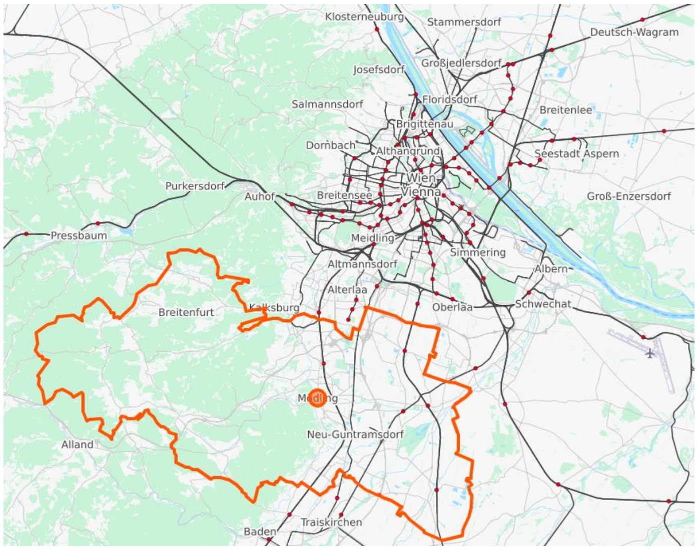


Figure 10 - Location of Mödling

The district has a size of almost 277 km^2 with a population of 118,998 people, that equals to 430 people/km^2. The fleet size in Mödling amounts up to 79,372 cars, or 0.67 cars per person, which is higher than the Austrian average of 0.57 cars per person. In 2017, 44,630 people commuted from Mödling to their workplace, while 58,163 commuted towards Mödling for their workplace. Overall, 205,586 commutes are done every day to or from Mödling. This figure does not include the number of commuters passing through Mödling, or any other trips made during the day. However, these trips are included in the total mileage. This is at the current level of demand of all private vehicles in Mödling, without ride sharing, is 940,271 km per day, with an average trip length of 12 km. The total mileage a car travels per day is about 39 km with an average duration of 25 minutes per trip. Thus, a vehicle drives for approximately 82.5 minutes a day, which is equivalent to 1.4 hours. This means that the vehicle stands idle for the remainder of the day, what sums up to 1,385 minutes or 22.6 hours. Hence, a vehicle is only used for about 5% of the day while it stands 95% of the day idle. Adding up, the total duration of all vehicle trips of one day would be 282,681 hours, while the total parking time of one day of all vehicles sums up to 1,795,784 hours. The total length of the street network in the district Mödling sums up to about 2,303 km, which is equivalent to around 7% of the total street network length in Lower Austria. For a better overview, all these indicators can be viewed in Figure 11 below. (Land Niederösterreich, 2020) (Planungsgemeinschaft-Ost, 2016) (Herry Verkehrsplanung/Consulting, 2011)

Indicator	**Unit**	
Population in 2019	#	118,998
Fleet size	#	79,372
Commutes per day	#	205,586
Street network length	km	2,303
Total mileage per day	km	940,271
Total mileage per car per day	km	39.09
Average mileage per car per trip	km	11.85
Average travel time per trip	min	25.00
Total travel time per car per day	h	1.38
Total parking time per car per day	h	22.63

Figure 11 - Base indicators

4.4. Simulation scenarios

Due to the general assumptions explained before, there are various scenarios for the performance of the simulation. The scenarios are influenced by the maximum waiting time each passenger accepts for the pick-up, and the maximum increase of travelling time accepted by the passengers. The different scenarios will then be compared to the base case which does not include an AMoD ride sharing service. However, at first the optimal number of maximum passengers will be calculated in order to simplify the simulation for the different scenarios. Figure 12 shows the variations of the scenarios.

