Technical University of Munich
Professorship for Modeling Spatial Mobility

ENVIRONMENTAL EVALUATION OF URBAN AIR MOBILITY OPERATION

Author:

ALONA PUKHOVA

Supervised by:

Prof. Dr.-Ing. Rolf Moeckel (TUM)

M. Sc. Raoul Rothfeld (Bauhaus Luftfahrt e.V.)

24.04.2019

Contents

Abstract

Urban air mobility (UAM) is a new concept of mobility that could significantly change the way urban mobility is understood in general and drastically influence the current manner of travelling. Taking into account the environmental concerns and the problems of heavily polluted air in the cities, new transportation solutions must be environmentally evaluated prior to their launch. Therefore, this work estimates the effects of UAM operation in Munich on current levels of traffic-related CO_2 and NO_x emissions. Using an open-source framework MATSim, the study compares two scenarios with and without UAM and for each of which five additional scenarios considering the technology improvement were calculated. Results showed that the UAM introduction in Munich did not effect on average trip distance and the total distance travelled. In total 4,480 UAM trips were simulated, which corresponds to 24.26 tonnes of CO_2 and 0.06 tonnes of NO_x emissions released by power plants. These amounts of exhaust did not have a significant effect on overall emission levels, increasing the overall levels of traffic-related CO_2 gases by 0.20 % and NO_x pollutants by 0.26 %. Based on the number of investigated scenarios, it was found that UAM operation is the most environmentally beneficial and can reduce daily CO_2 emission levels by 0.06 % when electricity consumed by eVTOL vehicles is fully generated from renewable sources. In contrast to that, the UAM operation is the least environmentally beneficial when it is used instead of ground-based electric light duty vehicle.

Acknowledgements

This thesis is the final step completing the Environmental Engineering Masters program at the Technical University of Munich. I would like to use this opportunity to thank the ones who helped me to complete this work. I would first like to thank my thesis advisor Prof. Dr.-Ing. Rolf Moeckel at Technical University of Munichfor his guidance and supervision. Also, I would like to thank Ana Moreno Chou and Carlos Llorca for answering my questions along the way. Especially to Carlos Llorca for his help and detailed explanations, and the data shared that was necessary for my work.

This thesis was written in cooperation with Bauhaus Luftfahrt e. V, a Munich-based aviation research institute. Following this, I would like to thank my external supervisor Raoul Rothfeld for initially accepting my idea for this thesis topic. I would like to thank him for helping me along the way and for engagement through the learning process. And I would like to thank Economics and Transportation team at Bauhaus Luftfahrt e. V for their help.

Finally, I would like to thank my loved ones for encouraging me and believing in me. And special thanks to Uygar for his love and support.

Acronym List

AEM	Advanced Emission Model
BaU	Business as Usual
BEV	battery electric vehicle
C	cruise
CI	carbon intensity
CO_2	carbon dioxide
COPERT	A European Road Transport Emission Inventory Model
CV	conventional vehicle
DEP	distributed electric propulsion
DC	direct current
EDMS	Emissions and Dispersion Modeling System
EEA	European Economic Area
EIP–SCC	European Innovation Partnership in Smart Cities and Communities
EM	electric motor
EV	electric vehicle
eVTOL	electric vertical take–off and landing
EU	European Union
GHG	greenhouse gas
GREET	The Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model
HBEFA	Handbook Emission Factors for Road Transport
HEV	hybrid electric vehicle
ICE	internal combustion engine

IPCC	Intergovernmental Panel on Climate Change
L	lift
LCA	life cycle assessment
LDV	light-duty vehicle
LNG	liquefied natural gas
MATSim	Multi-Agent Transport Simulation
MC Heavy	Multicopter Heavy
MITO	Microscopic Transportation Orchestrator
MOVES	MOtor Vehicle Emission Simulator
MVG	Münchner Verkehrsgesellschaft
NiMH	nickel metal hydride
NO_x	nitrogen oxides
PHEM	Passenger Car and Heavy Duty Emission Model
PHEV	plug-in-hybrid vehicle
ppm	parts per million
TTW	Tank-To-Wheel
UAM	Urban Air Mobility
V/STOL	vertical/short take–off and landing
WTW	Well-To-Wheel

1 Introduction

1.1 Urban Air Mobility

The transportation sector has been continuously growing especially since the industrial revolution. The demand for transportation is predicted to keep growing as more people are moving to urban areas from rural areas. The number of such moves is higher in the low to middle income countries. Simultaneously with the number of commuters, the number of private, public and freight vehicles is constantly growing.Insufficiency in the existing networks leads to induced congestion and thus money loss. In order to satisfy the transportation demand, road and rail networks are being developed. The city planners are taking into account the current and predicted future demands for transportation. The improved transport infrastructure triggers a new demand, consequently leading back to congestion and money loss. The Earth surface, as well as the city spaces are limited and the possible physical barriers of further network development have been already encountered in mega-cities (United Nations 2014, Beimborn, Kennedy, and Schaefer 1996).

As seen, the demand for transportation will continue to grow, consequently new transportation solutions must be found. Due to limited space for further ground city infrastructure development, the development of urban air transportation could be a promising opportunity. The urban use of air vehicles is not a futuristic idea anymore, but rather a well-known practice. Flying vehicles such as planes, helicopters and drones are already a part of transportation options. Cities are currently using helicopters for searching missions, ambulance and police emergencies, etc. On the other hand, the aim of urban air mobility is to make aerial transportation mode available for the use of citizens. Additionally, since this transportation mode does not require major investments in infrastructure, it would be also financially beneficial.

Currently, major mega-cities are investigating citizens acceptance and possibilities of urban air mobility (UAM) implementation into the transportation demand models. Cities such as Geneva, Hamburg, Ingolstadt have joined the UAM Initiative. This initiative is a part of the European Innovation Partnership in Smart Cities and Communities (EIP–SCC) and it aims to participate in the creation of the market for UAM (European.Commission 2018, European Commission 2018). Aside from European countries, Dubai is aiming to become a tech pioneer at implementing the electrically powered fleet of air-taxis, and cities in the USA are conducting studies on new air mobility solutions (Courtin et al. 2018,R. K. Antcliff, M. Moore, and K. R. Antcliff 2015, Mark D Moore et al. 2013, Kohlman and Michael D Patterson 2018, Vascik and Hansman 2017b, Noah Browning

2017). Consequently, it would be fair to say that the UAM trend is taking hold worldwide, with the main ventures in North America and Europe.

The physical infrastructure for UAM consists of veltiports. The roofs of existing buildings in the cities can be transformed for this purpose. Aside from the investments in vehicles themselves and veltiports, the major investments will be allocated processing big amounts of data regarding UAM operation. The air vehicle can be personally owned or it can be used on-demand (shared basis). Either way, in order to maintain a high level of safety and avoid collisions, big amounts of data needs to be processed.

A great benefit of the new air transportation mode is its electrification. In addition to the congestion issues, urban transport in mega-cities alone contributes around 25 % of the global amount of CO_2 gases (European Environmental Agency 2013). At this point it is important to investigate new possibilities for transportation and invest in the ones that support sustainable development. According to the European decarbonization program which aims to reduce the CO_2 levels by 60 % from the levels of 1990, the transportation sector is far away from meeting its targets. Moreover it continues to produce more CO_2 than it did before. Even though automotive manufacturers are adapting to new policies and improving vehicle performance, its energy efficiency and fuel economy, the continuously growing demand for transportation limits the ability to reach the targets (TRIP 2012).

To sum up, it is not a coincidence that electric air vehicles are now becoming more popular and gaining the investors' interest. The benefits for users are clear: people will spend less commuting times. Additionally, air transportation may have a positive affect on congestion. Finally, the electric propulsion of these vehicles offers zero local emissions and low noise pollution. Furthermore, an increase in demand for this transportation mode would lead to an increase in electricity consumption, which nay create possibilities for green-energy producers.

1.2 Advent of electric mobility and current state of the technology

The noise pollution problems, heavily polluted air and extensive amounts of greenhouse gases in the atmosphere have led to the emergence of transportation alternatives. Nowadays the term "electric vehicle" (EV) raises associations with something new, something modern and something which is currently under development. Nevertheless, the history of EV began in the 19$^{\text{th}}$ century. At that time, they were commonly in use and as well-known as steam and oil powered vehicles. Moreover, EVs were especially in favor in those days because they did not leave a cloud of smog and high noise as in oil-powered ones, and were much cheaper than steam-powered vehicles. Electricity was available in the cities and thus future success of electric vehicles was expected. Simultaneously, the propulsion system in oil-powered vehicles was significantly improved, luring more people to use it. The oil was known as a cheap fuel, which could be easily purchased at the stations. While electricity was not easily accessible in rural regions, making the combustion engine vehicles especially popular in such areas. At that point, the development and use of EVs slowed down significantly.

The following rise of EVs and the accompanying technology happened almost 100 years later, in the beginning of the 20th century, when electric, steam and gasoline powered vehicles competed on almost equal terms. The electric propulsion vehicles were in use in Europe in form of delivery trucks and vans, electric buses and industrialized trucks. The outbreak of electrified vehicle technology and increase in production were especially noticeable in the US, where up to 30,000 electrified vehicles were owned by citizens, whereas the number of gasoline cars was 900,000 (Struben and Sterman 2008). Nevertheless, privately owned electric vehicles, in most of cases, were seen as a hobby. Starting from 1905, the gasoline powered vehicles have doubled their range extension to about 100 km, where for EV the range was about 50 km. After being in a niche for over a century, it was difficult for EV to beat the range extension of conventional oil-powered ones. Moreover, the invention of serial production of gasoline vehicles and the discovery of new oil resources led to high reductions in the cost of oil and gasoline- and diesel-powered vehicles. As a result, the higher investment and operational costs of EVs compared to gasoline vehicles, have lowered their share on the roads (Mom 2004, Westbrook 2008, Udaeta et al. 2015).

World Wars I and II put on hold any new experiments with alternative fuels and the resurgence of EVs until 1970. The rapid industrialization, environmental problems and the oil crisis were the circumstances that resulted in bringing EVs back into focus of governments and investors as an alternative. The electric vehicles' technology was improved, extending the range to 100 km. However, long battery recharging times and the lack of required infrastructure affected the mass production and introduction of these vehicles on a large scale (Udaeta et al. 2015).

Years later, due to rising environmental concerns and air pollution in big cities, the interest in EVs began to increase once again. Automotive manufactures such as General Motors, Ford and Toyota introduced new models of electrically powered vehicles. Their technology was significantly better, making EVs more efficient than conventional vehicles, specially due to the introduction of lithium-ion batteries with higher storage capacity. Moreover, several studies were conducted regarding the battery cost, aiming to estimate the possible commercial future of EVs. However, this occurred at a time when oil prices were the lowest in history and, therefore, the resurgence of interest was not reflected in sales volumes (Schiffer, Butts, and Grimm 1994, Faia 2006, Udaeta et al. 2015).

The next comeback of EVs happened in 1997, with Toyota launching a hybrid four-door sedan, Prius, followed by Honda hybrid release in 1998. A hybrid electric vehicle (HEV) has a battery which is charged with electric energy. This energy is converted from kinematic energy from regenerative brakes. Additionally, in some models of HEVs the battery is charged by internal combustion engine (ICE). Depending on battery capacity and DC voltage, there are three types of HEV: a micro hybrid, a mild hybrid and a full hybrid. The micro hybrid vehicle uses a battery only for stopping and starting functions. The mild hybrid uses it for the same purpose and further, it has a bigger capacity which allows travelling distances up to 3 km and also assists the ICE and regenerative braking. The full hybrid is capable of driving distances up to 60 km using electrical energy only. The architecture of HEV can be divided into several groups:

- Parallel Hybrid, where both electric motor (EM) and ICE provide energy for propulsion (simultaneously or separately). This allows reduction of the ICE size, thus the vehicle consumes less fuel and emits less. This architecture is considered to be the simplest and and the least capital-intensive.
- Series Hybrid, where the wheels are driven directly by EM, providing energy for propulsion, and ICE extends the battery's range. This hybrid architecture reduces the propulsion complexity and minimizes the maintenance. Depending on the battery size, it may reach the highest emissions reduction levels and fuel economy among all existing hybrid's architectures.
- Series/Parallel Hybrid, which combines the benefits of series and parallel architectures, where ICE is used for high power efficiency and EM used for efficient operating conditions. This configuration has an additional planetary gear unit which allows operational dynamic of motors and generators to assure the flexibility and control of the power delivery.
- Complex architecture, known as "two-mode hybrid" or "dual hybrid", a relatively new system which is characterized by bi-directional power flow of EM. It has an additional gear set, to assure greater flexibility between the mechanical and electrical power delivered.

(NPTEL 2014, Serra 2011, IEC 2011)

A further development of the HEV is a plug-in-hybrid vehicle (PHEV), which is able to charge its battery by connecting to an external electricity source. The battery in PHEV can be recharged by ICE and regenerative braking as well. The larger batteries in these vehicles achieve a 100 km range of independent driving using the battery only. At the point when the battery is empty, ICE is used. PHEVs are considered to be cleaner than HEVs in terms of fuel consumption and amount of exhaust. Generally, because HEVs do not plugged into electric source, they are not considered as EVs (Graham-Rowea et al. 2012, IEC 2011).

Meanwhile, the most environmentally friendly among the various electric vehicle types is EV with driving range of 250 km. These vehicles have only battery and EM, and can be plugged into outlet. The main components of an EV are the battery, power converter, EM and transmission (Hannig et al. 2009). The performance of an EV depends on its battery. This is the one of the most important components in electric vehicle, characterizing the power capacity, range, weight and vehicle cost (Marra et al. 2012).

Batteries can be classified by energy storage capacity and power supplied per unit of weight, and lifetime (Udaeta et al. 2015). The batteries used in HEVs usually are lighter than the batteries in PHEVs and EVs. With the driving range extension, the amount of energy requirement is increasing, leading to the need for a battery with higher capacity. Therefore, the batteries with the highest power, energy and mass are used in EVs. As mentioned earlier, introduction of lithium-ion batteries provided a boost for EV's revival in 90s. Lithium batteries are considered to be the most promising technology nowadays. Among electrochemical approaches, the technology of the lithium-ion batteries holds the highest optimization potential for energy and power density. There are several types and configurations of lithium-ion battery chemistries, with different life time, energy and power. From the environmental perspective, the lithium-ion batteries present a better environmental performance than NiMH (nickel metal hydride) batteries, for example, but the supply of lithium is an area of concern and has to be monitored. The metal extraction and production process are the main contributors to the environmental burden of the battery production (IEA 2011, Majeau-Bettez, Hawkins, and StrØmman 2011, Notter et al. 2010).

Another important component of EV is a power converter, which converts the electricity taken from a battery to mechanical energy, regulates the power flow between the EM and the battery, and specifically converts fixed DC voltage into a variable voltage. Moreover, during regenerative braking, the kinetic energy is converted to electricity by a power converter, boosting energy efficiency of an EV by at most 25 % (Kumar, Gupta, and Jain 2013, Roscher, Roland, and Wolfgang 2013, Iqbal 2003).

EM in EVs consists of a stator and a rotor, both of them converting electric current into kinetic energy. There are many types of EMs and they can be divided into two main groups as brushed and brush-less, each of which can be classified further into subgroups (Chau, Chan, and C. Liu 2008). Rotational motion generated in the EM though the transmission drive shaft transmits the motion to the wheels. Because the EM has a high rotation speed, transmission is required to reduce the rotation speed and to multiply the associated torque. A power converter, an EM and transmission drive-shaft are the components of a drive-train of an EV, which is a linkage between the battery (energy source) and the wheels (Iqbal 2003).

The low number of components in EV leads to a high range of flexibility in design. Usually low drag air dynamic shapes are used for the EV design because low area resistance improves the vehicle efficiency. Specially, the location of the battery on a vehicle's underfloor is an advantage for aerodynamic design flexibility.

1.3 The impact of transportation on environment

According to the IPCC, climate change refers to any changes in climate over time caused by either natural or anthropogenic activity. The main contributors to the greenhouse gas (GHG) concentration are fossil fuel extractions and deforestation. Additionally, extensive amounts of exhaust gases have an impact on the environment and contribute to the global levels of GHGs. Since the advent of industrialization the global GHG levels have increased as a result of extensive human activities (IPCC 2018).

The GHG effect, which traps the heat in the atmosphere, is vital, because in its absence, the Earth's temperature would be below freezing. In the pre-industrial times there was a balance between incoming solar energy and energy emitted back to space. However, due to extensive anthropogenic activity, the current GHG effect is becoming stronger and contributes significantly to the amount of GHGs in the atmosphere, warming up our planet. The trapped gases within the atmosphere cause the global climate change, which influences the natural conditions of all living species on Earth, including the mankind.

The GHG CO_2 is the best-known gas and it has a concentrations in the atmosphere of 405.5 ppm, which is the highest among all gases. Moreover, the current CO_2 concentration is higher than it was for the last 2.1 million years, when atmospheric CO_2 levels fluctuated between 213 and 283 ppm (Hönisch et al. 2009).

Nowadays, there is the debate about the best approach towards dealing with the climate change, in which some countries aim to mitigate the climate change, while others are trying to learn adapting to it. If the climate change is an inevitable process, all countries will be affected by it and the poorest countries will be the first to witness its consequences and to suffer the most (IPCC 2007).

In order to mitigate climate change, current levels of GHG production must be reduced by 40 % from 1990 levels. The first international agreement and the world's only legally binding pact to mitigate GHG emission was signed in Kyoto, Japan in 2008. To reach the Kyoto protocol goals, each economic sector was assigned a specific reduction target, which varies among the participating countries. The Kyoto protocol aimed to reduce the following GHGs: Carbon dioxide (CO_2), Methane (CH_4), Nitrous oxide (N_2O), Hydro-fluorocarbons (HFC_S), Perfluorocarbons (PFC_S) and Sulphur hexafluoride (SF_6) (UNFCCC 2008). While many sectors were able to keep assigned amounts of GHG at current levels or to reduce them, the transportation sector, including land, marine and air transportation was not. As the biggest contributor to GHG emissions, it is responsible for the 26 % increase of GHG above 1990 levels in 2016. Road transport alone is responsible for 30 % of nitrogen oxides (NO_x) and 14 % of carbon dioxide released into the atmosphere globally and for more than 72 % of the total amount of greenhouse gases related to the transportation sector. Out of this share, 44 % of GHGs were produced by passenger cars, which also pose the highest demands on global oil production (World Bank Group n.d., International Energy Agency 2017, Sokhi 2011).

The Paris agreement on climate change is currently in force since 4 November 2016. The agreement aims to keep the temperature rise well below 2 °C above the pre-industrial temperature levels (UNFCCC 2015). As of December 1st 2018 the number of ratified countries that signed the agreement was 184, including the largest contributors to the world's GHG levels such as China, the U.S (intents on leaving) and India (UNFCCC 2018).

Over the last decade, vehicle technology and fuel technology have been improved in order to achieve the targets. Nevertheless, the demand for transportation is continuously increasing, wiping out any advance in technology to reduce the negative effect. In addition to the growing number of trips, commuting distances are increasing as well. Improved transportation infrastructure and public transportation services have made it economically beneficial for people to settle further away and therefore commute longer distances. Consequently, amounts of exhaust emissions are increasing.

Besides the negative impact of transportation on air quality and GHG levels, it contributes to land, water and air contamination and is a source of noise pollution. Additionally, the impact of transportation due to vehicle production and further disposal should not be neglected in the environmental impact estimation. Vehicle production consumes natural resources and energy, while its disposal contributes to land contamination. Transport infrastructure itself has a negative effect on the living conditions of species, disturbing their well-being, separating them and endangering their lives. Ground transportation infrastructure requires removal or lessening of natural surface, resulting in the loss of fertile and productive soils. Additionally, the usage of toxic materials, such as tar, contaminates soil and causes health hazards. Moreover, fuel and oil spills on roads are washed by the rain to soil, causing its erosion and contamination. The infrastructure itself requires extensive amounts of building materials, leading to deforestation and land draining, reducing wetland areas and driving out water plant species (Tahzib and Zvijáková 2012). To sum up, there is a wide range of traffic related causes which have negative impacts on the environment and the ecosystem.

1.4 Research questions

Taking into account the environmental concerns and governmental policies, and to maintain a path towards sustainable development, one must estimate the effects of new transportation modes on the level of traffic related emissions.

In which way will the introduction of UAM affect the total daily amounts of traffic related emissions?

To determine the answer to the stated question, the following questions shall be studied:

1. What is the amount of electricity consumed by UAM and what are the related emissions levels?
2. How much cleaner is urban air vehicle compared to conventional ground transportation modes in terms of exhaust gases?

2 Literature Review

This chapter provides an overview of the existing vehicle emission modelling tools and gives a summary of the studies investigating possible environmental benefits of electrification in the transportation sector.

2.1 Emission modelling tools, emission factor

An environmental evaluation must be performed in order to estimate the impact of transportation on the environment. To estimate the effects of the new or already existing transportation modes on environment, the amount of exhaust emissions has to be calculated. Depending on the task, the final result shows either the total weight of a produced pollutant or its concentration in the atmosphere (milligrams per cubic meter) over a specified period of time.

The most important variable for the emission calculation is the emission factor. It can be expressed as a weight of an exhaust pollutant or gas per distance or per amount of fuel. There are a number of different parameters affecting the emission factor which has to be taken into account, such as vehicle type, operational and weather conditions, road gradient, driving behavior.

To improve the emission factor estimation process and to make it more efficient and accurate, different emission modelling tools were created, containing various aspects which affect the emission factor (O 'mahony et al. 2002). Depending on the desired result, emission estimation tools provide the emission factor as a value or they provide result of total amount of a produced gas or pollutant. Additionally, depending on the scope of research, some models like GREET (The Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model) provide a result in CO_2eq, whereas models like HBEFA (Handbook Emission Factors for Road Transport), PHEM (Passenger Car and Heavy Duty Emission Model), MOVES (MOtor Vehicle Emission Simulator) and COPERT (A European Road Transport Emission Inventory Model) provide separate results for each selected pollutant or gas (EMISIA 2016, Vallamsundar and J. Lin 2011, Hausberger et al. n.d., Leonidas Ntziachristos et al. 2009).

Following international and national GHG and air pollutant regulations and agreements, countries have been developing different emission modelling tools in order to estimate current amounts of exhaust gases and the effect of implemented policies on GHG levels.