Scenario	**Base Case**	**1**	**2**	**3**
Maximum waiting time in min	0	5	10	15
Increase in travel time	0	10%	30%	50%

Figure 12 - Simulation scenarios

4.5. Results

At first the optimal capacity was evaluated in order to have a single input for the different scenarios. The optimal maximum number of passengers per AV was calculated to be 6. This would represent the current demand, corresponding with the current population of the district

Mödling and the vehicle fleet. However, to better correlate with future increase in population and a possible respective increase in vehicle size, the maximum number of passengers could be assumed to be 8. On the one side, this would lead to higher purchasing costs as the vehicle would be larger. However, on the other side, if population and demand are growing, this could save the municipality from needing to purchase larger vehicles after a certain time. Nevertheless, this would need to be re-evaluated in an actual case and when needed. Therefore, the simulation in this paper will work with a maximum passenger number and AV size of 6 people to better represent the current situation. Adding on, it needs to be mentioned, that capacities larger than 8 would not be feasible. A larger capacity would mean more passengers and thus, less vehicles needed. However, to fill this capacity many detours would need to be allowed for and the increase of travel time for each passenger would be severe. This would rather be a scenario for a normal bus line with a fixed route unlike an AMoD service with a dynamic route.

Scenario	**Base Case**	**1**	**2**	**3**
Vehicle fleet in %	100%	10%	8%	7%
Vehicle fleet in #	79,372	7,937	6,350	5,556
Mileage in %	100%	92%	89%	76%
Mileage in km	940,271	865,049	836,841	714,606
Parking time	100%	6%	4%	3%
Time on Road	100%	95%	93%	85%
Increase in travel time	-	7%	17%	25%
Emitted flue-gases	100%	0%	0%	0%

Figure 13 - Simulation results

Figure 13 shows the compiled results of the simulation with the three different scenarios. The base case scenario shows the current data of the district Mödling without AVs or ride sharing. This can be compared to the three simulation scenarios. They are designed to minimise the vehicle fleet and the total vehicle mileage under the different criteria.

Scenario 1, which has the lowest waiting time and travel time increase, would require the largest vehicle fleet compared to the other two scenarios. It allows for a maximum waiting time of 5 minutes and a maximum increase in travel time of 10%. This, however, is only to serve the stringent time windows. But when compared to the base case, only a vehicle fleet of 10% of the current level would be needed to serve the demand of the whole area. Accordingly, the total mileage decreases as well compared to the base scenario. Even though, the decrease of the total mileage is not as significant as of the vehicle fleet, this is because the AV fleet would still need to cover almost the same distance as in the base case. This is especially true when compared to scenario 2 and 3, as the time window criteria is more stringent. Hence, even though there are more vehicles, they would have to do straight tours and might not reach full passenger capacity, instead of doing slight detours which would need allow for more time. This goes hand in hand with the decrease in the time on the road. The total parking time of the AV fleet would only be 6%, which is mainly used for charging or during the night or off-peak hours. Nevertheless, while the allowed increase in travel time for this scenario would be 10%, the average increase is only 7%.

Scenario 2, which has the most likely acceptable criteria of a maximum increase in travel time of 30% and a maximum acceptable waiting time of 10 minutes, shows that only 8% of the current vehicle fleet would be needed to serve demand, with a reduction of the total mileage to 89% of the current level. Similarly to the first scenario, the parking time decreases further as well as the time on road. Also, the average increase in travel time does not reach the allowed maximum.

Scenario 3, with a maximum increase in travel time of 50% and a maximum acceptable waiting time of 15 minutes, would require the smallest vehicle fleet compared to the other scenarios and the base case. Correspondingly, the total mileage would only be 76% of the base case and thus, the lowest of all scenarios. Same goes for the total parking time with 3%, and total time on road with 85%. The average maximum waiting would only increase by 25%, instead of the allowed 50%. However, this would mean that passengers would have to wait rather long for their transportation. Thus, longer detours for further pick-ups are allowed for the AV to reach its maximum capacity.

For all three scenarios it can be stated that there would not be any flue-gases emitted by the AV trips. This is because the vehicles are all powered by a battery-electric engine which does not emit any flue-gases. Therefore, total flue-gas emissions of vehicles would decrease to zero. Thus, the larger the modal share of a BEV ride sharing service the lower are the direct emissions. Additionally, the energy needed for the BEV would need to be produced by renewable sources, such as photovoltaic power, hydro power, or wind power in order to have net zero emissions overall. If this would be the case, then the only emissions released would be due to the production of the AV itself. However, the assessment of these emissions is not within the scope of this paper. Nevertheless, it can be said that the emissions of a BEV AMoD service would be significantly lower than of a private vehicle fleet which covers the same demand, regardless whether they are powered by combustion or batter-electric engines.

Adding on, even though the total mileage of all scenarios decreases with ride sharing and AV trips when compared to the base case, they add mileage due to empty vehicle trips which are necessary for charging or first pick-ups. Therefore, it is incremental to understand whether these empty vehicle trips would contribute to congestion or not. The results of this assessment can be observed in Figure 14 below.

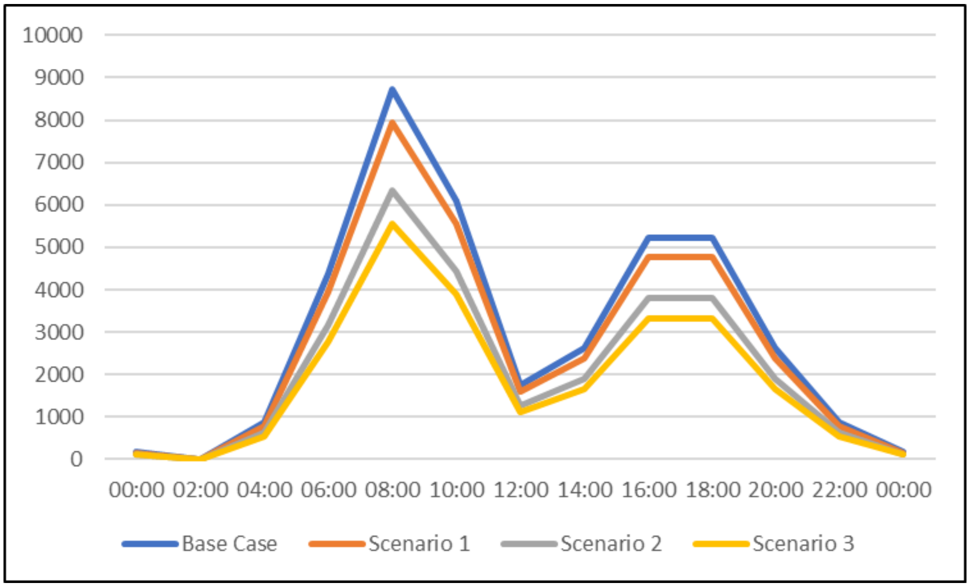


Figure 14 - Number of vehicles on the road

The figure shows the number of vehicles effectively on the road for the base case with private vehicles, and scenario 1, 2, and 3 during the day. Also, the figure shows the average rush hour times which could be observed. 60% of all trips are made during the rush hour times in the morning and afternoon. As it can be seen, all three simulation scenarios have at any time less vehicles on the road than the base case with all private vehicles. While scenario 1 is only slightly lower than the base case, scenario 2 and 3 result in significantly fewer vehicles on the road at any given time. Therefore, there will be less congestion in all scenarios and significantly less in scenario 2 and 3. Additionally, it can be assumed that most empty vehicle trips are made in a different direction than normal traffic as they drive towards the passenger and not the destination. Thus, this will decrease congestion even further.