The HBEFA handbook, as an example, was developed on behalf of the Environmental Protection Agencies of Germany, Switzerland and Austria and later gained support from Sweden, France and Norway. It enables the calculation of regulated and non-regulated pollutants and gases, estimates fuel consumption and contains the vehicle fleet composition of each country included. The different emission model, COPERT, contains the data for 28 EU members, including the information about 241 vehicle types, and estimates greenhouse gases, air pollutants and toxic species, as well as energy consumption. The model currently is in use by 22 European countries and Australia. The COPERT's methodology is a part of the EEA air pollutant emission inventory guidebook, since it was developed for road transport sector emission inventory preparation in EEA member countries (EMISIA 2016, Smit and L. Ntziachristos 2013, Keller et al. 2017).

The emission factor toolkit EFT developed by the UK is applicable only within the countries in UK. Similar to EFT, the GREET model developed in the United States contains the information regarding the U.S. fleet and country electricity generation mix. At the same time, the GREET model enables the entire well-to-wheel (WTW) emission calculation, e.g. fuel production and distribution, whereas the majority of existing models focus on tank-to-wheel (TTW) calculation, e.g. the operational phase of a vehicle (DEFRA 2017, Burnham 2009).

The emission modelling tool EMT can be used within the MATSim agent-based simulation by linking simulation output data to the HBEFA database. The handbook provides emission factors and fuel consumption for different vehicle categories taking into account hot and cold start, traffic states, ambient temperature and road gradient. When linked to the MATSim, HBEFA takes into account vehicle driving speed, stop duration, travel distance, parking time and vehicle characteristics. The ambient temperature is not measured, assumed to be HBEFA average, and road gradient is assumed to be 0 %. The output provides the information about traffic demand, amounts of produced pollutants or gases and their concentration in the air per road link (Hülsmann et al. 2011).

Similar to the possibility to link MATSim to the HBEFA database, the microscopic traffic flow simulator VISSIM can be linked to the PHEM or to the emission modelling tool MOVES. The large scale scenarios within this approach are not possible, whereas MATSim emission modelling tool is able to model those scenarios in less detail. Depending on the scope of the research, either of the approaches can be considered (Hülsmann et al. 2011, Kickhöfer 2016, Hülsmann 2014).

According to the scope of this thesis, the calculation of road and air traffic emissions were performed. At this point, it is important to have a look at the existing emission calculation tools for aviation, such as AEM, ALAQS and IMPACT. These tools are used by the International Civil Aviation Organization (ICAO) Council technical Committee on Aviation Environmental Protection (CAEP) in Europe. The Advanced Emission Model (AEM) is a stand-alone application which estimates the mass of burned fuel and calculates masses of gases and pollutants produced during the fuel burning phase. A broader spectrum of emission sources than in AEM is included in ALAQS (Airport Local Air Quality Studies) which, in addition to actual aircraft operation, takes into account other operational emission sources related to the airport, such as roads within the airport area, car traffic to/from the airport. One of the negative effects current aviation is struggling to overcome is the noise emissions. The IMPACT web-application enables robust assessment of noise and estimates amounts of operational gases while in operation, like AEM does, but additionally includes the trade-off analyses between fuel-burn/gaseous emissions (EUROCONTROL 2018).

One of the first air quality assessment tool EDMS (Emissions and Dispersion Modeling System) was specially engineered for the USA aviation community in mid-1980s. This emission estimation tool was initially designed to estimate the impacts of different airport projects on the current air quality. It includes estimation of both stationary and mobile sources. Since May 2015 the EDMS has been replaced by a software system called Aviation Environmental Design Tool (AEDT). This comprehensive tool estimates the fuel consumption, emissions, noise and following consequences for air quality, including the ground access vehicles and support equipment emission estimation like its predecessor. The scope varies from a complete gate-to-gate analysis of a single flight to a complete airport scenario at regional, national, and global levels (FAA 2015, U.S. Department of Transnportation 2013).

Because the task of this thesis is to estimate the total amount of CO_2 and NO_x gases produced by different public transport modes, private cars and on-demand air vehicles, none of mentioned emission tools can be applied.

2.2 Environmental evaluation of conventional transportation

The transportation sector contributes extensive amounts of greenhouse gases and air pollutants to global levels. As mentioned earlier, there are international agreements and policies aiming to reduce negative environmental impacts of transportation on the environment.

In order to regulate the amounts of traffic related emissions, the first European exhaust emissions standard for light duty vehicles (LDVs) was introduced in 1970. This was a part of legal requirements to govern air pollutants released into the atmosphere. The limits for permissible amounts of specific air pollutants from new vehicles sold in EU and EEA member states were defined. The standard was the instrument designed to achieve air quality standards and to protect human health (The Council of the European Communities 1970).

Later in 1991, the first vehicle emissions standard Euro 0 was introduced in the European Union for passenger cars only (The Council of the European Communities 1991). The following year a new emission standard was released for passenger and duty trucks, requiring an installment of catalytic converters to petrol cars to reduce carbon monoxide emissions. The emission standards are defined in a series of European Union directives, progressively introducing of increasingly stringent standards, where each new version sets up a new threshold to limit the amount of emissions (The Council of the European Communities 1993).

The "Euro classes" are separated between light and heavy duty vehicles, where Euro 0-6 pertains to light duty vehicles and Euro I-VI to heavy duty vehicles. Additionally, different limits are applied depending on the fuel type – gasoline or diesel. The latest emission standard existing today for LDV is EURO 6, which was introduced in 2014 and applies to all new cars registered from 1 September 2015 in EU countries (The Council of the European Communities 2014, The Council of the European Communities 2007).

To ensure that newly produced vehicles meet the stated limits of exhaust emissions, the vehicle manufactures use the New European Driving Cycle (NEDC) which is the legally mandatory method to test the exhaust emissions of passenger cars and light duty trucks (European Parliament 2016). Tests are laid out in standardized emission test cycles and used to measure emissions performance against the regulatory thresholds applicable to the tested vehicle. The driving test cycle should ensure the vehicle will not produce more pollutants and gases than allowed. Nevertheless, some studies claim that this driving cycle does not adequately capture real-world driving patterns (L. Yang et al. 2015, Williams and Carslaw 2011, Degraeuwe and Weiss 2017, Weiss et al. 2012).

2.3 Effect of electrification in transportation on the environment

The life-cycle assessment of conventional vehicle shows that the operational phase contributes 85 – 90 % to the total amount of greenhouse gas emissions and air pollution released (Faria, Marques, et al. 2013). In order to mitigate negative effects of transportation on the environment, different fuel alternatives have been investigated, tested and applied. Existing policies and tax reductions aim to increase the share of electric vehicles in the cities and consequently to reduce the negative environmental impact of transportation. Vehicles with electrically powered propulsion systems are considered to be clean in terms of local emissions and much quieter than conventional vehicles using ICE. While estimating possible environmental benefits from the shift from conventional vehicles to electric ones, different aspects can be included depending on the purpose of study. Even though, electric vehicles are generally considered to be emission-free, their production and disposal have a negative impact on the environment.

2.3.1 Conventional and electric cars

Generally, electrification of the existing car fleet is known as a way towards sustainable development which would reduce oil dependency and mitigates negative impacts of transportation on environment and local air quality. Electric vehicles are considered to be emission and noise free. Nevertheless, there is a need for a broader estimation of EVs total performance and their ability to contribute to a "fossil free future".

Following the vehicle electrification trend, China has a higher share at 25 % of EVs than EU countries, USA or Japan (Jungmeier et al. 2017). There are several studies conducted in China which consider a complete EV life-cycle assessment to estimate the amount of possible emission reduction (Huo, Q. Zhang, Wang, et al. 2010, Huo, Q. Zhang, F. Liu, et al. 2013). The study of Huo, Q. Zhang, F. Liu, et al. 2013 found that EVs produce higher amount of air pollutants than the conventional vehicles with ICEs. This is mainly because coal-based power plants provide the high share of the electricity in the country. As a result, 99 % of the fuel-cycle CO_2 emission of EVs are coming from power plant (Huo, Q. Zhang, Wang, et al. 2010). Interestingly, using the same emission estimation model GREET, the studies came to different conclusions regarding the greenhouse gas emissions. Huo, Q. Zhang, Wang, et al. 2010 states that the amount of CO_2 emissions from EVs is predicted to be 7.3 % more than from vehicles with ICEs, whereas the results of the study of Huo, Q. Zhang, F. Liu, et al. 2013, which was done 3 years later, showed that the amounts of greenhouse gases (including CO_2, CH_4 and N_2O) from EVs would be 20 % lower. At the same time, both studies claim the results may vary significantly regarding the geographical location (F. Yang, B. Li, and Yuan 2013).

A similar study was done by Nichols, Kockelman, and Reiter 2015 study in Texas, USA. The study compared PHEVs with gasoline powered CVs, as well as highlighted the importance of power plant locations. Additionally, more detailed approach was used for energy demand estimation, taking into account peak and off peak demands. Using the GREET model for the life-cycle assessment, the study enabled a fair comparison of EV and CV production, regarding the energy inputs for LDVs materials production. The results showed that 30 % higher CO_2eq emissions are released during EV production than CV production phase. This could be explained by higher energy demand for battery assembly, specifically global warming potential of the battery production contributes 35 – 41 % to EV production phase (Hawkins, Singh, et al. 2013). Electricity production in Texas, USA is highly dependent on coal-fired power plants. The consumed amounts of electricity were converted to electrified miles, and the results showed that EVs produced twice as much CO_2 as gasoline powered CVs and 125 % more than diesel powered CVs (Nichols, Kockelman, and Reiter 2015).

Different results were attained by Faria, Moura, et al. 2012 study, which considered EU electricity mix of 360 gCO_2/kWh. It was found that vehicles with electric motor emit lower CO_2 than conventional gasoline and diesel powered ones. Nevertheless, EVs produce higher amounts of GHGs, such as N_2O and CH_4, compared to the CVs. On the other hand, the amounts of NO_x and PM_10 air pollutants from EVs are lower, thus the local air quality can be improved. These results contradict Huo, Q. Zhang, F. Liu, et al. 2013 findings, which showed that EV could reduce the amounts of released GHGs but significantly contribute to the air pollutants levels.

In Europe, the comparison study was done in Germany with ICE vehicles using gas and diesel and two EVs with different battery capacities (Jöhrens and Helms 2014). Regardless of the battery capacity the production phase of EVs releases twice as much CO_2eq gases as CV production, which is higher than the findings of Nichols, Kockelman, and Reiter 2015. Nevertheless, the production phases of both vehicle types release the same amounts of CO_2eq if the battery production is not considered (Jöhrens and Helms 2014).

Another European study was done in Portugal, considering the LDVs fleet. The study compared the projected expectations of gasoline, diesel and electricity powered vehicles until 2050. As expected, at the TTW stage there are no local emissions and pollutants from EV, and the energy consumption of EV is almost 5 times lower than from gasoline and diesel vehicles. Nevertheless, despite the high share of renewables in the Portuguese electricity mix (51 %), the related CO_2 emissions of EVs are projected to be 7 and 9 times higher than gasoline and diesel vehicles emissions respectively (Ribau and Ferreira 2014).

Above all, EVs are primarily considered for urban driving due to the availability of the charging infrastructure within cities and the driving range of the batteries. Moreover, when HEVs and PHEVs drive on highways in rural areas, the amount of released CO_2eq gases per kilometer (CO_2eq/km) increases. The opposite occurs when CVs are considered. At the higher speeds allowed on highways, CVs tend to produce lower amounts of CO_2eq/km than in urban areas. Nevertheless, a WTW analysis showed, that amounts of released exhaust from vehicles containing EM are lower than those from vehicles equipped with ICE only. However, this analysis considered only the Ontario electricity mix, which is mainly nuclear (Raykin, MacLean, and Roorda 2012).

Investigating the exhaust emission dependency on different speeds of EVs, Matsuhashi et al. 2000 compared electric and gasoline vehicles operational phases, specifically the energy consumption at different speeds in urban areas. He found that at lower speeds vehicles tend to consume more energy and as speed increases, the energy consumption per km decreases. The results at the speed of 4.62 km/h for CVs are similar to the results by Ribau and Ferreira 2014 for EVs, where the latter consumes 5 times less energy than gasoline vehicle. As speed increases to 44.34 km/h the difference in the energy consumption of both vehicle types becomes smaller. At this point, EVs consume half as much energy as gasoline vehicle. The difference of related CO_2 emissions changes according to energy consumption changes (Matsuhashi et al. 2000).

A different approach is the comparison of different EVs: HEVs, PHEVs and BEVs. Regardless of the energy mix, BEVs show the lowest amount of CO_2 gases produced (Faria, Moura, et al. 2012, Szczechowicz, Dederichs, and Schnettler 2012). Nevertheless, the assessment of the two battery types used in EVs showed that during the operational phase a vehicle with bigger battery capacity releases higher amounts of CO_2eq per km than smaller capacity battery (Jöhrens and Helms 2014). Besides the battery size, its type affects the amounts of energy consumed and, consequently, the amounts of related emissions (Matsuhashi et al. 2000).

As seen, there are numerous factors that have to be taken into account while estimating the performance of electrified vehicles. Vehicle speed, type of battery and its size, degree of vehicle electrification and electricity mix have to be considered. Based on the scope and degree of details of the research, the results may vary significantly showing clear benefits of adoption of EVs as well as negative impacts. A higher share of EVs in vehicle fleets shifts emissions from the transportation sector to the electricity sector, which is positive overall (Helland 2009). The emissions related to electricity generation power plants are easier to regulate than scattered emissions from conventional vehicles with ICEs, which are maintained individually (Iqbal 2003).

2.3.2 Electric Buses

The continuously growing demand for transportation in recent decades has expanded the urban public bus fleets. This has resulted in another significant increase in traffic-related emissions. Heavily polluted air puts the overall climate state and public health at risk. Various solutions have been suggested and applied in several countries in order to overcome this problem. Replacing gasoline- and diesel-powered public bus fleets with electric bus fleets could be an effective strategy to reduce the amount of local pollutants. The amounts of carbon emissions from electric vehicles are estimated to be significantly lower than those from conventional vehicles with a strong dependency on carbon intensity (CI) of electricity grid (Moro and Lonza 2018, Doucette and McCulloch 2011, Tzeng, C.-W. Lin, and Opricovic 2005).

The results of S. Zhang and Zhao 2018 study show that usage of electric buses in Shenzhen, China, could reduce petroleum use by 85 – 87 % compared to conventional bus. This would lead to 19 – 24 % reduction in CO_2 related emissions. The amounts of CO_2 reduction levels strongly depend on the electricity grid, which is mostly based on coal-fired power plants in the selected study area.

The Doucette and McCulloch 2011 study provides a detailed estimation of possible CO_2 emissions reduction from public bus operations. This study considered the Ford Focus bus 2010, since this model produces the lowest amounts of CO_2 gases per km compared to the other models of the same manufacturer. Using the vehicle modeling tool, the ICE in the conventional bus was replaced by batteries. The performances of battery electric bus and plug-in hybrid electric bus were simulated in order to define the desired battery pack and to estimate the amounts of released CO_2 gases. Results showed that plug-in hybrid electric buses produced lower amounts of CO_2 gases per km than battery electric and conventional buses. Plug-in hybrid electric bus weighs less than battery electric bus as it requires fewer batteries, which leads to lower amounts of CO_2 gases produced per kilometer. Furthermore, ICEs in plug-in hybrid electric buses are found to be operated more efficiently than in conventional buses.

A similar analysis was conducted in South Korea, calculating the actual difference between the amounts of released CO_2eq from electric buses and buses running on natural gas.

Taking into account the carbon intensity of the power grid and local carbon emissions, electric buses release half as much CO_2eq as conventional buses (Choi, H.-K. Jeong, and S.-K. Jeong 2012). Additionally, a study requested by New York City Transit in 2016, as well pointed out the enormous difference in CO_2eq emissions between a diesel bus fleet and an entirely electrified public bus fleet. Electrified bus fleets enables yearly savings of almost 500,000 metric tons of CO_2eq emissions. The study claims that the results could be even greater if the power generator was located further away from the city (Aber 2016).

To sum up, the electrification of public bus fleets is beneficial in majority of the cases in terms of carbon reduction. Besides the importance of energy generation sources and their carbon intensity, the city structure, road topology, climate and geographical conditions are significant factors affecting the amount of locally produced CO_2 gases.

2.3.3 Electric bikes and scooters

Over the last decade, the electrification trend has been spreading around the world and new electric propulsion systems solutions are emerging. In most cases, transport electrification is intended to replace ICE usage and to reduce the amounts of released GHGs and air pollutants. A bike electrification is different from other cases since an electric bike emits more than its conventional predecessor (C. Cherry 2007). At the same time, electric bike is the most energy efficient mode of currently existing motorizes transportation modes. Considering the same distance travelled electric bike consumes one tenth of the electricity compared to electric vehicle (Zuev, Tyfield, and Urry 2018). As a result, the amounts of related pollutants and gases from electric bike are significantly lower than from electric car (Huo, Q. Zhang, F. Liu, et al. 2013).

Among all countries in the world, China has the highest number of electric bike ownership (Xie, Qi and Wagner, Armin 2010). Electric bike sales in China showed the highest raise on the buying market and the largest adoption of alternative fuel vehicle in the history (C. R. Cherry, Weinert, and Xinmiao 2009, Ji et al. 2012). At the same time, China is the largest manufacturer of electric bikes. It is the largest importer of electric bikes to EU countries and is also able to satisfy the high local demand (Muetze and Tan 2007, Zuev, Tyfield, and Urry 2018).

Electric bikes and scooters are advantageous for citizens due to the heavily congested traffic flow in cities, emerged due to the large increase in urban population. Currently, the number of bike owners is twice higher than the number of car owners (C. R. Cherry, Weinert, and Xinmiao 2009, Ji et al. 2012, Xie, Qi and Wagner, Armin 2010). At the same time, the increased number of electric bikes in the cities have led to higher number of fatalities, which is twice higher than the fatality rates of conventional bikes and is a quarter of the cars rate. This eventually have led to the fact that currently electrified bikes are banned in major Chinese cities (Xie, Qi and Wagner, Armin 2010, Zuev, Tyfield, and Urry 2018).

The survey results from electric bikes users in China showed that in most cases this mode is used instead of walking, conventional biking and using bus. In this instance, electric bike is a reasonable solution allowing to maintain urban mobility at a sufficient level. However, this does not eliminate the need to use carbon-centered, motorized modes of transportation (X. Lin, Wells, and Sovacool 2017).

Despite the fact that China's electricity sector heavily relies on coal, from the environmental perspective electric bike is still a reasonable solution for reduction of GHGs and air pollutants levels (Xie, Qi and Wagner, Armin 2010). Following this, the environmental evaluation is necessary in order to estimate the impact of extensive use of electric bikes. The majority of the studies evaluating the environmental impact of electric bikes and scooters are conducted in China. The comparison of emissions between electric bike and public bus, and private car showed that e-bikes emit much less than conventional cars and have comparable emission rates with public buses (C. R. Cherry, Weinert, and Xinmiao 2009, C. Cherry 2007). Additionally, depending on the emission standard used for ICE vehicle assessment, the results of Ji et al. 2012 showed, that Euro IV vehicles produce comparable emission rates of HC and NO_x to electric bicycles. Whereas electric scooters emit slightly more than e-bike (C. Cherry 2007, C. R. Cherry, Weinert, and Xinmiao 2009).

Electric bikes related emissions are significantly lower than emissions from any other type of electrified transportation mode and conventional private mode (Xie, Qi and Wagner, Armin 2010). Nevertheless, a complete LCA is important because of the use of lead acid batteries and related lead pollution. The LCA of electric bike must include battery recycling and manufacturing practices (C. Cherry 2007, Xie, Qi and Wagner, Armin 2010, C. R. Cherry, Weinert, and Xinmiao 2009). and Similarly, the production of lithium-ion batteries has the largest environmental impact than any other life cycle stage of electric bike (Elliot, McLaren, and Sims 2018). Still there is number of additional factors, such as route slope grade, wind, speed and weight of the bicyclist, which affect the energy consumption and therefore the emission rates of e-bikes (Muetze and Tan 2007, Elliot, McLaren, and Sims 2018).

2.4 Air vehicle types and characteristics

The enormous number of trips between neighborhoods, cities, countries and continents can be classified by their distance. Urban Air Mobility focuses specifically on intra-city trips providing a mode sufficient to substitute, to some extent, for ground transportation trips. As it was mentioned earlier, helicopters that are operating within the cities, can be considered as intra-city transportation modes which do not require a runway. This has a great benefit, especially for urban areas due to the lack of suitable and available free space. Nevertheless, helicopters can not be used by citizens on a daily-basis and are not available on-demand. Additionally, due to helicopter's concept design, the cruise speed and efficiency are compromised. Helicopters were initially designed to hover at the same location and now the hover efficiency is being optimized for mission tasks (UBER 2016). At this point, a conventional airplane has a better cruise speed performance, but it requires a runway since it is not designed for vertical take off. Limitations like the price of a single trip, noise and emission concerns would as well affect the intra-city use of both helicopter and airplane (Leishman 2006).

Due to these limitations, the need arose for a new technology which would combine the benefits of helicopter and conventional intercity plane. In this case, the solution should be able to perform vertical take off and landing with a high-speed forward flight (Hirschberg 2017). Hirschberg 2017 report presents 43 different types of aircrafts which combine these two concepts. All of the 43 designs have been build and tested. The "V/STOL Wheel" concept presents all the used methods were tested to accomplish vertical take off and landing, and high-speed forward flight on a fixed wing. Additionally, the different propulsion systems were tested with new air vehicle designs. Out of the 43, only 3 aircraft types were considered successful and developed for operational service. Yet, over the period from the 1960s till early 1990s, these aircraft types required a high mechanical complexity and were fuel inefficient. In the 20 years since then, technology has been improved and the number of engines and shafts on board were minimized. Though, there still remained a risk of system failure for powered-lift (Hirschberg 2017).

At the same time, the technology for electrically powered modes, especially electric engines and batteries, has been developing and has created a potential for new VTOL configurations which could solve many of the problems of conventional VTOL concepts (Hirschberg 2017, Alex M. Stoll et al. 2014). The relatively scale-free nature of electric motors allows the use of small electric motors. They are placed in strategic locations of the aircraft without increasing its complexity and weight, unlike the installation of a number of ICEs, gearboxes and drive-shafts (Alex M. Stoll et al. 2014). Moreover, the elimination of those components lowers the chance of mechanical failure and increases the safety of the aircraft. eVTOL aircraft is considered to be safer due to the potential of the highly-redundant propulsion system. Furthermore, the low maintenance requirement reduces the operational costs. Considering current battery technology, this type of aircraft cannot be used now for long-range trips. At the same time, it is practical for medium-range trips. It has high forward speed and it is more efficient than conventional helicopters (Alex M. Stoll et al. 2014, UBER 2016, Michael Shamiyeh, Rothfeld, and Mirko Hornung 2018).

Distributed electric propulsion (DEP) and its scale-free nature gives a degree of freedom in aircraft design. Currently, there is a relatively large number of different eVTOL vehicles developments with predetermined launch dates (Lineberger et al. 2018). At such an early stage, there are no boundary conditions for vehicle design, nor performance targets. According to lift production during cruise and the VTOL mechanism used, the eVTOL aircraft design can be divided into two groups, "Rotary-Wing Cruise" and "Fixed-Wing Cruise" (Michael Shamiyeh, Rothfeld, and Mirko Hornung 2018).

Figure removed due to possible copyright infringements

Figure removed due to possible copyright infringements

Figure 1: Rotary wing (left) and fixed-wing (right) octocopters with coaxial rotors (Finger et al. 2017)

The rotary-wing technology was developed after the end of the Cold War. Its development focused on long-distance flight efficiency and fuel consumption in cruise and hover phases (Kopp 2010). These technology models show better hover performance but are limited in forward speed and distance compared to fixed-wing aircraft (Thipphavong et al. 2018). The number of rotors in multi-rotor aircraft's design may vary from 2 to 18 (Aurora Flight Sciences 2019, Alex M. Stoll et al. 2014, A^3 by Airbus 2019, GmbH 2017, Silva et al. 2018, WORKHORSE Company 2019, Finger et al. 2017, Datta 2018). A copter with two rotors is called a Side-by-Side helicopter and can operate either with two turbo-shaft engines or batteries powered by two electric motors. The interconnected shaft joins both rotors, and it is used for synchronization and power transfer. The failure of one rotor is mitigated sending the power from the operative motor though the shaft to the other side of the vehicle (Silva et al. 2018). The tricopters have three rotors and three motors, and due to the uneven numbers, their torque can not be canceled out completely: one (sometimes two) rotor is activated to pivot and generate a torque to control yaw. The simplest control arrangement is offered by quadrocopters. The design may be a "plus" (+) or an X-layout. At the same time, its simplicity and low number of moving parts prohibit full redundancy in case of motor failure. The failure rates of tricopters and quadrocopters are similar. It is also worth mentioning the pentacopters, whose 5 pairs of rotors and motors follow a principle for yaw control similar to the tricopters. Hexacopters have 6 pairs of motors and rotors. Their design may be divided into two groups: conventional design with one rotor at one axis (six-arm layout), and coaxial propeller design (Y-layout) exhibiting superior efficiency over a single propeller. The coaxial propellers can also be used for a octocopters, which pair 8 rotors with 8 motors (Finger et al. 2017). The multicopter with 18 rotors aligned in two concentric circles has subsequently the highest redundancy. The large disk area provides an excellent hover efficiency, while the low rotor tip speed makes this multicopter's noise at minimum (M. Shamiyeh, Bijewitz, and M. Hornung 2017).

The "Fixed-Wing Cruise" group has a variety of aircraft designs, distinguished with different numbers of rotors, tilt-rotors, tilt-wings and rotors used as wing extenders (Sinha et al. 2015, Alex M Stoll, Stilson, et al. 2013). Usually the rotors are used for vertical take off and landing, where propellers and wings provide a sufficient forward cruise speed. Adding engines to the air-frame of any aircraft is the simplest way to enable VTOL capability (L + C). Another way to enable VTOL is by using the same propulsion system for lift and cruise (L = C). The third way is when cruise engines are used for lift and cruise, but during the lift there is an additional number of supplementing engines, which are disabled during the cruise phase of flight (L + L/C) (Finger et al. 2017). The number of rotors in this design may vary from 1 to 18 and, depending on the design, they may have different functions at each flight stage. The aircraft maybe assembled with multi- and tilt wing, as well as the multi- and tilt rotors (Seeley 2017, A^3 by Airbus 2019, GmbH 2017, WORKHORSE Company 2019, Alex M. Stoll et al. 2014).

Each configuration has benefits and drawbacks according to the purpose of its use. Some are able to provide long hovering time, but have a low forward speed and limited range (e.g. multi-rotors). Others have limited hover ability but extended range and higher forward speed, which can be achieved with tilt-wings aircraft, for example. The transition phases from vertical to horizontal flight and back are more seamlessly performed with an aircraft with separate lift and cruise concepts than those with tilt-wings and tilt-rotors

(Thipphavong et al. 2018, Alex M. Stoll et al. 2014, Alex M Stoll, Bevirt, et al. 2014).

A number of "flying car" manufacturers are working on VTOL electric vehicles prototypes, their testing and further production:

- Aurora flight sciences started its eVTOL development in 1989 (Lineberger et al. 2018). Currently it consists of 8 rotors, 1.8 meters long wings, and 1 propeller for cruise flight, and can reach a speed of 180 km/h. Aurora has a 2-seat capacity. (Aurora Flight Sciences 2019, The Vertical Flight Society 2019).

- Airbus began its development of Vahana in 2016 (Lineberger et al. 2018). It is an autonomous eVTOL aircraft with a 1-seat capacity and range of 200 km. The multicopter has a length of 5.7 meters and width of 6.2 meters. It is equipped with 8 rotors, which enable cruise flight at a maximum speed of 175 km/h (Lovering 2018, Vahana 2018).

- The rotary-wing eVTOL Volocopter's development begun in 2012 (Lineberger et al. 2018). Nowadays it has a 2-seat capacity and can either operate autonomously or be piloted. Nine independent Li-ion batteries supply the power to 18 rotors of the vehicle. This number of rotors allows climbing the height of 1,650 - 2,000 meters, at a climb rate of 3 m/s. The range of the vehicle is 27 km at a cruise speed of 70 km/h. In 2016, the Volocopter gained a "permit-to-fly" from German aviation authorities (GmbH 2017).

- A personal helicopter concept was developed by SureFly. The developed eVTOL vehicle has an X - layout with 8 coaxial propellers, which allows lift a height of 5,000 ft (1.524 meters). The vehicle's maximum speed is 70 knots (129 km/h), and the maximum travel time is 2,5 hours. The vehicle is equipped with gasoline engine and also battery which is used to extend the flight time by 10 minutes (WORKHORSE Company 2019).

- Joby Aviation (the USA) began the development of S2 in 2009 The vehicle has a 2-seat capacity. The eVTOL aircraft uses 12 tilt-rotors for VTOL, however only 4 of them are used for cruise. The cruise speed of the vehicle is 200 mph (321 km/h) and the range is 200 nm.
  The LEAPTech (Leading Edge Asynchronous Propeller Technology) concept by Joby Aviation is a possible application of DEP architecture, with 20 rotors located along the 31 ft (9.45 meters) long wing and can be powered by single small motors. The LEAPTech aircraft has a 4-seat capacity. The vehicle's forward speed is 200 mph (321 km/h) and a cruise attitude of 12,000 ft (3,657.6 m) (Alex M Stoll 2015, Alex M

Stoll, Bevirt, et al. 2014). This L + L/C technology has a high thrust-to-weight ratio, but the VTOL propulsion components do not contribute to the cruise segment of the flight (Y. Liu et al. 2017).

There are many more varieties of eVTOL designs and concepts. The eVTOL models are constantly being improved, as well are the batteries, in order to achieve longer range and higher speed (Datta 2018). Current speed and range of eVTOL vehicles are lower than conventional airplane range and speed, leading to skepticism about the future of electrified air transportation (Mark D Moore 2014). There are number of studies in which performance of manufactured conventional aircraft is compared to performance of the same aircraft after its electrification (Silva et al. 2018, Mark D Moore et al. 2013, Michael D. Patterson, German, and Mark D. Moore 2012, Hepperle 2017). In such comparisons, the aircraft design was not changed (Mark D Moore et al. 2013). The results of Michael D. Patterson, German, and Mark D. Moore 2012 comparison study showed that the electrified aircraft did not achieve a practical range capability equal to the conventional aircraft. This predicts that electric aircraft will not have a practical range capability in the nearest term. At the same time, it highlights the importance of an aircraft design dedicated specifically to the use of electricity as an energy source. The concept of distributed electric propulsion is very different from the existing propulsion solutions; therefore a direct comparison of both technologies is not reasonable for comparable results. The DEP offers compelling differences hence this technology is fundamentally changing the way propulsion integration is currently approached (Mark D Moore 2014).

The comparison of typical conversion chains of conventional turboprop systems, conventional turbofan systems, battery and fuel-cell powered systems, showed that battery powered systems reach almost twice the efficiency of the others. This is mainly due to the avoidance of fuel conversion to electricity. At the same time, the battery has the lowest ratio as mass and equivalent energy density among various electric power generation systems (Hepperle 2017). As the battery energy density sufficiently limits the range of air vehicles, the use of a range extender is an additional feasibility factor for longer routes (Mark D Moore et al. 2013, Alex M Stoll and Veble Mikic 2016).

The topic of UAM is relatively new, but a number of various research studies have been carried out and results published. However, to the best of author's knowledge, little work is available so far regarding environmental aspects of this mode. One of the most severe notional constraints is the aircraft noise, which is becoming stronger as the number of flights increases (Vascik and Hansman 2017a). eVTOL vehicles are thought to produce zero local emission and to be relatively quiet during the operational phase. The eVTOL vehicles are considered to be significantly quieter than conventional helicopters and airplanes because electric motors remove the source of mechanical, combustion and exhaust noises from aircraft (Vascik and Hansman 2017a). The operating propeller tip speed of eVTOL vehicle is 50 % lower than helicopter propeller tip speed, thus it reduces the noise, while maintaining the efficiency levels. The high number of rotors and smaller disk area in multicopters lead to great hover efficiency of eVTOL vehicles, despite low rotor tip speeds (Michael Shamiyeh, Rothfeld, and Mirko Hornung 2018). Moreover, some propellers may be de-powered during the cruise flight, thus further reducing the number of noise sources.

eVTOL aircraft can be considered as a zero emission vehicle as long as the electricity used is generated from renewable sources. One life cycle assessment, including both the vehicle and the electricity production related emissions, was conducted for electric and hydrocarbon-based small air vehicles (Mark D Moore et al. 2013). One of the most efficient engine in aviation today is the hydrocarbon-based, which was installed in a small SR - 22 aircraft and has 28 % fuel efficiency at ideal cruise conditions, whereas the EM efficiency is 97 %. This means a gain of 3.4 times in power generating efficiency for EM. Regarding the released emissions, the SR - 22 produces 857 gCO_2/kW of shaft power, while the EM produces 350 gCO_2/kW (with the California electricity mix - 329 gCO_2/kW) and 733 gCO_2/kW (with U.S. average electricity mix - 689 gCO_2/kW). Taking into account the 3.4 times difference in engine efficiencies, the total electric vehicle system efficiency is 5.9 times greater than hydrocarbon based aircraft system efficiency (Mark D Moore et al. 2013).

A different comparison using the GREET emission model was performed with electric aircraft Pipistrel G 4 and hydrocarbon aircraft SR - 22. The 30,000 hour air-frame lifetime results showed that vehicle and battery production are not essential comparing the 20 years operational time for both vehicle types. Nevertheless, the amounts of CO_2 gases released from G 4 are 5 times lower than SR - 22 emissions when using the U.S. average electricity mix, and 10 times lower when using the California electricity mix (Mark D Moore et al. 2013).

The Kohlman and Michael D Patterson 2018 study compared hybrid-electric power-train architecture fuelled by liquefied natural gas (LNG) and pure electric aircraft architecture, as well as amounts of CO_2 gases produced on daily basis by each in context of Uber-like network. By 2025 Uber is planning to operate a network of at least 5 vertiports with 300 - 500 vehicles of 4 - seat passenger capacities per vertiport, expecting to serve 60,000 passenger trips per vertiport per day. The results showed that amounts of produced CO_2 gases from ICE with LNG is 20.3 % lower than emissions related to pure electric vehicles. The Texas electricity mix of 539 gCO_2/MW, the California electricity mix of 282 gCO_2/MW and the country average electricity mix of 497 gCO_2/MW were used for calculations. The AvGas 100LL aircraft, which uses either ultra-low sulfur diesel or JP-A (jet fuel) fuels, were estimated to generate slightly lower amounts of CO_2 emissions than electrical aircraft power by either of the electricity mixes.

A similar aircraft comparison, which neglects the emissions released during vehicle and battery production, was done for 100LL AvGas conventional propulsion aircraft and electric air vehicles. The results of CO_2 emissions related to the operation of electric propulsion vehicles were highly dependent on electricity mix. Within the mission range of 100 miles (160 km), an electrically powered aircraft produces lower amounts of CO_2 gases than conventional propulsion aircraft, regardless of electricity composition. For longer missions up to 150 miles (241 km), the filthiest electricity mix has a significant impact on CO_2 related emissions. At this point, an electric aircraft produces 27 % higher amounts of CO_2 gases than a conventional 100LL AvGas aircraft. Considering the U.S. average electricity composition and the cleanest energy generation mixes, electric aircraft related CO_2 emissions are respectively 12.5 % and 70 % lower than CO_2 emissions from conventional 100LL AvGas aircraft (Vascik and Hansman 2017b).

The possible environmental benefits of pure electric air vehicles over conventional aircrafts are questionable. Moreover, considering current eVTOL vehicle range, electrically powered aircraft it is not a competitive mode for the conventional aviation. On the other hand, this range is practical within city areas, where air vehicles are planned to substitute for ground-based travel modes and possibly to have a positive effect on congestion. Assuming that 10 % of travellers across the U.S. will be using air vehicles to substitute for ground trips with a range of 24 – 160 km, the potential CO_2 reductions by 2025 would be from 50 million metric tonnes to 75 million metric tonnes annually, depending on amount of fuel wasted in ground congestion. The amounts of emissions related to electric air vehicle operation was calculated based on the assumption that electricity is fully generated by renewable sources (Seeley 2015). Considering the distance of 100 km, the direct point-to-point comparison of eVTOL aircraft with BEV and conventional vehicle with ICE showed that eVTOL related GHG emission are 35 % lower than emissions from conventional vehicle and 28 % higher than BEV emissions. Nevertheless, if the distance considered is shorter than 35 km, eVTOL vehicle is less efficient in amounts of released CO_2eq gases among considered modes (Kasliwal et al. 2019).

Even though the described studies asses environmental performance of purely electric aircrafts, comparing it with conventional aircrafts and ground vehicles, there is still lack of studies on the intra-city level which would estimate changes in traffic-related CO_2 and NO_x emissions if a defined share of ground trips is replaced by UAM. The aim of this thesis is to estimate the amounts of emissions produced over the simulated day with and without UAM.

2.5 Source and composition of electricity

The operational phase of a conventional vehicle is a major contributor to GHG emissions and air pollutants causing 85 – 90 % of life cycle emissions. Electricity composition is an important element for environmental evaluation of electrified vehicles, as electricity mix highly affects EV emissions performance. For an electricity mix in which fossil sources dominate, the operational phase of a vehicle will be the major contributor of GHG and air pollutants (Faria, Marques, et al. 2013). Therefore, as was explained in earlier chapters, the replacement of conventional vehicles by electric ones does not always mean reduction of emissions. Higher share of renewables in the electricity mix could reduce the amounts of EV related emissions, thus, traffic emission levels can be reduced.

The emerging interest and investments in electric vehicles are creating a market for renewable energy power plants, and the share of renewables has been growing in the EU since 2005 (European Environmental Agency 2018b). In 2016, for the second year in a row, low-carbon energy sources continued to dominate in the EU electricity mix and to generate more power than fossil fuel sources did. Another electricity source with low-carbon intensity is nuclear power, and countries like France, Lithuania and Belgium have reduced their carbon intensity by generating the greatest share of electricity via nuclear power plants.

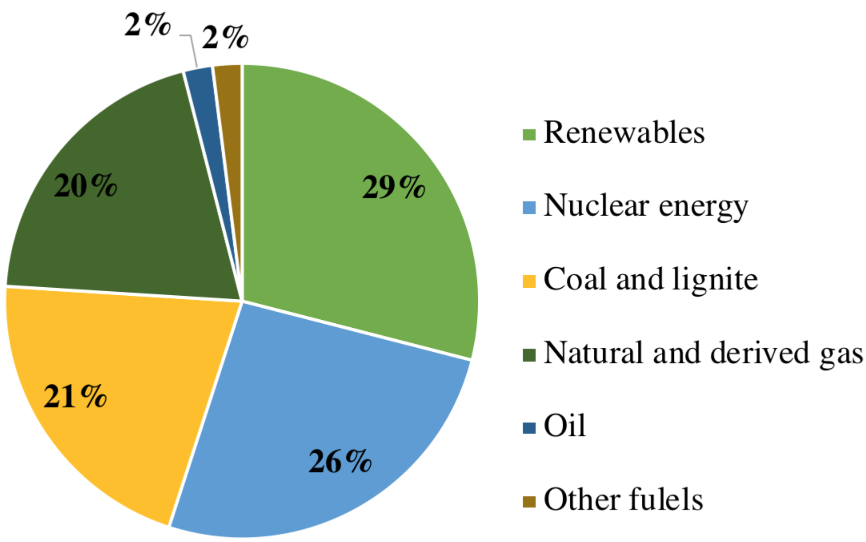

Figure 2: Electricity generation by fuel in EU, 2016
(own image based on European Environmental Agency 2018b)

In the wake the Fukushima accident in 2011, countries like Germany, Switzerland, Spain and Belgium began to plan the decommission their nuclear power plants. On the other hand, other countries are considering the increase of electricity produced by nuclear power plants (Bulgaria, the Czech Republic, Hungary, Poland, Romania and the United Kingdom). Moreover France, Finland and Slovakia are constructing new nuclear power plants and Sweden is extending the life-time of existing nuclear reactors. Nevertheless, the mentioned Fukushima accident has had an impact on the cost of nuclear power, increasing it by 20 % in France, due to the additional investments in maintenance and safety (European Environmental Agency 2018b).

Following the Kyoto protocol targets, participating countries were assigned emission reduction target based on the values of the year of 1990 (UNFCCC 2008). Over the period from 1990 till 2016 the EU reduced the CO_2 intensity of electricity generation from 523.5 to 295.0 gCO_2/kWh (by 44 %), whereas Germany achieved a reduction of 33 %, from 665.0 to 440.8 gCO_2/kWh. Nevertheless, Germany is planning to close all its nuclear plants by 2022, which means the loss of 13 % of its total gross electricity production (European Environmental Agency 2018b). Nuclear power plant closing means that others have to contribute a higher share of investments in new power plants, possibly renewable power plants, not only to keep the current CO_2 emission intensity levels but also consequently to reduce them. According to the German Energiewende ('energy transformation') which was announced by the conservative government in 2011, the country plans to reduce the amount of fossil fuels contributing to the energy supply to 20 % by 2050 (Renn and Marshall 2016).

Figure removed due to possible copyright infringements

Figure 3: German electricity generation by source (Evans and Pearce 2016)

A more ambitious target was set by the Bavarian capital Munich, which is planning to produce enough green electricity to power the entire city by 2025. The achievement of this goal would make Munich the first city in the world with more than one million residents, that uses "green electricity" only (SWM 2018). The city is developing and operating hydro power plants, solar technology plants, and geothermal energy plants. Together with the Sustainable NOW project, the city is reducing CO_2 amounts by 9,000 tonnes per year, by the means of the construction of hydro power plants on the Isar River. The reduction of 18,000 tones per year has been achieved by a large solar plant project with Gehrlicher Solar AG and the City of Munich (Lowe 2011). The city and its power providers (i.e. SWM) are investing in offshore power plants, as the regional potential is limited (SWM 2018). Munich and its partners have acquired 9 wind farms in Havelland and this contributes 280,000 tonnes of CO_2 reduction per year (Lowe 2011). The electricity sector in Bavaria is operated by various energy providers which own power plants in the region and in EU countries. Munich power provides own offshore wind parks in the North Sea, Poland, Croatia, France and photovoltaic plants in Germany and other lands. The power generated by a power plant is fed into the grid where power consumers draw it from. Therefore, each kilowatt hour produced by renewables and fed into the grid reduces the total carbon intensity of the electricity used (SWM 2018).

Currently there is no possibility to obtain the data necessary to estimate the carbon intensity of the electricity consumed in Munich. The amount of energy consumed and produced varies according to the time of the day as well as the carbon intensity, amounts of produced pollutants and gases. For this study, the electricity mix was estimated based on the capacities of power plants located within the Bavaria region (list of power plants located in the Bavarian region can be found in Appendix A). In total, there are 9 electricity providers which are running nuclear, gas, oil, hydro, coal, waste, biomass and pumped storage power plants in the Bavaria region. The sum of maximum power capacity produced is 6,049.6 MW of electricity, where the share of renewables is 12.03 % and the share of nuclear energy is 44.60 %. Depending on the type of power plant, the amounts of produced emissions and pollutants differ (own calculations from Fraunhofer ISE 2019). The following table contains the information about power plants' capacities, depending on type, and related amount of produced $kgCO_2$ and $kgNO_x$ per kWh (Table 1).

Energy source	NO_x, kg/kWh	CO_2, kg/kWh	Capacity, MW
Uranium	0.0001	0.0080	2,698.0
Gas	0.0007	0.4000	1,432.0
Oil	0.00275	0.9000	386.0
Hydro	0.000002	0.0050	653.6
Coal	0.0022	1.0700	805.0
Pumped storage	0.000002	0.0050	22.0
Waste	0.00245	0.3790	47.0
Biomass	N/A	N/A	6.0
Total			6,049.6

Table 1: Energy sources and related emissions of Bavarian power plants (Kessler 2012, own calculations from Fraunhofer ISE 2019)

The data for the amounts of CO_2 and NO_x released by electricity generated by pumped storage was assumed to be the same as the values for electricity production at hydraulic power plants. The data regarding the emissions produced by biomass burning strongly varies by the region and the biomass composition, i.e. forest, agricultural/domestic residues, dried animals waste (Hastings, Levy, and Carmichael 2000). During their life-cycle, plants store CO_2 though photosynthesis. During the heating process at the power plant, the stored CO_2 is released back to the atmosphere. Therefore, biomass burning is not carbon neutral (Deutscher Bundestag 2007). Unfortunately, there is no data available regarding the emissions from biomass burning power plants in Munich.

3 Methodology

This chapter provides the overview of UAM integration in MATSim and details of emission calculation of all travel modes used in MATSim.