4.6. Modelling of intermodal mobility

Besides the necessary infrastructure for autonomous driving, which is assumed to be available, the most important criteria are charging stations for the AVs. The number and the locations of charging stations needed depends of course on the capacity of the battery, its required range, and the size of the vehicle. Today, normal electric busses with a length of 18 m can have a range of more than 200 km per charge. (Sustainable Bus, 2020) On the other side, battery-electric passenger vehicles already have a range of up to 500 km per charge. However, in both cases this is only true for an average day with perfect test-like conditions, where systems like heating or cooling are not used to save battery. Therefore, it was assumed in this simulation that a single vehicle has range of 200 km per charge under any conditions. This represents realistic circumstances under which the AMoD service would usually operate. (McCraw, 2019)

From this, it was then calculated how many charging stations would be required for each scenario with the formula of Herron and Coleman (2017). The formula was adapted to the given information and the output of the simulation. The results can be seen below in Figure 15.

Scenario 1	Scenario 2	Scenario 3
167	161	138

Figure 15 - Number of charging stations

These charging stations should then be distributed over the whole service area. Main locations should be demand hotspots, large areas where space can be provided for charging and parking, most frequented public transportation stations, and remote locations. This is to ensure that any AV can reach a charging station if needed. The vehicles will be charged either by overhead lines through a pantograph located on the roof of the bus, or wireless charging, such as induction charging. Both would provide a maximum of automation and a minimum of human interaction needed for the charging process. (McCraw, 2019)

In addition to the AMoD transportation service, the region can promote further sharing models to promote intermodal mobility. Such sharing models would include bike sharing and e-scooter sharing. Both have the potential to be an additional solution for the last-mile-problem. The last-mile-problem can be described as the problem to transport a person or a good from hubs or stations to the final destination. It is commonly regarded as one of the more expensive, least efficient, and most polluting sections of the entire logistics chain.

(Gevaers, et al., 2011) Both bike and e-scooter sharing, can provide a cost-effective and more sustainable option to transportation than most other modes, including an AMoD service. Therefore, they would further decrease the public vehicle fleet as well as the AV fleet. However, their impact to a reduction of the AV fleet would not be too significant since their efficiency has limitations due to their reach and operation area. This is because they are ineffective in widespread areas with low population. Also, they are highly impacted by weather conditions, as bikes and scooters are less used during rainy weather or in winter. Nevertheless, for higher populated towns and cities, such smart sharing concepts provide a viable addition to public transport and AMoD services. (Zvolska, et al., 2019) This way, passengers have an easy, fast, and sustainable mode of transport to reach their destination. Whether it is for work commute, business or private trips, passengers can easily reach their destination within the service region, or another mean of transport, such as the train or coach for further transportation. Hence, people have the chance to commute from doorstep to doorstep between Mödling and Vienna for example without a private vehicle and without worrying about the last mile.

4.7. Discussion

For the analysis proposed in this thesis, a macroscopic traffic flow simulation model was designed to find the desired results. The regional district of Mödling, which is in the southern metropolitan region of Vienna, was used as an example for the simulation. Based on this, a possible ride sharing scheme was set up to better simulate its operation and to interpret the results. Furthermore, three different scenarios were defined to allow for possible differences in the operational model. The distinctive differences in the three scenarios are the maximum waiting time for each passenger for the AV to arrive, and the maximum acceptable increase in travel time for each passenger. In accordance with this, the optimal maximum passenger number per vehicle was determined. With a maximum of 8 passengers per vehicle, they would be fit for their purpose and for future demand increase, but cannot reach capacity and thus, would have too many empty or half-empty rides. Therefore, it was chosen to have a maximum capacity of 6 passengers per vehicle to better simulate current statistics and demand. With this, the simulation was designed and modelled to achieve results.

The results for the three different scenarios could then be compared to the base case scenario which assumes the current situation of transportation in the simulated area, while the three scenarios assume a 100% replacement of the private vehicle fleet by AV ride sharing. All three scenarios would indicate that the current transportation demand of more than 940,000 km per day in the simulated area can be met by an AV ride sharing fleet with maximum 10% of the current fleet size. With this, all private and business commutes, as well as leisure and shopping trips can be met during the whole day at every day during the week. While the fleet size would decrease significantly with the application of an AMoD ride sharing service, the total mileage of the vehicles, the total parking time and the total time on the road decrease as well. This is due to the more efficient transportation management. More importantly, since the AV vehicles are all equipped with battery-electric engines, they do not emit any direct GHGs which makes them carbon neutral, and thus more sustainable than a fleet of private vehicles with internal combustion engines. The only emissions of the AV fleet would be indirect, during the production of the vehicles and of the required infrastructure. Nevertheless, because of the significantly smaller fleet, the production emissions of the AV fleet would be substantially lower than the production emissions of a private vehicle fleet needed to cover the same demand. Therefore, all three scenarios propose a more sustainable option for public transport than a private vehicle fleet. Furthermore, by analysing current travel data and behaviour, that an AMoD ride sharing service would contribute to a significantly lower traffic volume on the roads. Even during rush hour times (6-10 and 3-7 pm) the traffic volume is decreased by the AMoD ride sharing service. This is best seen in the third scenario, in which almost only half of the current traffic volume can be observed during rush hours. Especially the empty trips of the AVs reduce congestion as they drive in the opposite direction to the normal traffic flow (out of the city centre instead of into), in order to pick up new passengers.

Adding on, such an AMoD ride sharing service should be modelled in order to eliminate private vehicle demand and the last mile problem. Thus, the AVs should be used to either transport them directly to their desired destination or to a public transportation station. Therefore, an AMoD ride sharing service would need to be clustered in multiple areas to avoid long travel distances. Otherwise the distribution of the vehicles would not accord with regional demand and their original operational areas. Nevertheless, each regional cluster would need to be equipped with the required infrastructure to support BEV ride sharing service, most importantly the battery charging stations. By assessing the average daily mileage of each vehicle and assuming a maximum battery range of 200 km, the required number of charging stations could be calculated. For this simulation and the simulated area, a maximum of 167 charging stations would need to be installed to cover the charging demand for all AVs.

When comparing the results found in this paper to those of others, it can be seen that an AMoD ride sharing service always has the potential to fully replace a private vehicle fleet. Since most studies use different areas for their simulations, it is natural that the results differ. However, it can be observed that an AV fleet with roughly 10% of the size of the current private vehicle fleet would be sufficient to cover demand. The most notable difference to other works is that they simulate traffic within city limits or only in city centres, while this study focuses on the metropolitan region of a large city. Furthermore, other studies mostly use agent-based modelling or microsimulations. In this paper, a macrosimulation was used in order to understand the full impacts of the AMoD ride sharing service. Therefore, this study can positively contribute to research.

Nevertheless, there are limitations to the results as well. It cannot be said whether people would accept an autonomous ride sharing service, even though previous research shows that acceptance can be assumed. Adding on, the results of this study assume, that people would completely switch from their private vehicle towards the ride sharing providers. However, some people might refuse to give up driving their private vehicles on a regular basis or owning and using one in addition to utilizing ride sharing providers. This will need to be evaluated in future studies, when the technology is ready to market and autonomous ride sharing available to the public. Also, it needs to be investigated how large the environmental impact of the production of the AVs and the respective infrastructure, as well as energy production for the electricity in order to get a complete picture of their emissions. Nevertheless, this work can serve as a basis for future research on this topic.

5. Conclusion

In order to conclude this research, the research questions as well as the hypothesis need to be evaluated and answered. This helps to identify the influence of this work on other research and helps to highlight strengths and limitations of this paper.