3.1 MATSim and UAM Extension

The purpose of this study is to estimate the daily amounts of CO_2 and NO_x emitted by different transportation modes in Munich. The investigated scenarios can be divided into two groups: with and without UAM. The base scenario without UAM includes the following transportation modes: private cars, buses, trams, underground trains, suburban and regional trains. The second scenario contains the same modes and integrated UAM as well.

The simulation is conducted using an open-source framework for implementing large-scale agent-based transport simulations, MATSim (Multi-Agent Transport Simulation), programmed in Java (Horni, K. Nagel, and K.W. Axhausen 2016). The 5 major stages of MATSim simulation are: initial demand, execution, scoring, replanning and analysis. The iterative parts of MATSim execution loop (MATSim cycle) are Execution (mobility simulation, Mobsim), Scoring and Replanning (Figure 4). Over the iteration process agents score points, aiming to achieve higher score by evolving and optimizing their plans. Eventually, co-evolutionary algorithm leads to a stochastic user equilibrium and at that point agents can not further improve their plans.

Figure removed due to possible copyright infringements

Figure 4: MATSim execution loop (Horni, K. Nagel, and K.W. Axhausen 2016)

MATSim is designed to trace the daily schedules of synthetic travelers' decisions (Horni, K. Nagel, and K.W. Axhausen 2016). These schedules contain information about activity types, start and end times, locations, etc (Ziemke, Kai Nagel, and Moeckel 2016). The scheduled trips are realized via available transportation modes, road network or public transport.

The UAM is designed to operate on demand, and the DVRP extension (Dynamic Vehicle Routing Problem) is a basis for UAM extension for MATSim. Nevertheless, UAM extension differs from DVRP extension for ground vehicles operating on demand since it requires specific VTOL infrastructure, urban space and aerial network management, and an air vehicle fleet with specification of capacity, speed, range, etc. The UAM extension consists of three main blocks: the UAM infrastructure, vehicles, and airspace usage (Rothfeld, Balac, Kay O. Ploetner, et al. 2018).

UAM infrastructure consists of a number of vertiports (UAM stations), each of which has a unique identifier, specific location, and capacity for simultaneous VTOL placement. Each UAM station consists of one ground- and one flight-access node; these nodes are connected by a station link. The ground access node connects the UAM station with a conventional ground network, whereas the flight-access node connects the UAM station to one or more flight level nodes positioned above the flight access node. The flight level nodes are transition points between vertical and horizontal flight and connect the UAM station to UAM network. Similarly, each *UAM vehicle* has a unique identifier, initial location, UAM station where vehicle is parked overnight, seat capacity, cruising and VTOL speeds, operating range and operating time. The *UAM network* consists of nodes and links, where nodes are characterized by a unique identifier, location and height (i.e. x, y, and z coordinates). Links of the *UAM network* are each assigned a unique identifier, including specified origin and destination nodes, length, throughput capacity and maximum allowed/possible speed during cruise flight. The UAM network modelled being fixed with one lane in which only UAM modes are allowed (Rothfeld, Balac, Kay O. Ploetner, et al. 2018).

3.2 Munich City Scenario

The study area of this thesis is Munich, the administrative center of Bavaria. The year 2011 is taken as the base year, with the population of 1.3483 million at that time (Population City 2015). The modelled day-to-day travel behaviour is based on the household travel survey "Mobilität in Deutschland" (MID) from 2008 (Follmer et al. 2010). This survey has been carried out approximately every 5 years since 1970. The survey contains socio-demographic and mobility information of individuals within different population groups and regions. It provides information like gender, income, living area, information regarding travel choices, etc. The households participating in the survey are selected carefully, still this selection is random in order to ensure the reliability of the information gained and its accuracy to represent the country's demographic. (Follmer et al. 2010).

The survey data was adapted to represent the travel behavior of the entire Munich population using MITO, Microscopic Transportation Orchestrator (Moeckel et al. 2019). The output data contains information regarding all the trips performed during the day. Each trip includes the information of its origin and destination, its purpose, travel mode used. Each trip has an ID and one person can have multiple trips during the day. The travel modes are differentiated between walking, biking, public transport use, and car trips, with differentiation between driver and passenger (the data provided by the professorship of Modeling Spatial Mobility).

It was estimated that in an average day there are around 15 million trips took place. To simulate this amount of trips, high computational power as well as long run times are required. Since this thesis focuses on total daily amounts of gases produced, and not on agents' travel behaviour, running 5 % of randomly sub-sampled trips is sufficient. At this point, it is important to downsize the Munich road network capacity to achieve equivalent with selected 5 % trips (forthcoming Llorca and Moeckel 2019). The storage and flow capacity factors are estimated to be 0.106 and 0.050 respectively. According to the forthcoming Llorca and Moeckel 2019 a high number of iterations coupled with the use of a relatively small 5 % scale factor, would not significantly affect final results. Therefore, the number of iterations was set to 20. The MATSim model for this thesis is provided by BauHaus Luftfahrt e.V..

In addition to the scenarios with and without UAM, the scenarios including technology improvements were calculated. In the initial scenario no changes were considered. For Scenario 1 and Scenario 2 it was assumed that 50 and 100 % respectively of all car trips were driven by EVs. The Scenarios 3 and 4 were calculated assuming changes in electricity production, anticipating that 50 and 100 % of electricity respectively were generated from renewable sources. Because the current Bavarian electricity mix used in this thesis consists of almost 11 % electricity generated by hydro-power stations, for Scenarios 3 and 4 the increased shares of renewables were assumed to be generated by hydro-power stations as well. Scenario 5 was calculated based on improvements in the public bus fleet, assuming that the amount of released emissions was reduced by 50 %.

3.2.1 Status quo (baseline)

The baseline scenario has no air transportation option within the city. The travel demand data was generated using MITO and the results were used as an input data for MATSim. For this study, agents ability to select between different transportation modes was disabled. Moreover, the abilities to reschedule or to cancel trips were excluded as well. Nevertheless, agents were able to select between different routes.

The simulation output results contain information regarding all trips made during the day. Specifically, the output data contains information regarding each trip origin and destination, as well as trip distance, travel time, and many others. This output data is used for the following emission calculations.

3.2.2 UAM integration

As mentioned earlier, there are currently no specific guidance regarding UAM operations within cities. For this thesis it was assumed that UAM was operating between vertiports, the selected points of interest in Munich. One of the ways to determine the suitable locations for UAM stations can be found in Rothfeld, Balac, Kay O Ploetner, et al. 2018. For this study, the locations of 8 selected UAM Stations in Munich are shown on Figure 5. As seen, the UAM network has a direct point-to-point structure, where each station can be reach from any other station in the network.

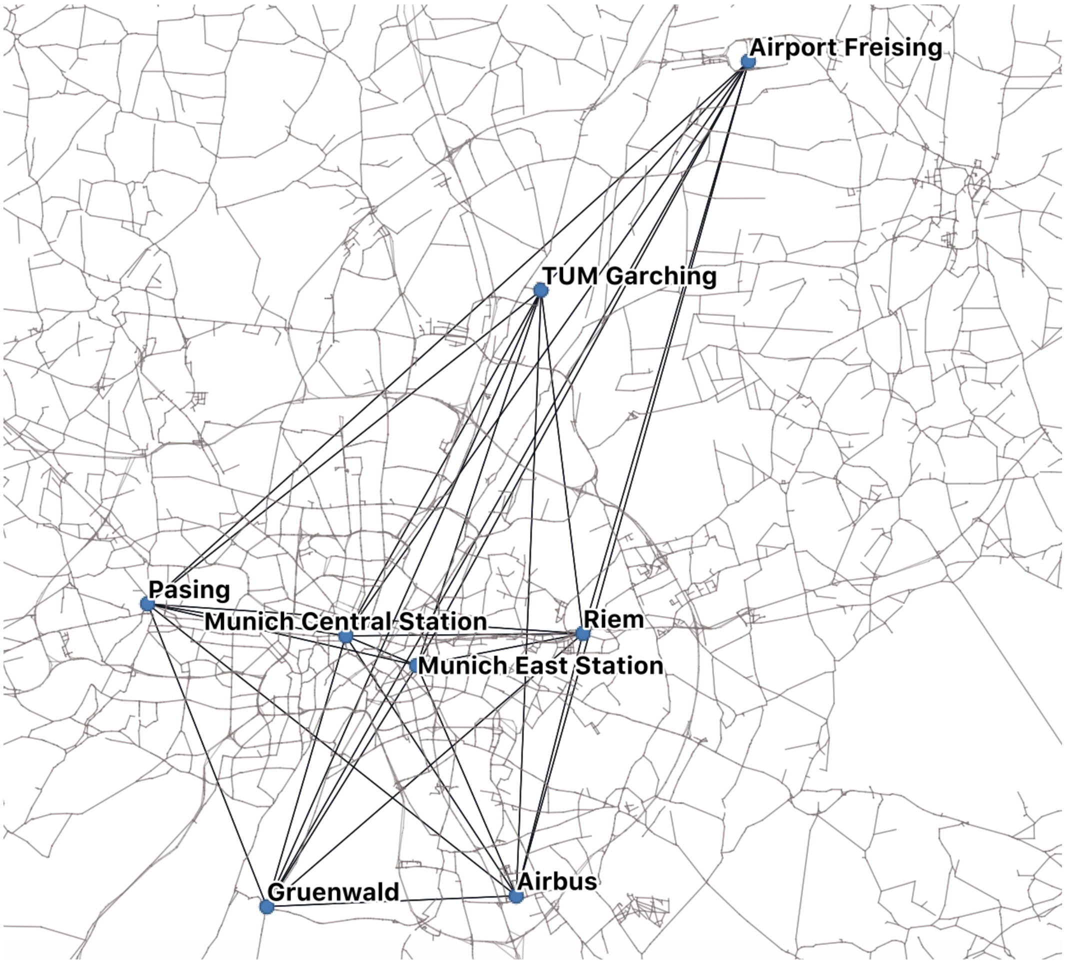

Figure 5: The locations of UAM stations in Munich

For this study the UAM was integrated to operate without any constrains. The VTOL fleet was not limited to specific number of vehicles. It means that there is always an air vehicle available at the requested station, thus agents did not wait for an available vehicle to arrive to the requested UAM station.

Since the ability to initially select between different transportation modes was disabled, prior to the simulation, UAM mode was assigned to selected trips that meet the previously established criteria. Trips considered to be suitable to use UAM were defined based on their distances to/from UAM station and trip length. The general assumption has been made that the sum of the distances to and from UAM stations should not be longer than one third of the total trip length (Figure 6). This selection enabled a reasonable assignment of UAM trips. Following this selection, it was assumed that agent spent at least two thirds of its complete trip distance in UAM vehicle and air vehicle was the main travel mode in this case. In this work the UAM was integrated to substitute for ground car and public transport trips. It was assumed that UAM was not a competitor for walking and biking travel modes. That is why the trips commuted by these modes were not considered as potential the UAM trips and were excluded from UAM trip selection.

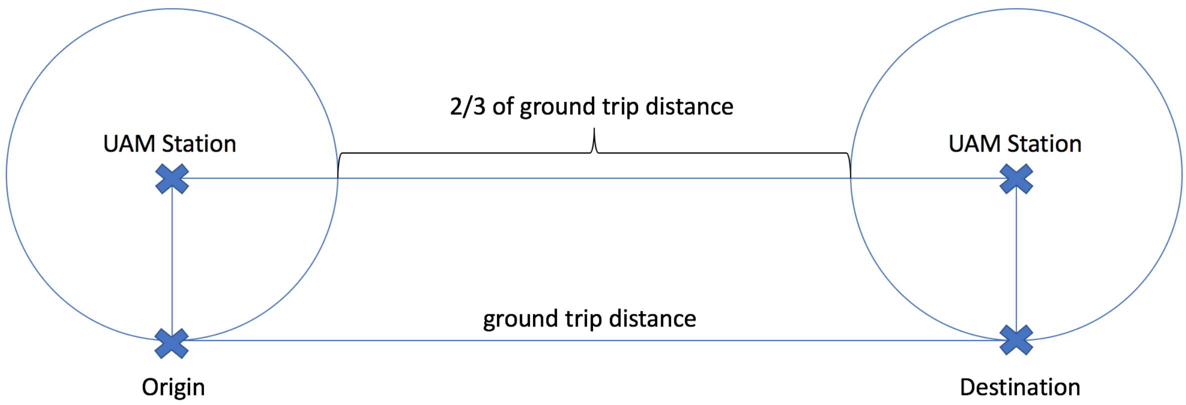

Figure 6: Trip requirement for UAM consideration

Even though, the mode choice was excluded, in order to reach UAM station agents could choose between walking, public transport and car modes. Based on this, it was assigned that if the distance from agent's origin or destination location to the UAM station was shorter than 500 meters, only walking mode was available. For distances longer that 500 meters agents could choose between public transportation and car modes (Schuessler and Kay Axhausen 2008, Burian et al. 2018).

3.3 Emission Calculation

Transportation sector is responsible for high amounts of released gases and pollutants into the atmosphere. One of the most known GHG is CO_2. It is known to contribute extensively to global GHG levels due to the high share of anthropogenic processes that produce enormous amounts of CO_2 gases. It is not a surprise that many articles, estimating impacts of new transportation solutions, are reporting on CO_2 emissions (Hawkins, Gausen, and Strømman 2012, Requia et al. 2018). Including aviation and shipping, transportation sector is responsible for 23 % of CO_2 emissions globally (IEA 2016, IEA 2017). Regarding the air pollutants, NO_x ($NO_x = NO + NO_2$) is the most reported among them (Hawkins, Gausen, and Strømman 2012, Requia et al. 2018). It does not contribute to GHG levels but affects the air quality. Specifically, NO_x reacts in the atmosphere with sun light and NMVOC (non- methane volatile organic compounds) to form ozone (O_3). Tropospheric ozone is an air pollutant, whereas stratospheric ozone protects from ultraviolet radiation.

The amounts of released NO_x emissions by aviation sector were investigated in various studies since 1970s, even though it contributes only 1 – 2 % to the total amounts of NO_x emissions from both natural and androgenic sources (Hidalgo and Crutzen 1977, D. S. Lee et al. 2010, Myhre et al. 2011, Gauss et al. 2006, Frömming et al. 2012, Skowron, D. Lee, and León 2013). Despite the relatively small share, aircraft NO_x emissions are released in the upper troposphere level and lower stratospheric regions, where it has longer life-time, allowing for NO_x and O_3 accumulation (Gauss et al. 2006).

Although the high number of different exhaust gases released from the transportation sector, this study focuses on the amounts of produced CO_2 and NO_x emissions from transportation in Munich. Other GHGs and air pollutants, as well as noise emissions are important for environmental evaluation. Nevertheless, they are excluded from calculations, due to the limited amount of time and data availability.

As explained in the sub-chapter 3.1, the MATSim was used to model agents transportation behavior in Munich. The output data contains the information about each trip that took place, regarding modes used and distances covered. This gives an ability to calculate amounts of released pollutants from each trip. Different transportation modes that were in use during the simulation are included in the calculations, and each of them has a specific emission factor. Multiplication of trip distance and selected mode emission factor provided result of amounts of produced CO_2 and NO_x for each specific mode. Due to the variety of modes, different approaches were used in order to estimate an emission factor for each of them.

In this work, an approach estimating the amounts of produced pollutants based on passenger kilometers travelled and it is preferred above vehicle kilometers driven. Initially, emission estimation based on the vehicle kilometers driven was not feasible to conduct due to the insufficient amount of data required. Specifically, there was lack of data regarding different public transportation modes. For vehicle kilometer driven estimation, emission factor should reflect different aspects such as detailed information regarding vehicle type used and number of wagons on specific route regarding on/off peak hours, vehicle speed, passenger occupancy, etc. The passenger kilometers travelled approach is beneficial for this study. With the strong focus on passenger mode choice, it was important to know the chain of modes used by each agent. By assigning UAM modes to the selected trips, the distance driven earlier by conventional mode was excluded from calculations. This approach would not be feasible working with mode kilometers travelled. In that case, when agent changed current public transportation mode to UAM, this would not change the amount of public transportation related emissions. This approach would only add additional emissions related to UAM operation to the total traffic related emissions. As this study focuses on different scenarios regarding the introduction of a new mode, it was crucial to see the impact of shift of each selected agent from the current mode to UAM mode.

As mentioned, the emission factor is a crucial variable for the emission estimation. For this study, car, bus, tram, underground train, sub-urban train and regional trains were modelled and each of these modes has a specific emission factor. The MATSim output data contains the information regarding all trips taking place during the simulated day and for car trips, it differentiates between driver and passenger. For BaU scenarios car passengers kilometers driven were excluded from emission calculation, taking into account only car driver related emissions. Nevertheless, after UAM implementation, in case of shift of car passenger to UAM vehicles, this shift contributed to UAM related emissions and it was included in the emission calculation. The detailed explanation of emission factor estimation for each mentioned mode is presented in the following sub-chapters. Walking and biking modes were available for agents to use and assumed to produce zero CO_2 and NO_x emissions.

3.3.1 Electricity Mix

As mentioned earlier, the Bavarian electricity mix was used for the estimation of CO_2 and NO_x released in order to generate the required amount of electricity for electrically powered modes. It was assumed that each power plant within the Bavarian region works on its full capacity. Regarding the share, each power plant contributes to the total energy production, the amounts of produced emission were calculated proportionally. As an example, power plant that generates electricity using uranium contributes 44 % to the sum of total power plant capacities and the emission factor for power plant that uses uranium is 8.00 gCO_2/kWh (Table 1). Following this, its contribution to the total emission factor from all power plants considered to be 3.52 gCO_2/kWh. Following this procedure, contribution shares were calculated for each power plant considered in this work for CO_2 and NO_x emissions. Afterwards, the estimated shares of each power plant contributing regarding the selected pollutant or gas were summed up to calculate the total amount of emissions produced when all power plants are working on their full capacities. (*Electricity Emission Factor* - EF_{El}, kg/kWh).

The additional scenarios were calculated as well, assuming the electricity mix consisting of 50 % and 100 % of electricity generated by renewable resource. To estimate the new emission factors for the electricity mix consisting of 50 % of electricity generated from renewable sources, the overall capacity of selected power plants was divided by two. The result is new power plant capacities for each group of power plants, using renewable and non-renewable sources. Afterward, using the new capacity of power plants, a factor was derived that shows how much the capacity of power plants using non-renewable sources should be reduced. And for power plants using renewable sources, the factor shows how many times its capacity must be increased, in order to keep the current total power capacity level (Table 2). Proportional to the new capacities, new emission factors for CO_2 and NO_x were calculated. The emission calculation process was explained earlier in the beginning of this sub-chapter. The amount of 6 kWh of electricity generated by biomass burning was excluded from the total power plant capacity calculation, due to the lack of data regarding the biomass mix.

Total power plant capacity - 6,043.6 kWh	
Power plants working with non-renewable sources	**Power plants working with renewable sources**
Current capacity - 5,321.0 kWh	Current capacity - 722.6 kWh
New capacity - 3,021.8 kWh	New capacity - 3,021.8 kWh
Factor - 0.6	Factor - 4.2

Table 2: New power plants capacities where 50 % of the electricity produced comes from the renewable sources

Similarly, the factor for power plants was calculated for the scenario where electricity is generated by renewable sources only. The factor was estimated to be 8.4 and the capacities of all power plants running on renewable electricity were multiplied with this factor. The following table contains emission factors for each of the scenarios (Table 3).

Current electricity mix		**50 % of renewables in electricity mix**		**100 % of renewables in electricity mix**	
CO_2, kg/kWh	NO_x, kg/kWh	CO_2, kg/kWh	NO_x, kg/kWh	CO_2, kg/kWh	NO_x, kg/kWh
0.30186	0.00070	0.18410	0.00047	0.02933	0.00016

Table 3: Bavarian electricity mix

(own calculations from Fraunhofer ISE 2019, Kessler 2012 and O'Brien 2006)

These CO_2 and NO_x emission factors were used in further calculations of emissions related to the operation of modes that use electricity as source of energy.

3.3.2 Air Vehicle

In this study purely electric vehicles were considered to operate UAM in Munich. The longest distance between two UAM stations is 39 km and based on this distance the Multicopter Heavy was selected as the air mode to perform the flights. This vehicle flight profile is rectangular, and vehicle reaches a cruise altitude of 300 meters. The multicopter's design has 18 rotors with the dimension of 9.15 meters by 9.15 meters. The high number of rotors and their large disk area enables excellent hover efficiency and low rotor noise.

Figure removed due to possible copyright infringements

Figure removed due to possible copyright infringements

Figure 7: Multicopter Heavy (Michael Shamiyeh, Rothfeld, and Mirko Hornung 2018)

These vehicles are charged with electricity and the Bavarian average electricity mix was used in calculations. The electricity emission factors for CO_2 and NO_x are 301.86 g/kWh and 0.70 g/kWh respectively. For the scenarios with 50 % and 100 % of electricity generated from renewable sources emission factors change accordingly to the data in Table 3. The vehicle energy consumption per km varies regarding the distance traveled. Table 4 contains the information of MC Heavy energy consumption when one passenger is on board. In order to avoid bias in the calculations an interval was assigned to each trip distance.

The output results from MATSim simulation contain information regarding each flight origin and destination stations, trip length. Based on the distance travelled by air vehicle and following corresponding intervals, energy consumption was assigned to each flight (Table 4). Important to mention that air vehicle energy consumption depends on the number of passengers it carries. Despite the fact that MC Light can carry up to four passengers, the number of passengers that can be simultaneously on board was assigned as one.

Distance, km	**Energy consumption, kWh**	**Assigned interval, km**
0	7.51	0 - 2.5
5.0	10.86	2.5 - 7.5
10.0	14.25	7.5 - 12.5
15.0	17.67	12.5 - 17.5
20.0	21.12	17.5 - 22.5
25.0	24,60	22.5 - 27.5
30.0	28.10	27.5 - 32.5
35.0	31.61	32.5 - 37.5
40.0	35.11	37.5 - 42.5

Table 4: Energy consumption of Multicopter Heavy (data provided by BauHaus Luftfahrt e.V., based on methodology by Michael Shamiyeh, Rothfeld, and Mirko Hornung 2018)

The Energy Consumption of each flight was summed up to estimate the total amount of energy UAM operation consumed during the simulated day. Knowing the amount of energy consumed, it is possible to calculate the amounts of CO_2 and NO_x emissions released by power plants in order to generate required amount of electricity (Eq. 1).

$$Emissions_{UAM} = EnergyConsumption_{UAM} * EF_{El}, \tag{1}$$

where
$Emissions_{UAM}$ - amounts of produced pollutant or gas by power plants due to UAM operation, $[kg]$;
$EnergyConsumption_{UAM}$ - amount of energy consumed by UAM operation, $[kWh]$;
EF_{El} - electricity emission factor, amount of gas/pollutant released by producing 1 kWatt of electricity, $[kg/kWh]$.

3.3.3 Conventional and electric cars

Ground transportation modes available in MATSim for Munich scenario can be divided into two groups as public and private modes. The private modes were walking and biking (both were considered to produce zero emissions), and car mode. There are many different types of cars in Munich. Regarding the scope of this research heavy duty vehicles, such as delivery trucks were not included in the MATSim simulation, and agents perform daily activities using LDVs. Unfortunately, there was a lack of information regarding types of LDVs used in Munich. Based on the statistical data from Kraftfahrt-Bundesamt from 24.01.2011, the number of LDVs registered in Germany was 42.3 million. Out of this, the shares of gasoline and diesel powered vehicles were 72.1 % and 27.9 % respectively. These shares were used to proportionally separate the number of car trips from simulation results into groups of gasoline- and diesel-powered vehicles. The number of hybrid and electric vehicles according to Kraftfahrt-Bundesamt was estimated to be 40,000 units, which corresponds to 0.095 % from the total number of LVDs (Kraftfahrt-Bundesamt 2018). The relatively small share of battery vehicles was neglected in the initial emission scenarios calculations.

Diesel and gasoline powered vehicles release different amounts of CO_2 and NO_x per km. The data regarding emission factors for gasoline- and diesel-powered vehicles was taken from HBEFA for the year 2010 (Table 5):

Gasoline-powered vehicle		**Diesel-powered vehicle**	
CO_2, g/km	NO_x, g/km	CO_2, g/km	NO_x, g/km
185.295	0.166	160.035	0.749

Table 5: Emission factors of light-duty vehicle operation (Umweltbundesamt n.d.)

This data includes only emissions released per kilometer travelled and does not include vehicle start emissions. These emission factors were averaged for different road categories, road gradients and traffic states (stop&go, free flow, saturated and dense). These emission factors were used for the calculation of amounts of released CO_2 and NO_x emissions from all car trips (Eq. 2).

$$Emissions_{CV} = EF_{CV} * D_{CV}, \tag{2}$$

where

$Emissions_{CV}$ - total amount of released gases from conventional vehicle, $[kg]$;

EF_{CV} - CV emission factor regarding fuel used, $[kg/km]$;
D_{CV} - sum of distances driven by conventional vehicle, $[km]$.

For the future scenarios higher shares of EV were calculated. For Scenario 1 it was assumed that 50 % of all car trips were driven by EVs. Following this, the total distances travelled by car were divided into 3 groups as gasoline, diesel and electric vehicles with the respected shares of 36.05 %, 13.95 % and 50 %. For Scenario 2, all of the car trips are assumed to be performed with EVs.

As mentioned earlier, EV consumes less energy while driving within urban areas compared to its energy consumption in rural areas. For this study, it was assumed that all car trips took place in urban areas and EV consumed 0.168 kWh/km (Wu et al. 2015). Considering the current Bavarian electricity mix, following the specified EV energy consumption the EV's emission factors are 0.05058 $kgCO_2/km$ and 0.00012 $kgNO_x/km$. The total amounts of released CO_2 and NO_x emissions due to EV operation were calculated by the following formula (Eq. 3):

$$Emissions_{EV} = EF_{EV} * D_{EV}, \tag{3}$$

where
$Emissions_{EV}$ - sum of emissions related to EV operation, $[kg]$;
EF_{EV} - EV emission factor regarding the energy consumption of EV, $[kg/kWh]$;
D_{EV} - sum of distances driven by EVs, $[km]$.

Important to mention, the MATSim results do not contain the information regarding the distances travelled by car to and from UAM stations. The beeline distances were calculated based on coordinates of origin, destination of activities, and UAM stations' origins and destinations. Afterwards, the estimated distance was multiplied with the detour index 1.417 (Boscoe, Kevin, and Zdeb 2012).

3.3.4 Bus

One of the public transport modes used in MATSim Munich scenario was the bus mode. Public bus fleet in Munich is operated by Münchner Verkehrsgesellschaft, MVG (MVG 2019). The fleet consists of 310 vehicles among them are 22 trailer buses, 225 articulated buses and 63 conventional buses. Additionally, 199 buses are being operated by private partners on behalf of MVG. The information regarding subcontractors' bus types and models was not available. Following this, only the bus fleet belonging to MVG, was considered in this study (MVG 2014).

According to European Environmental Agency 2002 the German bus occupancy rate was 18 passengers per vehicle. The emission factor for public bus was taken from HBEFA database for the year 2010. Considering only the operational phase of vehicle, emission factors are presented in Table 6.

Local bus		**Regional bus**	
CO_2, g/km	NO_x, g/km	CO_2, g/km	NO_x, g/km
1,139.005	8.341	762.74	6.698

Table 6: Emission factors of local and regional diesel-powered buses (Umweltbundesamt n.d.)

Unfortunately, it was not known which bus types operate on regional routes and which bus types operate on local routes. Hence, the emission factors of both bus types were averaged to 950.8725 gCO_2/km and 7.5645 gNO_x/km. Having an average of 18 passengers on board, the emission factors per passenger kilometer were 52.826 gCO_2/pkm and 0.420 gNO_x/pkm. These emission factors were taking into account for bus related emission calculations. They were assumed to be reasonable compared to the data available for bus emission factor in Sweden which is 70 gCO_2/pkm, the U.S. bus emission factor of 181 gCO_2/pkm and with 107.3 gCO_2/pkm bus emission factor in the U.K. (Network for Transport Measures 2018, Hodges 2010, AEA 2008). Regarding the NO_x emission factor of 0.420 gNO_x/pkm, it is as well assumed to be reasonable compared to the study by (Yu, T. Li, and H. Li 2015) where, depending on the passenger load, gNO_x emission factor varies from 0.42 to 1.1 gNO_x/pkm.

The calculation of bus related emissions were done using the following equation (Eq. 4):

$$Emissions_{Bus} = EF_{Bus} * D_{Bus}, \tag{4}$$

where
$Emissions_{Bus}$ - sum of emissions related to bus operation, $[kg]$;
EF_{Bus} - bus emission factor emission factor for CO_2 and NO_x, $[kg/pkm]$;
D_{Bus} - sum of distances traveled by bus, $[km]$.

Scenario 5 estimates public bus fleet improvement, considering the future possibilities when bus related amounts of emissions could be twice lower than current levels. For this scenario, the amount of released CO_2 and NO_x emissions from the public bus operation were halved.

3.3.5 Tram

Tram operation began in Munich in 1876 with a horse drawn tram on rails. As well as the bus operation, tram operation in the city is provided by MVG. Among bus and underground train trips, trams carry the lowest number of passenger per year (119 million passengers in 2015). The tram rail network has a length of 79 km and covers 166 tram stations (MVG 2019). Munich tram fleet consists of 113 vehicles and their passenger capacity characteristics are summarized in Table 7.

Tram type	**Discription**
T1	69 seats and 147 stand places
TZ	two parts assemble – 29 seats and 72 stand places three parts assemble – 47 seats and 109 stand places four parts assemble – of 65 seats and 150 stand places
S1	75 seats and 146 stand places
R3	67 seats and 151 stand places
R2	58 seats and 99 stand places
P	40 seats (+ 42 seats in sidecar; 82 seats in total) 70 stand places (+ 75 stand places in sidecar; 145 stand places in total)

Table 7: Trams operating in Munich (MVG 2014)

According to the Forschungs Informations System, in Germany tram requires 12,5 kWh per 100 passenger-kilometers on average (Forschungs-Informations-System 2011). Considering the BaU scenario, Scenario 3 and Scenario 4, Table 8 contains the emission factors used for tram emission calculations for each of mentioned scenarios.

BaU Current electricity mix		**Scenario 3 50 % of renewables in electricity mix**		**Scenario 4 100 % of renewables in electricity mix**	
CO_2, kg/pkm	NO_x, kg/pkm	CO_2, kg/pkm	NO_x, kg/pkm	CO_2, kg/pkm	NO_x, kg/pkm
0.03773	0.00009	0.02301	0.00006	0.00367	0.00002

Table 8: Emission factors of tram operation

The total amounts of CO_2 and NO_x released by tram operation were calculated by the following equation (Eq. 5):

$$Emissions_{Tram} = EF_{Tram} * D_{Tram}, \tag{5}$$

where
$Emissions_{Tram}$ - total amount of released gases related to tram operation, $[kg]$;
EF_{Tram} - tram emission factor for CO_2 and NO_x, $[kg/pkm]$;
D_{Tram} - sum of distances traveled by tram, $[km]$.

3.3.6 U-Bahn (Underground Train)

Underground train operation in Munich is provided by MVG as well. This public transportation mode carries the highest amount of passengers per year (398 passengers in 2015). Its fleet consists of 562 underground carriages, and its network length is 95 km, servicing 100 stations (MVG 2014). The underground train fleet consists of the carriage types presented in Table 9.

Subway type	**Discription**
Train C2	220 seat and 720 stand places; in use since 2016
Train C	252 seat and 660 stand places; in use since 2002
Double railcar B	98 seat and 192 stand places; in use since 1987 - 1995 (prototype 1981)
Double railcar A	98 seat and 192 stand places; in use since 1970 - 1984 (prototype 1967)

Table 9: Subways operating in Munich (MVG 2018)

The underground train fleet contains electric motor ,hence, it requires electricity for its operation. An average German underground train requires 11.6 kWh per 100 passenger-kilometers (Forschungs-Informations-System 2011). Taking into account the current electricity generation emissions for base scenario and higher share of renewables in future scenarios, CO_2 and NO_x emission factors for each of scenarios are summed up in Table 10.

BaU Current electricity mix		**Scenario 3 50 % of renewables in electricity mix**		**Scenario 4 100 % of renewables in electricity mix**	
CO_2, kg/pkm	NO_x, kg/pkm	CO_2, kg/pkm	NO_x, kg/pkm	CO_2, kg/pkm	NO_x, kg/pkm
0.03502	0.00008	0.02136	0.00005	0.00340	0.00002

Table 10: Emission factors of underground train operation

These emission factors were used for the tram emission calculations. The data regarding underground train ride distances was summarized and amounts of related gases were calculated by the following equation (Eq. 6):

$$Emissions_{UT} = EF_{UT} * D_{UT}, \tag{6}$$

where
$Emissions_{UT}$ - total amount of released gases related to underground train operation, $[kg]$;
EF_{UT} - underground train emission factor for CO_2 and NO_x, $[kg/pkm]$;
D_{UT} - sum distances travelled by underground train, $[km]$.

3.3.7 Sub-Urban and Regional Trains

Besides buses, trams and underground trains operating within the city, longer distances in sub-urban areas are covered by sub-urban train – S-Bahn ("Stadtschnellbahn", German). The sub-urban train network consists of 8 lines servicing 150 stations. The total length of S-Bahn network is 530 km. Sub-urban train train fleet consists of 238 vehicles Series ET 423 and 15 vehicles series ET 420 with a maximum speed of 140 km/h (Deutsche Bahn 2019b). The current sub-urban train is operated by electric motor and was estimated to require 22 Wh/pkm (Bahn 2018). Regarding the current electricity mix and the proposed scenarios with higher share of energy derived form renewable sources, Table 11 contains the emission factors related to sub-urban train operation for each of the scenarios.

BaU Current electricity mix		**Scenario 3 50 % of renewables in electricity mix**		**Scenario 4 100 % of renewables in electricity mix**	
CO_2, kg/pkm	NO_x, kg/pkm	CO_2, kg/pkm	NO_x, kg/pkm	CO_2, kg/pkm	NO_x, kg/pkm
0.00664	0.00001	0.00405	0.00001	0.00065	0.000003

Table 11: Emission factors of sub-urban train operation

These emission factors were used to calculate the amounts emissions released in order to generate the required amounts of electricity for sub-urban train operation (Eq. 7):

$$Emissions_{ST} = EF_{ST} * D_{ST}, \tag{7}$$

where
$Emissions_{ST}$ - total amount of released gases related to sub-urban train operation, $[kg]$;
EF_{ST} - sub-urban train emission factor for CO_2 and NO_x, $[kg/pkm]$;
D_{ST} - sum of distances travelled by sub-urban train, $[km]$.

The further areas were serviced by regional trains. The regional train operation is provided by Deutsche Bahn, and it requires 34 Wh/pkm at the speed over 200 km/h and 21 Wh/pkm at the speed below 200 km/h (Deutsche Bahn 2019a, Bahn 2018). For the purpose of this study the average energy consumption was used, which was estimated to be 27.5 Wh/pkm. Based on this energy consumption the amounts of released CO_2 and NO_x were estimated. Table 12 contains the information about regional train emission factors for the BaU scenario, and Scenarios 3 and 4, which consider electricity composition changes.

BaU Current electricity mix		Scenario 3 50 % of renewables in electricity mix		Scenario 4 100 % of renewables in electricity mix	
CO_2, kg/pkm	NO_x, kg/pkm	CO_2, kg/pkm	NO_x, kg/pkm	CO_2, kg/pkm	NO_x, kg/pkm
0.00830	0.00002	0.00506	0.00001	0.00081	0.0000004

Table 12: Emission factors of regional train operation

According to the Equation 8 the amounts of gases produced due to regional train operation were calculated.

$$Emissions_{RT} = EF_{RT} * D_{RT}, \tag{8}$$

where
$Emissions_{RT}$ - total amount of released gases related to regional train operation, $[kg]$;
EF_{RT} - regional train emission factor for CO_2 and NO_x, $[kg/pkm]$;
D_{RT} - sum of distances travelled by regional train, $[km]$.

4 Results

This chapter contains the results based on the output data from MATSim simulations. The base year is 2011. The amounts of emissions were calculated considering possible improvements in technology: electrification of LDVs and generation of higher shares of electricity by renewable sources, the public bus fleet improvement. Prior to the scenarios with UAM estimation, the chapter provides the analysis of the urban air vehicle Multicopter Heavy selected for this study. Afterwards, the results of UAM scenarios and the differences in amounts emissions are presented. The results presented in this page were scaled up from 5 % to 100 % of simulation size.

4.1 Baseline Scenario

The BaU scenario is the MATSim simulation of one day travel behaviour of a synthetic population. The population's plans were modelled in MITO. This scenario represents currently existing transportation modes. Each agent was assigned to use a specific transport mode and over the iteration processes agents were able to select the best route in terms of distance and time travelled. Any changes such as mode change, departure time change and others were disabled. Based on the output the following figure presents the shares of distances travelled by each of the assigned modes (Figure 8). The share of distances were estimated from the total number of person-kilometers travelled by each of the available modes. As seen from the graph, great majority of distances were travelled by car.

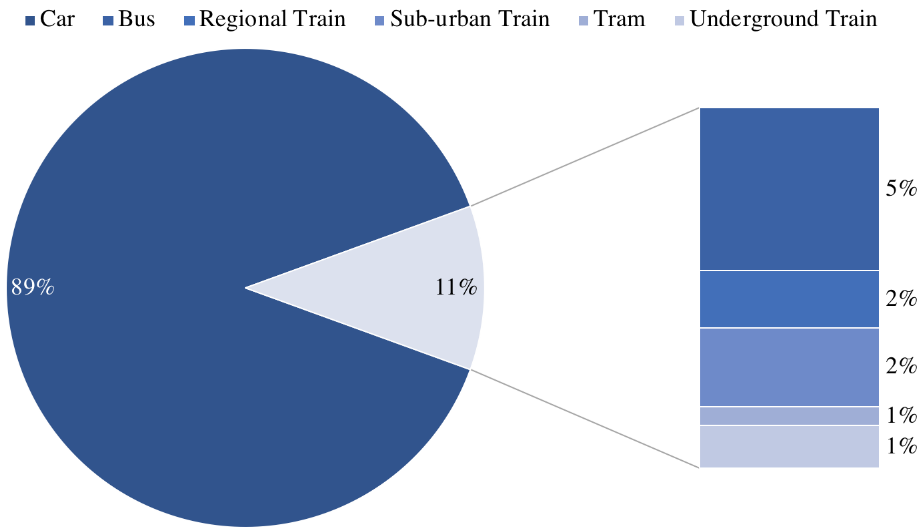

Figure 8: Shares of kilometers travelled by different modes

Based on the results, car trips are responsible for 11,570.46 tonnes of CO_2 and 21.33 tonnes of NO_x emissions released, whereas the public transport in total released 266.05 tonnes of CO_2 and 1.71 ton of NO_x emissions. Considering the total amount of CO_2 and NO_x emissions released during the simulated day, the amount of CO_2 emissions in the base year of 2011 was 3.132 tonnes per capita and the amount of NO_x was 6.24 kg per capita. According to the World Bank data the amount of CO_2 emissions per capita in Germany in 2011 was 9.125 tonnes (Bank 2019). Pursuant to European Environmental Agency 2018a, one third of CO_2 emissions per capita were released by burning of fossil fuels. Based on this, it was assumed that calculated amount of CO_2 emissions were adequate. As for NO_x emissions, according to European Environmental Agency 2016 NO_x emissions in 1990 were estimated to be 39 kg per capita and approximately 50 % of it was emitted by road transport. Seeing the improvements in vehicle technology during the period 1990 – 2011, the calculated results were assumed to be reasonable.

Considering possible future changes in private vehicle types, namely an increased share of EVs on roads, the significant reduction in amounts of CO_2 and NO_x can be achieved. In case, if 50 % of all car trips modelled were driven by EVs the total amount of CO_2 emissions from LDVs could be reduced to 7,427.09 tonnes, and the amount of NO_x emissions to 14.47 tonnes. Even higher emission reduction rates were achieved in case when all car trips were conducted by EVs (detailed calculation results can be found in Appendix B). Table 13 contains the detailed information regarding the amounts of exhaust gases released from the conventional and electric vehicles in selected scenarios. Important to note, emission calculation procedure included only emissions due to the operational phases of vehicles.

	Current fleet composition		**50 % of EV in fleet composition**		**100 % of EV in fleet composition**	
Vehicle type	CO_2, tonn	NO_x, tonn	CO_2, tonn	NO_x, tonn	CO_2, tonn	NO_x, tonn
CV	11,570.46	21.33	5,785.23	10.67	-	-
EV	-	-	1,641.87	3.80	3,283.73	7.60

Table 13: Conventional and electric vehicles emissions (BaU scenario)

Considering the fact that majority of the distances were travelled by cars, the amounts of released CO_2 and NO_x from car operation were the main contributors to total amounts of gases released during the simulated day. The share of CO_2 and NO_x emissions related to public transport operation from total daily amounts were 2.25 and 7.41 % respectively, even though, the share of distances travelled by public transport was 11 %. Scenario 3 considered 50 % of electricity to be generated from renewable sources and the shares of emissions related to public transport operation were reduced to 2.01 % of CO_2 and 7.09 % of NO_x pollutants from total amounts of emissions released. Considering the scenario where 100 % of electricity used by public transport was generated from renewable sources, the shares of related pollutants have shrunken further, accounting for 1.79 and 6.89 % CO_2 and NO_x of total daily levels. Finally, the scenario where public bus fleet emission levels were reduced by 50 %, the reduced share of CO_2 gases dropped to 1.44 % and NO_x pollutants to 4.20 % (detailed calculation results can be found in Appendix B).

4.2 Urban Air Vehicle

Urban air vehicle Multicopter Heavy was selected to operate UAM flights in this study. The information regarding the vehicle's characteristics was presented earlier in Chapter 3. Based on MC Heavy and EV energy consumption, the amounts of related emissions per kilometer were calculated considering the current Bavarian electricity mix. Moreover, the following Figure 9 and Figure 10 present the amounts of released CO_2 and NO_x emissions from MC Heavy, EV, and from conventional diesel and petrol powered LDVs (the exact values can be found in Appendix C).

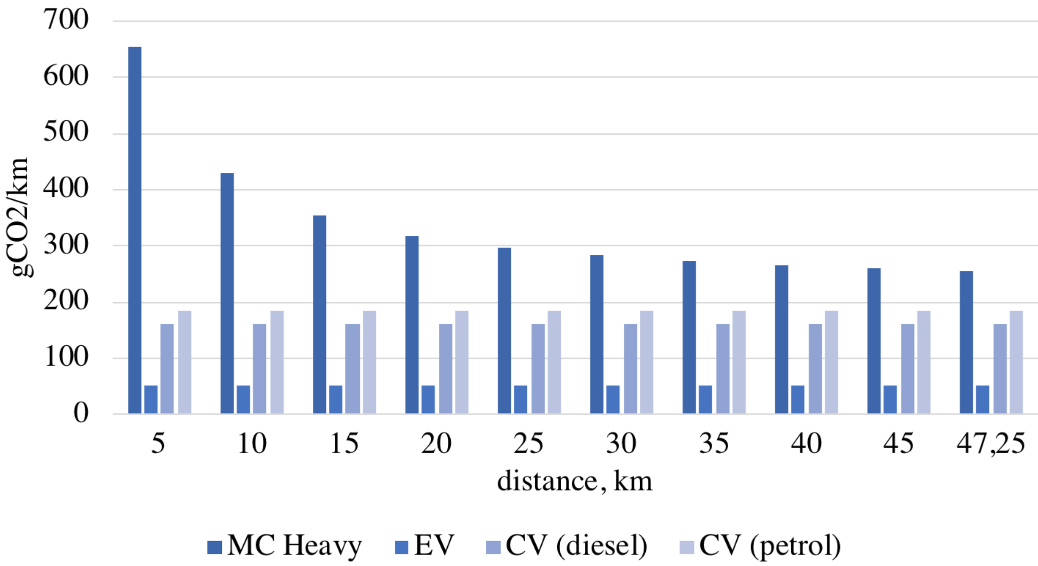

Figure 9: Amounts of CO_2 gases released per kilometer travelled from different transportation modes depending on the trip distance

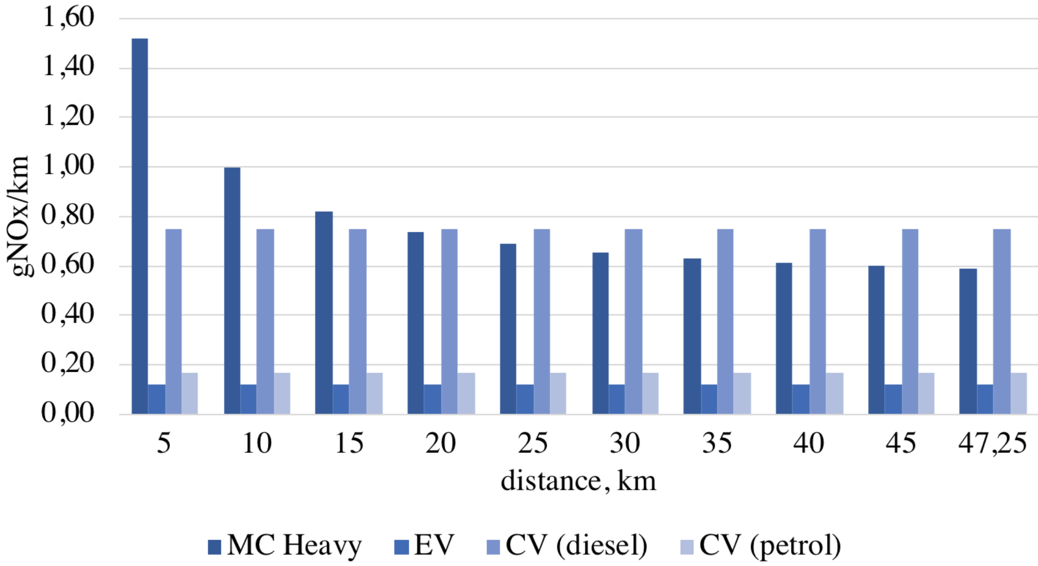

Figure 10: Amounts of NO_x pollutants released per kilometer travelled from different transportation modes depending on the trip distance

As seen from Figure 9, when MC Heavy reaches its maximum flying distance of 47.25 km, the amounts of CO_2 gases per kilometer are comparable to the amounts of CO_2 gases per kilometer travelled by conventional diesel- and gasoline-powered vehicles. From Figure 10 it is clear that the amounts of NO_x emissions from MC Heavy are lower than the amounts of released NO_x emissions from diesel powered vehicle when the considered distance is 20 kilometers or longer.