The hypothesis made in the beginning was:

> *With the introduction of a shared autonomous electric vehicle service, commuters would switch from private vehicles to public transportation. This would result in a decrease of congestion on main commuting roads and overall emissions by transportation.*

The associated research questions are:

> *How would such an intermodal transportation concept be designed for the metropolitan region of Vienna?*

> *What would the effect of an intermodal transportation concept with a shared autonomous electric vehicle service be on congestion and emissions?*

Regarding the first research question, this paper does not necessarily describe and design an intermodal transportation concept for the metropolitan region of Vienna. Mainly, an AMoD ride sharing service concept is described and simulated. Through this simulation, the effect of such a service on the region can be calculated and assessed. In this simulation, it could be observed that the vehicle fleet required by a ride sharing service to serve current demand would decrease drastically. Furthermore, the necessary infrastructure to operate this service effectively could be analysed. However, it is not assessed what the effect of an AMoD ride sharing service would be on other modes of public transportation. For future research, it would therefore be necessary to analyse multiple modes of public transportation together in order to have a full result for a mobility concept. It is necessary to analyse the effect they have on other transportation modes, on themselves, and what their combined impact on mobility would be. Another limitation of this work is that it does not consider any public transportation alternatives to a ride sharing service. Such alternatives could simply be more and flexible bus routes, more train or underground lines, more frequent service on current lines, or even the installation of a cable car. These would all be possibilities for a city to reduce individual traffic and promote public transportation. Nevertheless, AMoD presents a promising and suitable solution to reduce individual traffic in the future.

The second research question was about the effects an autonomous ride sharing service would have on the region. Whether the most important indicators, congestion and emissions, would be reduced by the implementation of a ride sharing service or not. The answer to this question was the main goal of the macroscopic simulation. As stated before, through the introduction of an AMoD ride sharing service, the vehicle fleet could be reduced by at least 90% compared to the original level, if the whole population would switch from private vehicles to public transport. Together with this, the overall mileage would be significantly reduced, as many rides would be shared. However, the empty rides of the vehicles for a new pick-up or to a charging station would then again increase mileage. Even in that case, the total mileage would still stay below the current level. Additionally, as the vehicle fleet and the total mileage would decrease, also the time on the road and the parking time would decrease. As a result, there would be significantly less traffic on streets at any given time during the day. Consequently, this leads to less congestion on the roads, especially during rush hours as less vehicles are on the road at the same time. Adding on, due to the significantly lower number of vehicles needed for the ride sharing service, the emissions would decrease as well. However, since the AV fleet would consist of BEVs only, there would be no direct emissions by the vehicles at all. There would only be indirect emissions through the vehicle or energy production. And even if these two production processes would not be sustainable, their emissions would be lower compared to the production and operation of a private vehicle fleet, as the ride sharing fleet is significantly lower. Therefore, the impact of the implementation of a battery electric AMoD ride sharing service would highly benefit the environment, since less GHGs are emitted in the production process and during operation. However, this work did not analyse the financial aspect of such a service. This is a major aspect of such a concept as many elements can determine the feasibility. Especially the energy price, which can fluctuate over time, and the price of the required technology for the vehicles and the infrastructure play an important role towards the cost-effective and efficient operation of such a service. Additionally, it needs to be investigated how the current infrastructure will need to be adapted and upgraded to facilitate the operation of AVs. However, the economic and technological aspects and researches are subject for future studies when AV and AMoD services are possible. Adding to that, early investments into infrastructure and testing of AVs would be advisable for early results and a fast introduction of such an autonomous ride sharing service.

Thus, the hypothesis made in the beginning can be claimed to be true as the required indicators would be reduced by the implementation of an AMoD ride sharing service. This highlights the usefulness of this research. It proves to be a viable option for cities and regions in the future to decrease individual traffic and private vehicle fleets. Furthermore, it helps to decrease congestion and emissions by vehicles. Therefore, in combination with other modes of public transportation, an intermodal mobility concept can even further reduce the size of the vehicle fleet, congestion, and emissions. This can support cities and countries on their way to climate neutrality. However, it is not a substitute for any other measures, as it will only be available within the next 20 to 30 years. Thus, other concepts need to be introduced for emission reduction as well.

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Table of figures