As estimated earlier in Scenarios 1 and 2, the higher share of EVs in car trips reduces the amounts of emissions released. Scenarios 3 and 4 showed that the higher share of electricity produced by renewable sources reduces the amounts of total emissions as well. The following Figure 11 and Figure 12 present the difference in the amounts of released pollutants and gases considering different electricity mixes (the exact values can be found in Appendix C).

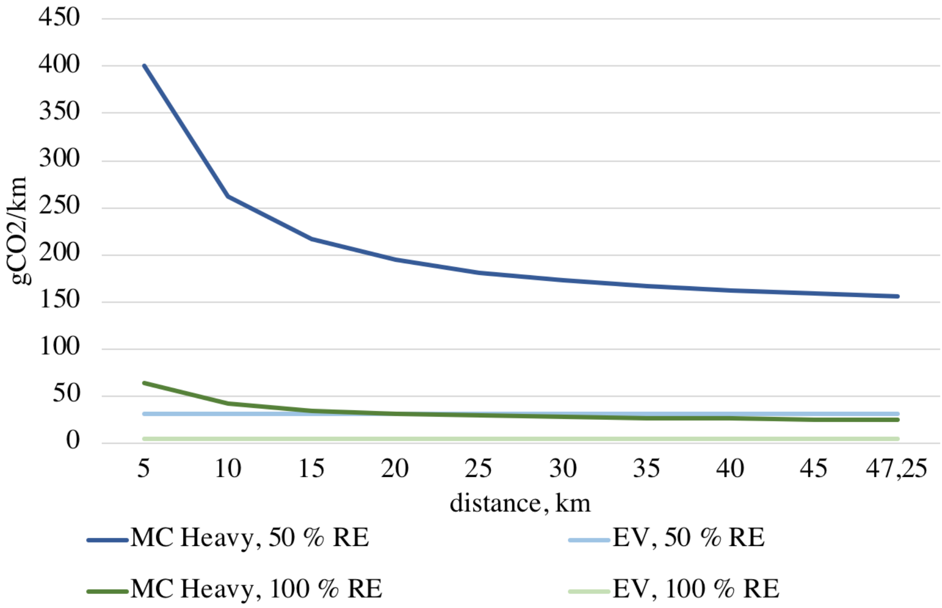

Figure 11: Amounts of released CO_2 gases per kilometer travelled considering different electricity mixes

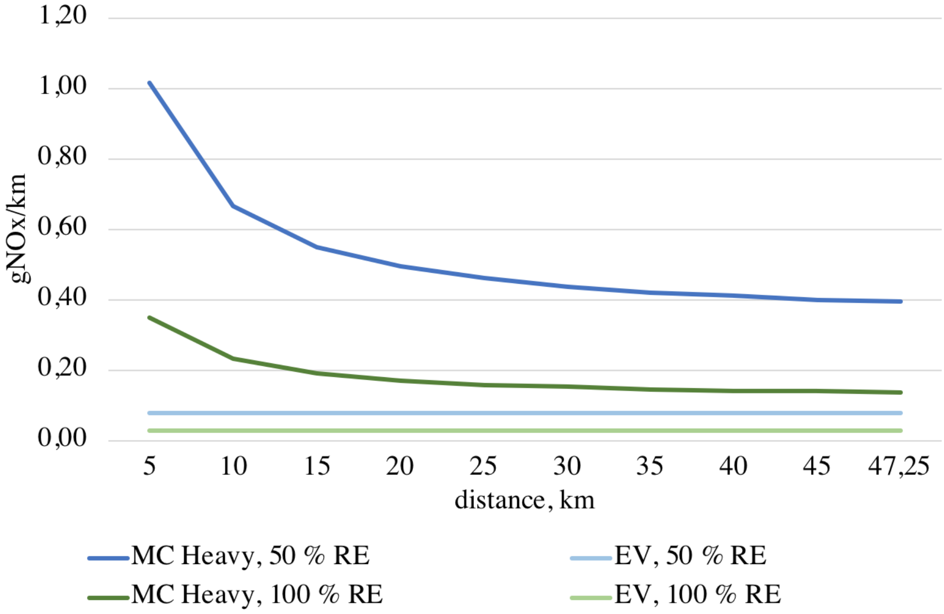

Figure 12: Amounts of released NO_x pollutants per kilometer travelled considering different electricity mixes

As seen from Figure 9 and Figure 10, emission levels related to MC Heavy operation are above emission levels of EV. The following Figure 13 and Figure 14 present the difference in the amounts of emissions released from MC Heavy operation and considered ground modes depending on trip length.

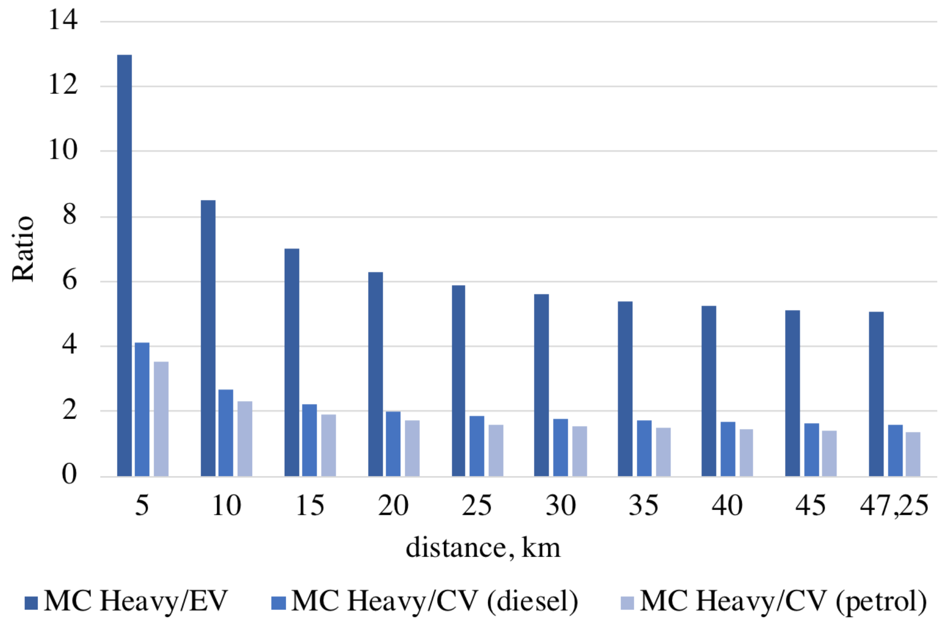

Figure 13: Ratio of the amounts of CO_2 emissions between MC Heavy and gasoline-, diesel- and electrically-powered LDVs

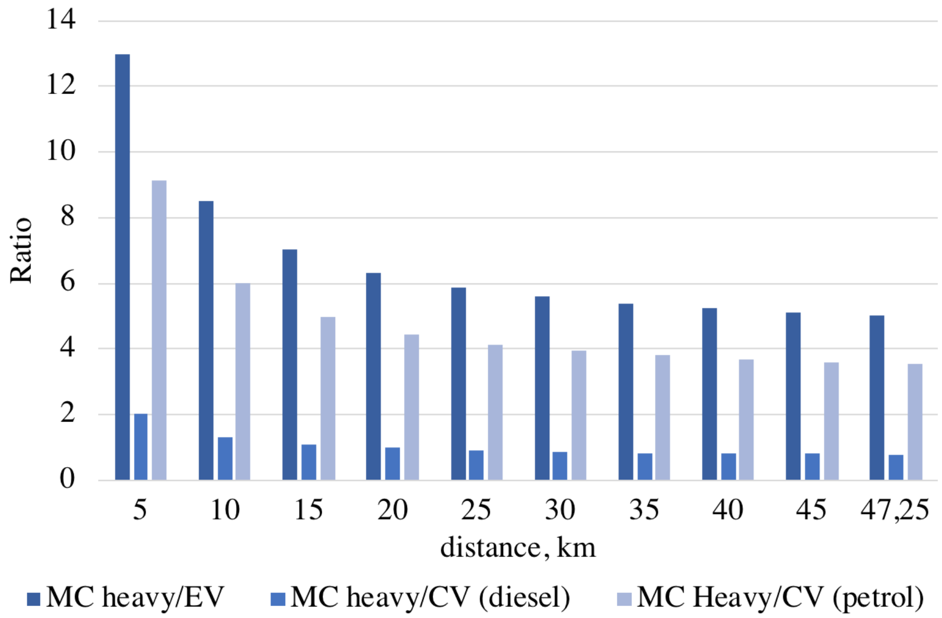

Figure 14: Ratio of the amount of NO_x emissions between MC Heavy and gasoline-, diesel- and electrically-powered LDVs

4.3 UAM Scenario

The UAM Scenario includes all transportation modes as BaU Scenario and an additional air transportation mode. In order to integrate the new transportation mode into the simulation, the input data was changed. The number of trips was selected based on the UAM trip selection requirement, which can be stated as that the ground transportation part of the trip should not be longer than one third of the complete trip length. The distribution of number of trips regarding their origins, destinations and trip lengths is shown in Figure 15.

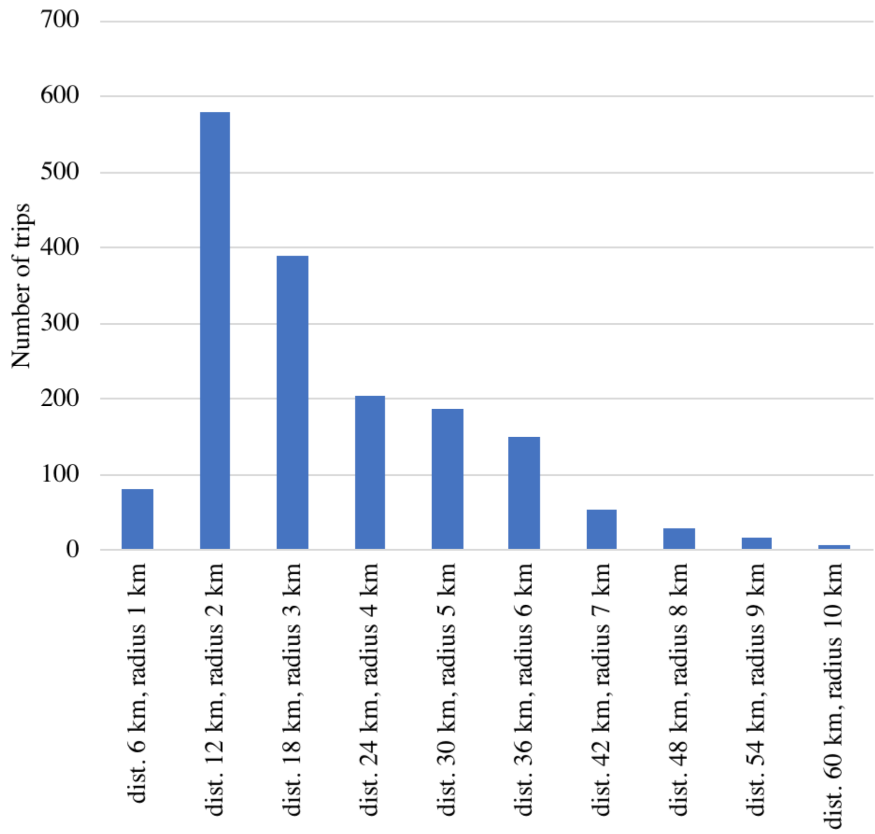

Figure 15: Trip distribution regarding the selected requirements (5 % sample)

As it is not known at this point of time, when UAM launches its operation in Munich and what will be its market share. Following this, the UAM Scenario was modelled with 10 % of the trips that follow the selection conditions and previously used transportation mode in the BaU scenario was changed to the UAM mode. This was done because agents' ability to select between different transportation modes was disabled.

For the UAM scenario, possible improvements in the technology were calculated as well as for the BaU scenario. The calculated changes in the amounts of released CO_2 and

NO_x emissions from car trips were similar to the BaU scenario results (Table 13). The results considering changes in the electricity mix are presented in Table 14. In total, over the simulated day, 4,480 UAM trips were conducted and 80,383 kWh of electricity was consumed. As seen, changes in electricity mix composition have significant impact on amounts of released emissions (detailed calculation results can be found in Appendix D).

	Current electricity mix		**50 % of electricity from renewable sources**		**100 % of of electricity from renewable sources**	
Mode	CO_2, tonn	NO_x, tonn	CO_2, tonn	NO_x, tonn	CO_2, tonn	NO_x, tonn
MC Heavy	24.26	0.06	14.80	0.04	2.36	0.01
Public Transport	265.83	1.71	237.66	1.63	200.64	1.58

Table 14: Effect of electricity mix on the amounts of emissions from MC Heavy and public transport operation (UAM scenario)

The distribution of kilometers travelled by each of modes was not affected by the introduction of a new mode, and it remained unchanged (Figure 8). The sum of distances travelled by air transportation in the UAM scenario had 0.18 % share of the total sum of distances travelled during the simulated day.

4.4 Comparison of BaU and UAM Scenarios

In order to estimate the effect of UAM introduction on the daily amounts of produced CO_2 and NO_x emissions, scenarios with and without UAM were compared. As described earlier, for both of the scenarios, additional scenarios were also calculated. The aim of the additional scenarios was to estimate the effect of technological changes on the amounts of emissions. Table 15 contains the information regarding the changes in the amount of CO_2 and NO_x released during the simulated day in BaU and UAM scenarios (for detailed information please see Appendices B and D).

BaU Scenario		UAM Scenario		Difference, %	
CO_2, tonn	NO_x, tonn	CO_2, tonn	NO_x, tonn	CO_2, tonn	NO_x, tonn
Current Technology					
11,836.51	23.04	11,861.21	23.10	+0.20	+0.26
Scenario 1 - 50 % of EV					
7,693.14	16.17	7,717.61	16.23	+0.32	+0.37
Scenario 2 - 100 % of EV					
3,549.77	9.31	3,574.01	9.36	+0.68	+0.54
Scenario 3 - 50 % of electricity from renewable sources					
11,808.30	22.96	11,823.57	23.00	+0.13	+0.17
Scenario 4 - 100 % of electricity from renewable sources					
11,771.21	22.91	11,774.11	22.93	-0.06	+0.09
Scenario 5 - public bus fleet improvement by 50 %					
11,739.65	22.27	11,764.42	22.33	+0.21	+0.27

Table 15: Comparison of BaU and UAM scenarios results

Taking into account the focus of this work, it is important to look specifically at the travel behavior of agents that use air transportation, and to compare the amounts of emissions released by modes used in the BaU scenario with the modes used in the UAM scenario. Following this, the number of agents that used air transportation in UAM scenario were selected from BaU scenario. Table 16 presents the summed up amounts of CO_2 and NO_x emissions related to agents' travel modes before and after UAM was introduced. The detailed calculation results can be found in Appendix E.

BaU Scenario		UAM Scenario		Difference, %	
CO2, tonn	NOx, tonn	CO2, tonn	NOx, tonn	CO2, tonn	NOx, tonn
Current Technology					
12.92	0.02	28.97	0.07	+224.23	+350.00
Scenario 1 - 50 % of EV					
8.37	0.02	27.34	0.06	+326.64	+300.00
Scenario 2 - 100 % of EV					
3.82	0.01	25.72	0.06	+673.30	+600.00
Scenario 3 - 50 % of electricity from renewable sources					
12.88	0.02	19.49	0.05	+151.32	+250.00
Scenario 4 - 100 % of electricity from renewable sources					
8.27	0.02	5.41	0.02	-34.59	0.00
Scenario 5 - public bus fleet improvement by 50 %					
12.87	0.02	28.90	0.07	+225.10	+350.00

Table 16: Comparison of BaU and UAM trips of agents who used air transportation

It was presented earlier that MC Heavy energy consumption varies depending on the distance. As the distance increases, the amount of emissions per kilometer travelled decreases (Figure 9 and Figure 10). In order to find whether the presented pattern repeats itself in the MATSim simulation, the number of UAM flights conducted in the UAM scenario was divided into groups depending on the distance flown. The UAM scenario results show that in total 4,480 air trips were performed and they were separated into the following groups:

1. trips < 10 km (300 trips);
2. 10 km < trips < 20 km (3600 trips);
3. 20 km < trips < 30 km (440 trips);
4. 30 km < trips < 40 km (140 trips).

For the selected trips, the amounts of CO_2 and NO_x emissions released in the BaU and UAM scenarios were calculated. As noted above, the trips selected for UAM usage had to satisfy the requirements under the assumption that people may consider driving longer distances to UAM stations for longer flights (Figure 6). Figure 16 provides the comparison of CO_2 and NO_x released per trip. The UAM scenario results include the total amounts of released emissions, which means that access and egress modes were included whether it was LDV, public transport modes or walking. Yet, the BaU scenario emission calculation does not include car passenger emissions. Nevertheless, in case car passenger from the BaU scenario used air vehicle in the UAM scenario, these emissions calculations were included. The detailed information can be found in Appendix F.

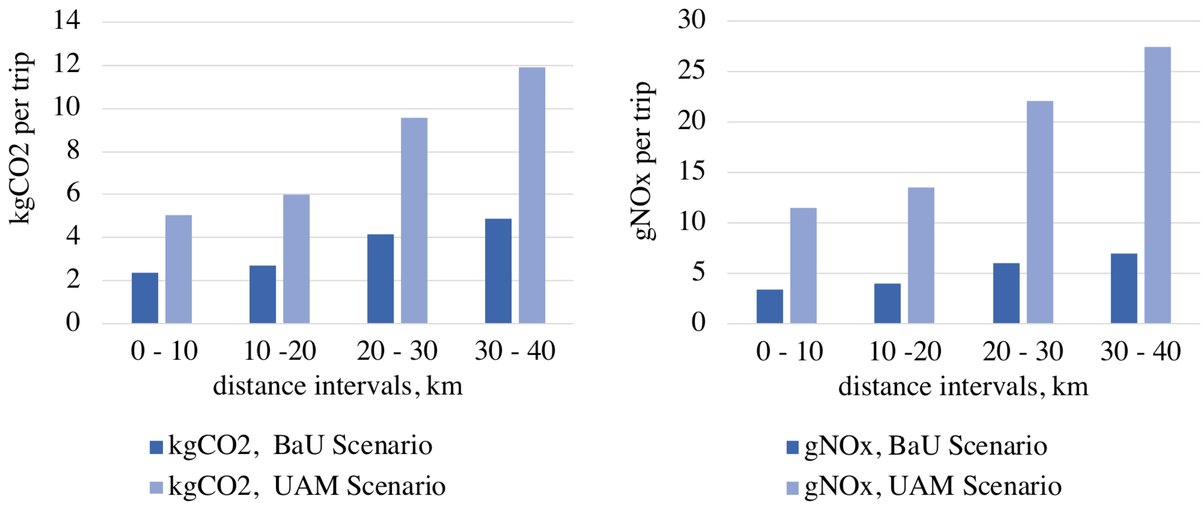

Figure 16: Amounts of released CO_2 and NO_x emissions per trip in BaU and UAM scenarios

Figure 17 presents the difference in the amount of gases released per trip in the UAM and BaU scenarios depending on the trip length. As seen in Figure 17, as trips distance increases, the difference between air and ground trips becomes larger. This result differs from the pattern presented earlier in Figure 13 and Figure 14, where as trip distance increases, the difference becomes smaller for both CO_2 and NO_x emissions.

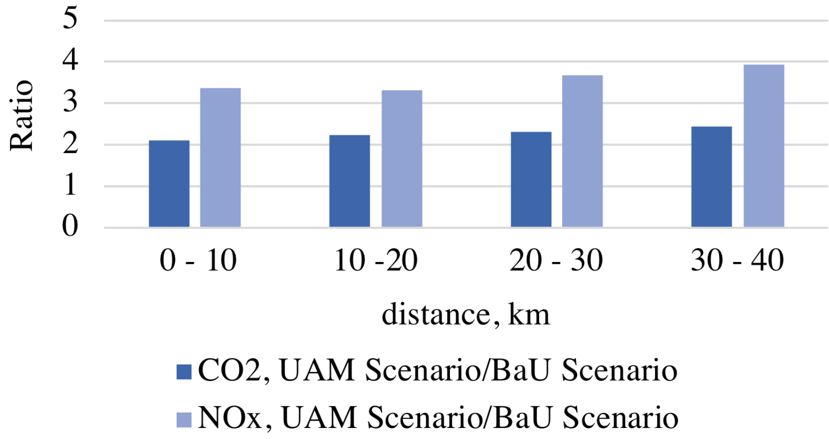

Figure 17: Ratio of the amounts of CO_2 and NO_x emissions per trip between BaU and UAM scenarios

Currently, the effect of the UAM introduction on remained ground modes is not known. The total sum of kilometers traveled by car in the UAM scenario was 0.076 % higher than the BaU scenario, considering only the agents who did not used air transportation. In order to verify this result, 4 additional simulation runs for the UAM scenario were performed. Table 17 presents the outputs of the additional runs. As seen, the deviation is within the 98 % confidence interval and following this, the slight increase in the amount of kilometers travelled by car in the initial UAM scenario can be addressed to statistical noise. The average car trip distance in both the BaU and the UAM scenarios is 10.91 km.

Scenario	Average trip distance, km	Deviation, %	Sum of distances travelled, thousand km	Deviation, %
BaU Scenario	10.91		65,159.12	
UAM Scenario	10.91	-0.14	65,199.66	-0.52
Reruns				
UAM Scenario, rerun 1	10.90	-0.03	64,890.54	-0.04
UAM Scenario, rerun 2	10.91	-0.17	64,950.22	-0.13
UAM Scenario, rerun 3	10.88	+0.15	64,529.98	+0.51
UAM Scenario, rerun 4	10.88	+0.19	64,746.26	+0.18
UAM Scenario, average	10.90		64,863.33	

Table 17: Deviation in the results from additional UAM scenario runs

5 Discussion of the Main Findings

This section highlights the important findings and discusses the possible reasons for the achieved results.

This work investigated the effect of urban air mobility operation in Munich on the current CO_2 and NO_x emission levels. Initially, the study presented the comparison of amounts exhaust gases released by the eVTOL MC Heavy and LDVs. The comparison between MC Heavy and conventionally diesel- or gasoline-powered LDVs showed that, as travelled distance increases, the difference in the amounts of CO_2 gases released per kilometer decreases. Compared to diesel-powered LDVs, MC Heavy emissions are 2 to 4 times greater, and compared to gasoline-powered LDVs, MC Heavy emissions are 1 to 4 times greater. Starting at 15 km, the difference in the amounts of released NO_x pollutants between MC Heavy and diesel-powered LDVs becomes negligible. Moreover, considering a distance of 25 km and higher, MC Heavy NO_x related emissions become lower than conventional diesel-powered vehicle emissions. Considering a 5 km distance, NO_x pollutants related to MC Heavy operation are 9 times greater than those of gasoline-powered vehicles. At longest distance 47.25 km, the difference becomes smaller and MC Heavy related emissions are 4 times greater than gasoline-powered LDVs emissions (Figure 13 and Figure 14).

Considering electrically powered vehicles only, it was found that despite the electricity mix EV always performs better than eVTOL vehicle, selected in this work. Prior to the emission calculation, it was seen that the energy consumption per kilometer of both vehicles is drastically different. Considering the lowest possible MC Heavy energy consumption per kilometer, EV consumes 5 times less (Figure 13 and Figure 14). As known, the amounts of released pollutants and gases are depending on the energy consumption and consequently, MC Heavy emits 5 times more than EV does. Considering the electricity mixed where 50 % and 100 % electricity generated by renewable sources, the actual amount of related gases decreases, nevertheless, MC Heavy still emits more than EV (Figure 11 and Figure 12).

The comparison of both the BaU and the UAM scenarios did not indicate a worthwhile difference in the amounts of daily produced CO_2 and NO_x emissions. Even though the emission rates of MC Heavy are significantly higher than any other ground modes emissions, on a large scale, its operation did not significantly affect the daily emission rates. Nevertheless, the best results were achieved in Scenario 4 where 100 % electricity was generated by renewable sources and the UAM introduction reduced the total daily amount of CO_2 gases by 0.06 %. On the other hand, under this scenario conditions, the amount of NOx pollution increased by 0.09 %, which is still the lowest increase from all scenarios considered. The worst effect on the total amounts of daily produced gases was found in Scenario 2 where EVs were assumed to substitute for conventional LDVs trips. In this scenario the UAM introduction increased the total amounts of daily CO_2 and NO_x pollutants by 0.68 and 0.54 % respectively (Table 15). The investigated scenario where the public bus fleet was considered to emit 50 % less than it does in initial scenario, did not have a significant effect on total amounts of gases released due to its 5 % share in total kilometers travelled (Figure 8).

Due to the relatively small UAM market share of 0.03 %, UAM operation had no effect on ground modes travel distances. At this point, it was important to compare the actual changes in emissions, focusing only on agents who used air transportation. Estimating the modes agents used prior to UAM introduction, it was found that with the current state of technology, switching from ground mode to air mode would increase the amounts of CO_2 gases by 224 % and amounts of NO_x pollutants by 350 %. This difference became twice larger when EVs are considered as initial ground modes used prior to UAM introduction. In the scenario where electricity was generated fully from renewable sources, the UAM operation did not have an effect on NO_x pollution levels, however, it reduced the amounts of CO_2 gases by 34,59 % (Table 16).

It was estimated earlier that energy consumption of eVTOL per kilometer decreases as the trip distance increases. Nevertheless, considering the actual sum of distances flown, the amount of emissions increases as distance becomes longer, and longer UAM trips produced higher amounts of emissions compared to shorter UAM trips (Figure 16). The comparison of the amounts of emission from the trips where UAM was used with previously used ground modes in the BaU scenario showed that as the trip distance increases, the difference in the amounts of emissions produced becomes larger. These findings differ from the findings discussed earlier (Figure 13 and Figure 14). The sum of emissions released per trip in UAM scenario included UAM mode and modes used to reach and to leave the UAM stations. Moreover, in some cases the UAM stations were located in opposite direction from the agent's destination. Subsequently, agents tend to drive further away from the destination point. Similar situations were observed at destination stations when agent needed to drive in the opposite direction of its flight in order to reach the destination point. As a result, point-to-point number of kilometers travelled in the UAM scenario was longer than number of kilometers travelled by ground mode in the BaU scenario. Additionally, the cases were observed when agents did not use the closest UAM stations to their origins and destinations. In these cases, distances travelled by UAM modes were shorter than distances travelled by ground mode. And as it was already mentioned, short UAM trips produce more emissions per kilometer than longer UAM trips. These factors could affect the results.

The observations discussed above have led to the necessity of implementation of factors and parameters in the model that would affect agents choice whether to use UAM. Moreover, UAM stations locations, cost of the UAM trip and UAM search radius should be carefully estimated in order to avoid long travel distances and subsequently higher amount of released harmful gases and pollutants.

6 Conclusions and Future Work

This section summarizes the main findings and draws conclusions from the results achieved. Afterwards, it highlights the main limitations of the study as well as the possible further research areas.

6.1 Conclusions

This work focuses on estimating the possible additional burden imposed on the environment by UAM operation in Munich. Using the open-source framework MATSim, 4,480 UAM trips were modelled. In total, the modelled UAM operation consumed 80,383 kWh of electricity, which corresponds to 24.26 tonnes of CO_2 and 0.06 tonnes of NO_x emissions.

For both groups of scenarios, with and without UAM, 5 additional scenarios were calculated. By comparing the results of investigated scenarios, it was found that UAM may have an almost neutral effect on the current emissions levels if the electricity consumed is fully generated by hydro-power plants. The direct comparison of distances traveled showed that, as distance increases, the difference between eVTOL and conventional gasoline- and diesel-powered LDVs, in terms of released gases, becomes smaller. Moreover, eVTOLs can be more environmentally beneficial than conventional diesel-powered LDVs in terms of NO_x pollutant amounts as eVTOLs produce slightly lower amounts of such pollutants when distance flown is longer than 20 km. Additionally, it was found that eVTOL vehicles are not competitors to EVs due to the significant difference in energy consumption and because, under the technological assumptions used in this work, eVTOL vehicles would never reach results similar to EVs in emissions per kilometer, regardless of the distance traveled.

Based on the output of MATSim, it was found that agents do not always choose the closest UAM station. As a result, the longer the distance travelled with ground modes, the shorter the distance travelled with air modes. Consequently, the amounts of eVTOL vehicles emissions per kilometer increase since the flown distances become shorter. Unfortunately, this finding eliminates the possibility of drawing any conclusions regarding the dependency of emissions per kilometer on the trip length. Additionally, it was found that in order to reach the target UAM station, some agents tend to drive in the opposite direction from their destinations. In this case, point-to-point distance travelled in the UAM scenario becomes longer than the distance travelled in the BaU scenario, and the amount of emissions increases accordingly.

In the use-case Munich, introduction of UAM might not be environmentally beneficial. Each individual city itself, its infrastructure and station locations will provide different results. The topography of other cities with mountainous terrain, terrain with a large number of reservoirs, or areas which are divided by rivers into two parts, could gain higher benefits by utilizing air transportation. The Munich study area is mostly flat without any topographic hindrances, so air transportation in this case does not significantly reduce the distances travelled. Finally, it is important to add that, within this work, UAM introduction did not have an effect on the distances travelled by remaining ground modes.

6.2 Limitations

There are several aspects that this study does not cover. The UAM area is relatively new, and, given the amount of available time and necessary data, some aspects had to be simplified or ignored.

First of all, the study does not take into account the time aspects. Waiting times, boarding times, charging times, flight times and others were left out. Nevertheless, these aspects are important because time-wise UAM could be faster than any ground mode. Secondly, the actual potential of existing power plants to supply the amount of electricity required for UAM was not considered.

Regarding the operational constraints, the eVTOL vehicle fleet for this study was unlimited, which means there was always a vehicle available at the station. This, in its turn, reduces the amounts of released emissions since the eVTOL vehicle does not need to travel to the requested UAM station. If this aspect was included, it would increase total distances travelled, amount of electricity consumed, thus, amount of emissions released. In addition to this, the number of passengers on board of any selected MC Heavy was set to one, whereas the vehicle has a 4-seat capacity; therefore, the vehicle was not fully utilized. Neither time length of vehicle operation nor maximum distances flown on one charge were considered.

Regarding the MATSim simulation, the mode choice was excluded due to the lack of required parameters. Thus, based on author's assumption that it was rational to use an air vehicle only if the distance it travelled was twice as long as the sum of distances travelled by the ground mode in order to reach and leave the target UAM station. Based on this, certain trips were selected as potential UAM trips.

The study was limited to the estimation of CO_2 and NO_x emissions only and did not consider the noise pollution of air vehicles or additional harmful gases and pollutants. Moreover, the areas that are flown over were not investigated. Besides, the direct comparison of point-to-point distance travelled in the BaU and UAM scenarios did not take into account the amount of fuel wasted in congestion. This could have an effect on amounts of emissions released by ground modes and reduce the difference in amounts of gases released in the BaU and UAM scenarios.

6.3 Recommendations and Future Work

This study is the starting point for investigating the environmental performance of electrified urban air transportation. A number of different aspects were not included in this work and should be studied in further work. First of all, the estimation of the environmental performance of a new air transportation mode could investigate a broader field of pollutants or gases. Moreover, vehicle noise pollution during operation could be included. Noise pollution is becoming critical, so if the acceptable levels of noise are exceeded, UAM operation may not be launched on a large scale.

Considering the whole ecosystem, it is important to estimate a possible effect of UAM operation on birds. The eVTOL vehicle MC Heavy investigated in this study reaches the height of 300 meters before the cruise part of the flight starts. City birds do not fly as high as eVTOL vehicles, but VTOL phases of flights could be hindered by birds and they in turn could be injured by eVTOL vehicles. It would be important to estimate the possible collisions with birds and potential solutions to protect both birds and vehicles.

From a positive perspective, UAM operation may have a favourable effect on local air quality, first of all because emissions from ground vehicles are shifted to power plants. In the majority of cases, these are located outside cities. Second, the rotation movement of propellers may disperse clouds of smog over the city. These effects could be explored in further works. Also, within the scope of environmental research and climate, it is important to investigate of UAM operation under various weather conditions. Temperature changes, humidity, strong wind squalls and heavy rains may affect eVTOL performance.

UAM operation can be argued to be more environmentally friendly as no new infrastructure is required. Ground network construction, on the other hand, exploits natural resources and contaminates ground, air and water. UAM network construction requires a fairly less resources, since it is assumed to operate from tops of high constructions. Nevertheless, it is important to estimate which resources are needed in order to establish properly operating UAM stations.

A comparison of eVTOL vehicles and conventional LDVs or EVs can be more precise if complete life-cycle assessments are performed. As known, the ground vehicle production phase is responsible for 85 – 90 % of the total emissions released during the vehicle life-cycle. A life-cycle assessment of eVTOL vehicles could shed light on other previously unexplored aspects. Additionally, vehicle disposal and/or possible further use of specific vehicle parts for other constructions can be investigated as well.

The number of vehicles in a fleet as well as their initial positions at the beginning of a day are important. The correct vehicle allocation can reduce waiting times during peak hours, and also total number of trips, therefore distances travelled. Moreover, the charging options should be considered, whether battery swapping or direct charging from an outlet, because the selected option will have an effect on waiting times. Following this, prior to launching UAM operation on a large scale, the necessary amount of electricity must be determined, and charging options depending on peak and off-peak hours in electricity demand must be explored.

References

A^3 by Airbus (2019). *Vahana*. [Online; accessed January-2019]. URL: https://www.airbus-sv.com/projects/1.

Aber, Judah (2016). *Electric Bus Analysis for New York City Transit*. Tech. rep. Columbia University, p. 37.

AEA (2008). *2008 Guidelines to Defra's GHG Conversion Factors: Methodology Paper for Transport Emission Factors*. Tech. rep. London: Department for Environment, Food and Rural Affairs, p. 35. URL: http://www.sthc.co.uk/documents/DERFA_ghg-cf-passenger-transport_2008.pdf.

Antcliff, R Kevin, Mark Moore, and Kevin R Antcliff (2015). "Silicon Valley Early Adopter CONOPs and Market Study". In: *2015 Transformative Vertical Flight Workshop*, pp. 1–34. URL: https://nari.arc.nasa.gov/sites/default/files/attachments/Antcliff-SV-TVFW-Aug15.pdf.

Aurora Flight Sciences (2019). *Aurora*. [Online; accessed January-2019]. URL: http://www.aurora.aero/pav-evtol-passenger-air-vehicle/.

Bahn, Deutsche (2018). *Grundlagenbericht zum UmweltMobilCheck*. Tech. rep. Berlin: DB Regio AG, DB Umwelt, p. 21. URL: https://www.bahn.de/wmedia/view/mdb/media/intern/umc%7B%5C_%7Dgrundlagenbericht.pdf.

Bank, The World (2019). *CO2 emissions (metric tons per capita)*. [Online; accessed April-2019]. URL: https://data.worldbank.org/indicator/EN.ATM.CO2E.PC?end=2014&locations=EU-DE&name_desc=true&start=1960&view=chart.

Beimborn, Edward, Rob Kennedy, and William Schaefer (1996). *Inside the Blackbox: Making Transportation Models Work for Livable Communities*. Wisconsin-Milwaukee: University of Wisconsin-Milwaukee, Citizens for a Better Environment, The Environmental Defense Fund, p. 63. URL: https://www4.uwm.edu/cuts/blackbox/blackbox.pdf.

Boscoe, Francis P., A. Henry Kevin, and Michael S. Zdeb (2012). "A Nationwide Comparison of Driving Distance Versus Straight-Line Distance to Hospitals". In: *The Professional Geographer* 64 (2), pp. 188–196. DOI: 10.1080/00330124.2011.583586.

Burian, Jaroslav et al. (2018). "Attitudes and Motivation to Use Public or Individual Transport: A Case Study of Two Middle-Sized Cities". In: *Social sciences* 7, p. 25. DOI: 10.3390/socsci7060083.

Burnham, Andrew (2009). *User Guide for the GREET Fleet Footprint Calculator 1.1.* Tech. rep. Argonne National Laboratory, p. 8. URL: https://greet.es.anl.gov/publication-4elg4zj7.

Chau, K. T., C. C. Chan, and C. Liu (2008). "Overview of Permanent-Magnet Brushless Drives for Electric and Hybrid Electric Vehicles". In: *IEEE Transactions on Industrial Electronics* 55.6, pp. 2246–2257. ISSN: 0278-0046. DOI: 10.1109/TIE.2008.918403.

Cherry, Christopher (2007). "Electric Bike Use in China and Their Impacts on the Environment, Safety, Mobility and Accessibility". UC Berkeley: Center for Future Urban Transport: A Volvo Center of Excellence. URL: https://escholarship.org/uc/item/8bn7v9jm%7B%5C%%7D0A.

Cherry, Christopher R., Jonathan X. Weinert, and Yang Xinmiao (2009). "Comparative environmental impacts of electric bikes in China". In: *Transportation Research Part D: Transport and Environment* 14.5, pp. 281–290. ISSN: 1361-9209. DOI: 10.1016/j.trd.2008.11.003.

Choi, Uk-Don, Ho-Kwon Jeong, and Sun-Kyu Jeong (2012). "Commercial operation of ultra low floor electric bus for Seoul city route". In: *2012 IEEE Vehicle Power and Propulsion Conference*, pp. 1128–1133. DOI: 10.1109/VPPC.2012.6422619.

Courtin, Christopher et al. (2018). "Feasibility Study of Short Takeoff and Landing Urban Air Mobility Vehicles using Geometric Programming". In: *2018 Aviation Technology, Integration, and Operations Conference*. DOI: 10.2514/6.2018-4151.

Datta, Anubhav (2018). *Commercial intra-city on-demand electric-vtol status of technology.* Tech. rep. University of Maryland at College Park AN, p. 57.

DEFRA (2017). *Emisson Factors Toolkit v8. User Guide.* Tech. rep. Agriculture, Environment and Rural Affairs, p. 30. URL: https://laqm.defra.gov.uk/documents/EFTv8-user-guide-v2.pdf.

Degraeuwe, Bart and Martin Weiss (2017). "Does the New European Driving Cycle (NEDC) really fail to capture the NOX emissions of diesel cars in Europe?" In: *Environmental Pollution* 222, pp. 234–241. ISSN: 0269-7491. DOI: 10.1016/j.envpol.2016.12.050.

Deutsche Bahn (2019a). *DB.* [Online; accessed February-2019]. URL: https://www.bahn.de/p/view/index.shtml.

— (2019b). *S-Bahn München.* [Online; accessed February-2019]. URL: https://www.s-bahn-muenchen.de.

Deutscher Bundestag (2007). *CO2-Bilanzen verschiedener Energieträger im Vergleich*. Tech. rep. Wissenschaftliche Dienste des Deutschen Bundestages, p. 32.

Doucette, Reed T. and Malcolm D. McCulloch (2011). "Modeling the prospects of plug-in hybrid electric vehicles to reduce CO2 emissions". In: *Applied Energy* 88.7, pp. 2315–2323. ISSN: 0306-2619. DOI: 10.1016/j.apenergy.2011.01.045.

Elliot, Thomas, Sarah J. McLaren, and Ralph Sims (2018). "Potential environmental impacts of electric bicycles replacing other transport modes in Wellington, New Zealand". In: *Sustainable Production and Consumption* 16, pp. 227–236. ISSN: 23525509. DOI: 10.1016/j.spc.2018.08.007.

EMISIA (2016). *Copert. Introduction.* [Online; accessed April-2019]. URL: http://copert.emisia.com/manual.

EUROCONTROL (2018). *Modelling tools to measure the environmental impacts of aviation.* [Online; accessed April-2019]. URL: https://www.eurocontrol.int/environment-modelling-tools.

European Commission (2018). *Mobility and Transport: Commission welcomes European cities joining the Urban Air Mobility initiative.* [Online; accessed December-2018]. URL: https://ec.europa.eu/transport/media/news/news/2018-05-30-commission-welcomes-european-cities-joining-urban-air-mobility-initiative_en.

European Environmental Agency (2002). *TERM 2002 29 EU — Occupancy rates of passenger vehicles.* [Online; accessed April-2019]. URL: https://www.eea.europa.eu/data-and-maps/indicators/occupancy-rates-of-passenger-vehicles-2/eu-occupancy-rates-of-passenger-vehicles.

— (2013). *TERM 2013 : transport indicators tracking progress towards environmental targets in Europe*. Tech. rep. European Environmental Agency, p. 112. DOI: 10.2800/94848.

— (2016). *NITROGEN OXIDES - NOx.* [Online; accessed April-2019]. URL: https://www.eea.europa.eu/publications/92-9167-031-6/page005.html.

— (2018a). *CO2 emissions (metric tons per capita).* [Online; accessed April-2019]. URL: https://data.worldbank.org/indicator/EN.ATM.CO2E.PC?end=2014&locations=EU-DE&name_desc=true&start=1960&view=chart.

European Environmental Agency (2018b). *Overview of electricity production and use in Europe*. [Online; accessed April-2019]. URL: https://www.eea.europa.eu/data-and-maps/indicators/overview-of-the-electricity-production-2/assessment-4.

European Parliament (2016). *Committee of Inquiry into Emission Measurements in the Automotive Sector*. Tech. rep. Committee of Inquiry into Emission Measurements in the Automotive Sector, p. 13. URL: http://www.europarl.europa.eu/sides/getDoc.do?pubRef=-//EP//NONSGML+COMPARL+PE-594.081+01+DOC+PDF+V0//EN&language=EN.

European.Commission (2018). *Smart Cities*. [Online; accessed December-2018]. URL: https://ec.europa.eu/info/eu-regional-and-urban-development/topics/cities-and-urban-development/city-initiatives/smart-cities_en.

Evans, Simon and Rosamund Pearce (2016). *Power Sources in Germany*. [Online; accessed November-2018]. URL: https://www.carbonbrief.org/how-germany-generates-its-electricity.

FAA (2015). *Emissions and Dispersion Modeling System (EDMS)*. [Online; accessed December-2018]. URL: https://www.faa.gov/about/office_org/headquarters_offices/apl/research/models/edms_model/.

Faia, S.M.R. (2006). "Optimization of Vehicle Propulsion Systems for Fleet". Thesis of M.Sc. Instituto Superior Técnico.

Faria, Ricardo, Pedro Marques, et al. (2013). "Impact of the electricity mix and use profile in the life-cycle assessment of electric vehicles". In: *Renewable and Sustainable Energy Reviews* 24, pp. 271–287. ISSN: 1364-0321. DOI: 10.1016/j.rser.2013.03.063.

Faria, Ricardo, Pedro Moura, et al. (2012). "A sustainability assessment of electric vehicles as a personal mobility system". In: *Energy Conversion and Management* 61, pp. 19–30. ISSN: 0196-8904. DOI: 10.1016/j.enconman.2012.02.023.

Finger, Dominik Felix et al. (2017). "A Review of Configuration Design for Distributed Propulsion Transitioning VTOL Aircraft A Review of Configuration Design for Distributed Propulsion Transitioning VTOL Aircraft". In: *Asia-Pacific International Symposium on Aerospace Technology, Seoul, Korea 2017*, pp. 1–15.

Follmer, Robert et al. (2010). *Mobilität in Deutschland 2008*. Tech. rep. Bonn und Berlin: DLR, infas, Mobilität in Deutschland, p. 208. URL: http://www.mobilitaet-in-deutschland.de/pdf/MiD2008%7B%5C_%7DAbschlussbericht%7B%5C_%7DI.pdf.

Forschungs-Informations-System (2011). *Daten und Fakten zum Energieverbrauch des Schienenverkehrs*. [Online; accessed December-2018]. URL: www.forschungsinformationssystem.de/servlet/is/342234.

Fraunhofer ISE (2019). *Energy Charts*. [Online; accessed February-2019]. URL: https://www.energy-charts.de/power.htm.

Frömming, Christine et al. (2012). "Aviation-induced radiative forcing and surface temperature change in dependency of the emission altitude". In: *Journal of Geophysical Research (Atmospheres)* 117 (D19104), pp. 19104–. DOI: 10.1029/2012JD018204.

Gauss, M. et al. (2006). "Impact of aircraft NOx emissions on the atmosphere – tradeoffs to reduce the impact". In: *Atmospheric Chemistry and Physics* 6, pp. 1529–1548. URL: https://www.atmos-chem-phys.net/6/1529/2006/acp-6-1529-2006.pdf.

GmbH, e-volo (2017). *Volocopter*. [Online; accessed January-2019]. URL: https://www.volocopter.com/en/product/.

Graham-Rowea, Ella et al. (2012). "Mainstream consumers driving plug-in battery-electric and plug-in hybrid electric cars: A qualitative analysis of responses and evaluations". In: *Transportation Research Part A: Policy and Practice* 46.1, pp. 140–153. URL: https://www.sciencedirect.com/science/article/pii/S0965856411001418.

Hannig, Florian et al. (2009). "„ Stand und Entwicklungspotenzial der Speichertechniken für Elektroenergie – Ableitung von Anforderungen an und Auswirkungen auf die Investitionsgüterindustrie " Abschlussbericht". In: *BMWi-Auftragsstudie*.

Hastings, Meredith, Hiram Levy, and Gregory Carmichael (2000). "Impacts of biomass burning on tropospheric CO, NOx, and O3". In: *Journal of Geophysical Research* 105, pp. 6633–6654. DOI: 10.1029/1999JD901113.

Hausberger, a.o. Univ.-Prof. Dr. Stefan Hausberger et al. (n.d.). *Emission Factors from the Model PHEM for the HBEFA Version 3*. Tech. rep. Graz: Graz University of Technology, p. 76. URL: http://www.hbefa.net/e/documents/HBEFA_31_Docu_hot_emissionfactors_PC_LCV_HDV.pdf.

Hawkins, Troy R., Ola Moa Gausen, and Anders Hammer Strømman (2012). "Environmental impacts of hybrid and electric vehicles-a review". In: *International Journal of Life Cycle Assessment* 17.8, pp. 997–1014. ISSN: 09483349. DOI: 10.1007/s11367-012-0440-9.

Hawkins, Troy R., Bhawna Singh, et al. (2013). "Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles". In: *Journal of Industrial Ecology* 17.1, pp. 53–64. DOI: 10.1111/j.1530-9290.2012.00532.x.

Helland, Asgeir [1] (2009). "Well-to-wheel CO2 analysis of electric and ICE vehicles: are global CO2 emission reductions possible". In: *International Journal of Global Warming* 1.4, pp. 432–442. ISSN: 0960894X. DOI: 10.1504/IJGW.2009.029214.

Hepperle, Martin (2017). *Electric Flight – Potential and Limitations.* Tech. rep. Braunschweig: Institute of Aerodynamics and Flow Technology, p. 30. URL: https://elib.dlr.de/78726/1/MP-AVT-209-09.pdf.

Hidalgo, Henry and P. J. Crutzen (1977). "The tropospheric and stratospheric composition perturbed by NOx emissions of high-altitude aircraft". In: *Journal of Geophysical Research. Oceans and Atmospheres* 82.37, pp. 5833–5866. DOI: 10.1029/JC082i037p05833.

Hirschberg, Mike (2017). "Electric VTOL Wheel of Fortune". In: *VERTIFLITE*, p. 2. URL: https://vtol.org/files/dmfile/CommentaryMA17-ElectricVTOL-Wheel-of-Fortune1.pdf.

Hodges, Tina (2010). *Public Transportation's Role in Responding to Climate Change.* Tech. rep. Federal Transit Administration, U.S. DOT, p. 19.

Hönisch, Bärbel et al. (2009). "Atmospheric carbon dioxide concentration across the mid-pleistocene transition". In: *Science* 324.5934, pp. 1551–1554. ISSN: 00368075. DOI: 10.1126/science.1171477. arXiv: arXiv:1308.5367.

Horni, A., K. Nagel, and K.W. Axhausen (2016). *The Multi-Agent Transport Simulation MATSim.* London: Ubiquity Press. DOI: 10.5334/baw.

Hülsmann, Friederike (2014). "Integrated agent-based transport simulation and air pollution modelling in urban areas". PhD thesis. Technischen Universität München. URL: https://mediatum.ub.tum.de/doc/1210046/1210046.pdf.

Hülsmann, Friederike et al. (2011). "Towards a multi-agent based modeling approach for air pollutants in urban regions". In: *Proceedings of the Conference on "Luftqualität an Straßen".* Proceedings of the Conference on "Luftqualität an Straßen", pp. 144–166.

Huo, Hong, Qiang Zhang, Fei Liu, et al. (2013). "Climate and Environmental Effects of Electric Vehicles versus Compressed Natural Gas Vehicles in China: A Life-Cycle

Analysis at Provincial Level". In: *Environmental Science & Technology* 47.3. PMID: 23276251, pp. 1711–1718. DOI: 10.1021/es303352x.

Huo, Hong, Qiang Zhang, Michael Q. Wang, et al. (2010). "Environmental Implication of Electric Vehicles in China". In: *Environmental Science & Technology* 44.13. PMID: 20496930, pp. 4856–4861. DOI: 10.1021/es100520c.

IEA (2011). *Technology Roadmaps Electric and plug-in hybrid electric vehicles (EV/PHEV)*. Tech. rep. International Energy Agency, p. 52. URL: https://webstore.iea.org/technology-roadmap-electric-and-plug-in-hybrid-electric-vehicles.

— (2016). *CO2 emissions from fuel combustion*. Tech. rep. Paris: International Energy Agency, p. 156. URL: https://emis.vito.be/sites/emis.vito.be/files/articles/3331/2016/CO2EmissionsfromFuelCombustion_Highlights_2016.pdf.

— (2017). *Energy technology perspectives 2017—catalysing energy technology transformations*. Tech. rep. International Energy Agency, p. 438. URL: http://www.acs-giz.si/resources/files/Energy%7B%5C_%7Dtechnology%7B%5C_%7Dperspectives.pdf.

IEC (2011). *Electrical Energy Storage White Paper*. Tech. rep. Geneva: International Electrotechnical Commission, p. 78. URL: https://www.iec.ch/whitepaper/pdf/iecWP-energystorage-LR-en.pdf.

International Energy Agency (2017). *Energy technology perspectives 2017—catalysing energy technology transformations*. Tech. rep. International Energy Agency, p. 438. URL: http://www.acs-giz.si/resources/files/Energy_technology_perspectives.pdf.

IPCC (2007). "Climate change 2007 : impacts, adaptation and vulnerability". In: *In: Change, Intergovernmental Panel on Climate* 1.July, p. 976. ISSN: 1537-2537. DOI: 10.2134/jeq2008.0015br. arXiv: 1109.1006v1.

— (2018). *The Intergovernmental Panel on Climate Change*. [Online; accessed April-2019]. URL: https://www.ipcc.ch/.

Iqbal, Husain (2003). *Electric and Hybrid Vehicles Design Fundamentals*. CRC Press LLC, p. 523. ISBN: 0-8493-1466-6.

Ji, Shuguang et al. (2012). "Electric Vehicles in China: Emissions and Health Impacts". In: *Environmental science & technology* 46, pp. 2018–24. DOI: 10.1021/es202347q.

Jöhrens, Julius and Hinrich Helms (2014). "How to Green Electric Vehicles. Analysis of key factors for Reducing Climate Impacts of Electric Vehicles". In: *Electric Vehicle Conference (IEVC), 2014 IEEE International. Florenz 2014.*

Jungmeier, Gerfried et al. (2017). *Life-cycle Based Environmental Effects of 1 . 3 Mio . Electric Vehicles on the Road in 35 Countries – Facts & Figures from the IEA Technology Collaboration Program on Hybrid & Electric Vehicles.* Tech. rep. x. Argonne National Laboratory, USA, 3DLR, Germany, 4IREC, Spain, 5CIRAIG, Canada, pp. 1–11. URL: https://core.ac.uk/download/pdf/154791785.pdf.

Kasliwal, Akshat et al. (2019). "Role of flying cars in sustainable mobility". In: *Nature Communications* 10.1, p. 1555. ISSN: 2041-1723. DOI: 10.1038/s41467-019-09426-0.

Keller, Mario et al. (2017). *HBEFA Version 3.3.* Tech. rep. Bern, Craz: IVT Institute for internal combustion engines and thermodynamics, MKC Consulting GmbH, INFRAS, p. 32.

Kessler, G. (2012). "Chapter 1 The Development of Nuclear Energy in the World". In: *Sustainable and Safe Nuclear Fission Energy.* Springer-Verlag Berlin Heidelberg, p. 466. ISBN: ISBN 978-3-642-11990-3. DOI: 10.1007/978-3-642-11990-3.

Kickhöfer, Benjamin (2016). "Emission Modeling". In: *The Multi-Agent Transport Simulation MATSim.* London: Ubiquity Press, pp. 247–252. DOI: 10.5334/baw.36.

Kohlman, Lee W and Michael D Patterson (2018). "System-Level Urban Air Mobility Transportation". In: *2018 Aviation Technology, Integration, and Operations Conference.* Atlanta, Georgia: AIAA AVIATION Forum, pp. 1–38. DOI: 10.2514/6.2018-3677.

Kopp, Dr Carlo (2010). "New rotary wing technologies". In: *Defence Today.* URL: https://www.ausairpower.net/SP/DT-Helo-Futures-Jun-2010.pdf.

Kraftfahrt-Bundesamt (2018). *Pressemitteilung Nr. 6/2018 - Der Fahrzeugbestand am 1. Januar 2018.* [Online; accessed January-2019]. URL: https://www.kba.de/DE/Presse/Pressemitteilungen/2011_2015/2011/Fahrzeugbestand/fz_bestand_pm_text.html?nn=654808.

Kumar, L., K. K. Gupta, and S. Jain (2013). "Power electronic interface for vehicular electrification". In: *2013 IEEE International Symposium on Industrial Electronics*, pp. 1–6. DOI: 10.1109/ISIE.2013.6563780.

Lee, D. S. et al. (2010). “Transport impacts on atmosphere and climate: Aviation”. In: *Atmospheric Environment* 44.37, pp. 4678–4734. DOI: 10.1016/j.atmosenv.2009.06.005.

Leishman, J. G. (2006). *Principles of Helicopter Aerodynamics*. 2nd ed. New York: Cambridge University Press.

Lin, Xiao, Peter Wells, and Benjamin K. Sovacool (2017). “Benign mobility? Electric bicycles, sustainable transport consumption behaviour and socio-technical transitions in Nanjing, China”. In: *Transportation Research Part A: Policy and Practice* 103, pp. 223–234. ISSN: 0965-8564. DOI: 10.1016/j.tra.2017.06.014.

Lineberger, Robin et al. (2018). *Elevating the future of mobility. Passenger drones and flying cars*. Tech. rep. Deloitte Insights, p. 20.

Liu, Yaolong et al. (2017). “Overview of recent endeavors on personal aerial vehicles: A focus on the US and Europe led research activities”. In: *Progress in Aerospace Sciences* 91, pp. 53–66. ISSN: 0376-0421. DOI: 10.1016/j.paerosci.2017.03.001.

Llorca, Carlos and Rolf Moeckel (2019). “Effects of scaling down the population fr agent-based traffic simulations”. In: *The 10th International Workshop on Agent-based Mobility, Traffic and Transportation Modesl, Methodologies and Applications (ABMTrans 2019)*. unpublished manuscript. Leuven.

Lovering, Zach (2018). *Exploring Control Allocation for eVTOL Vehicles*. [Online; accessed January-2019]. URL: https://vahana.aero/exploring-control-allocation-for-evtol-vehicles-78c5dbad2eb4.

Lowe, Tim (2011). *Energy and Emissions Monitoring before and after Sustainable NOW*. Tech. rep. Sustainable NOW, p. 11.

Majeau-Bettez, Guillaume, Troy R. Hawkins, and Anders Hammer StrØmman (2011). “Life cycle environmental assessment of lithium-ion and nickel metal hydride batteries for plug-in hybrid and battery electric vehicles”. In: *Environmental Science and Technology* 45.10, pp. 4548–4554. DOI: 10.1021/es103607c. arXiv: 1302.1406.

Marra, F. et al. (2012). “Demand profile study of battery electric vehicle under different charging options”. In: *2012 IEEE Power and Energy Society General Meeting*, pp. 1–7. DOI: 10.1109/PESGM.2012.6345063.

Matsuhashi, Ryuji et al. (2000). "Life cycle of CO2-emissions from electric vehicles and gasoline vehicles utilizing a process-relational model". In: *International Journal of Life Cycle Assessment* 5.5, pp. 306–312. ISSN: 0948-3349. DOI: 10.1007/BF02977584.

Moeckel, Rolf et al. (2019). "Microscopic Travel Demand Modeling: Using the Agility of Agent-Based Modeling Without the Complexity of Activity-Based Models". In: *The Transportation Research Board 99th Annual Meeting*. Washington DC.

Mom, Cijs (2004). *The electric vehicle: technology and expectations in the automobile age*. Baltimor, London: The Johns Hopkins University Press, p. 423. ISBN: 0801871387.

Moore, Mark D (2014). "Misconceptions of Electric Aircraft and their Emerging Aviation Markets". In: *52nd Aerospace Sciences Meeting*. AIAA SciTech Forum. American Institute of Aeronautics and Astronautics. DOI: 10.2514/6.2014-0535.

Moore, Mark D et al. (2013). "High-Speed Mobility through On-Demand Aviation". In: *2013 Aviation Technology, Integration, and Operations Conference*. NASA Langley Research Center, pp. 1–27. DOI: 10.2514/6.2013-4373.

Moro, Alberto and Laura Lonza (2018). "Electricity carbon intensity in European Member States: Impacts on GHG emissions of electric vehicles". In: *Transportation Research Part D: Transport and Environment* 64. The contribution of electric vehicles to environmental challenges in transport. WCTRS conference in summer, pp. 5–14. ISSN: 1361-9209. DOI: 10.1016/j.trd.2017.07.012.

Muetze, A. and Y. C. Tan (2007). "Electric bicycles - A performance evaluation". In: *IEEE Industry Applications Magazine* 13.4, pp. 12–21. ISSN: 1077-2618. DOI: 10.1109/MIA.2007.4283505.

MVG (2014). *Munich Transport Corporation (MVG) Sustainability Report 2014/2015*. [Online; accessed January-2019]. URL: https://www.mvg.de/dam/mvg/ueber/nachhaltigkeit/mvg-nachhaltigkeitsbericht-eng.pdf.

— (2018). *Unsere Fahrzeuge*. [Online; accessed February-2019]. URL: https://www.mvg.de/ueber/das-unternehmen/fahrzeuge.html.

— (2019). *Münchner Verkehrsgesellschaft mbH*. [Online; accessed February-2019]. URL: https://www.mvg.de.

Myhre, G. et al. (2011). "Radiative forcing due to changes in ozone and methane caused by the transport sector". In: *Atmospheric Environment* 45, pp. 387–394. URL: http:

//folk.uio.no/gunnarmy/paper/myhre%7B%5C_%7Datm%7B%5C_%7Denv%7B%5C_%7D2011.pdf.

Network for Transport Measures (2018). *Bus travel baselines 2018*. URL: https://www.transportmeasures.org/en/wiki/evaluation-transport-suppliers/bus-travel-baselines-2017/.

Nichols, Brice G., Kara M. Kockelman, and Matthew Reiter (2015). "Air quality impacts of electric vehicle adoption in Texas". In: *Transportation Research Part D: Transport and Environment* 34, pp. 208–218. ISSN: 1361-9209. DOI: 10.1016/j.trd.2014.10.016.

Noah Browning (2017). *Dubai starts tests in bid to become first city with flying taxis*. [Online; accessed April-2019]. URL: https://www.reuters.com/article/us-emirates-dubai-drones/dubai-starts-tests-in-bid-to-become-first-city-with-flying-taxis-idUSKCN1C0232.

Notter, Dominic A. et al. (2010). "Contribution of Li-ion batteries to the environmental impact of electric vehicles". In: *Environmental Science and Technology* 44.17, pp. 6550–6556. DOI: 10.1021/es903729a.

NPTEL (2014). *Architecture of Hybrid and Electric Vehicles*. Joint initiative of IITs and IISc, p. 43. URL: https://nptel.ac.in/courses/108103009/download/M3.pdf.

Ntziachristos, Leonidas et al. (2009). "COPERT: A European road transport emission inventory model". In: *Conference: Information Technologies in Environmental Engineering, Proceedings of the 4th International ICSC Symposium, ITEE 2009, Thessaloniki, Greece, May 28-29, 2009*. Thessaloniki, Greece: ITEE 2009. DOI: 10.1007/978-3-540-88351-7_37. URL: http://emisia.com/copert.

O 'mahony, Margaret et al. (2002). "Scope of Transport Impacts on the Environment (2000-DS-4-M2)". In: *Environmental RTDI Programme*, p. 47. URL: www.epa.ie.

O'Brien, Jeremy K. (2006). "Comparison of Air Emissions from Waste-to-Energy Facilities to Fossil Fuel Power Plants". In: 14th North American Waste to Energy Conference, pp. 69–78. DOI: 10.1115/NAWTEC14-3187.

Patterson, Michael D., Brian J. German, and Mark D. Moore (2012). "Performance Analysis and Design of On-Demand Electric Aircraft Concepts". In: *12th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference and 14th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*. Aviation Technology, Integration, and Operations (ATIO) Conferences. American Institute of Aeronautics and Astronautics. DOI: 10.2514/6.2012-5474.

Population City (2015). *Munich.Population.* [Online; accessed March-2019]. URL: http://population.city/germany/munich/.

Raykin, Leon, Heather L. MacLean, and Matthew J. Roorda (2012). "Implications of Driving Patterns on Well-to-Wheel Performance of Plug-in Hybrid Electric Vehicles". In: *Environmental Science & Technology* 46.11. PMID: 22568681, pp. 6363–6370. DOI: 10.1021/es203981a.

Renn, Ortwin and Jonathan Paul Marshall (2016). "Coal, nuclear and renewable energy policies in Germany: From the 1950s to the "Energiewende"". In: *Energy Policy* 99, pp. 224–232. ISSN: 0301-4215. DOI: 10.1016/j.enpol.2016.05.004.

Requia, Weeberb J. et al. (2018). "How clean are electric vehicles? Evidence-based review of the effects of electric mobility on air pollutants, greenhouse gas emissions and human health". In: *Atmospheric Environment* 185, pp. 64–77. ISSN: 18732844. DOI: 10.1016/j.atmosenv.2018.04.040.

Ribau, João P. and Ana F. Ferreira (2014). "Life cycle analysis and environmental effect of electric vehicles market evolution in Portugal". In: *International Journal of Energy and Environment* 5.5, 535–558 Journal.

Roscher, Michael A., Michel Roland, and Leidholdt Wolfgang (2013). "Improving Energy Conversion Efficiency by means of Power Splitting in Dual Drive Train EV Applications". In: *International Journal of Vehicular Technology* 2013, p. 5. DOI: 10.1155/2013/398361.

Rothfeld, Raoul, MIlos Balac, Kay O. Ploetner, et al. (2018). "Agent-based Simulation of Urban Air Mobility". In: *2018 Modeling and Simulation Technologies Conference*, pp. 1–10. DOI: 10.2514/6.2018-3891.

Rothfeld, Raoul, MIlos Balac, Kay O Ploetner, et al. (2018). "Initial Analysis of Urban Air Mobility?s Transport Performance in Sioux Falls". In: *2018 Aviation Technology, Integration, and Operations Conference.* AIAA AVIATION Forum. American Institute of Aeronautics and Astronautics. DOI: 10.2514/6.2018-2886.

Schiffer, Michael B., Tamara C. Butts, and Kimberly K. Grimm (1994). *Taking charge: the electric automobile in America.* Smithsonian Institution Press, p. 225. ISBN: 1560983558.

Schuessler, Nadine and Kay Axhausen (2008). "Identifying Trips and Activities and Their Characteristics from GPS Raw Data Without Further Inormation". In: *8TH International Conference on Survey Methods in Transport: ANNECY, France, May 25-31, 2008*. Vol. 502. ETH, Eidgenössische Technische Hochschule Zürich, IVT, p. 28. DOI: 10.3929/ethz-a-005589980.

Seeley, Brien A (2015). "Regional Sky Transit". In: *15th AIAA Aviation Technology, Integration, and Operations Conference*. AIAA AVIATION Forum. American Institute of Aeronautics and Astronautics. DOI: 10.2514/6.2015-3184.

— (2017). "Regional Sky Transit III: The Primacy of Noise". In: *55th AIAA Aerospace Sciences Meeting*. AIAA SciTech Forum. American Institute of Aeronautics and Astronautics. DOI: 10.2514/6.2017-0208.

Serra, Joao Vitor Fernandes (2011). *Electric Vehicles*. London: Routledge, p. 224. ISBN: 9781136452086. URL: https://doi.org/10.4324/9780203125755.

Shamiyeh, M., J. Bijewitz, and M. Hornung (2017). "A Review of Recent Personal Air Vehicle Concepts". In: *Aerospace Europe 6th CEAS Conference*. Bucharest, Romania.

Shamiyeh, Michael, Raoul Rothfeld, and Mirko Hornung (2018). "A Performance Benchmark of Recent Personal Air Vehicle Concepts for Urban Air Mobility". In: *ICAS Congress*.

Silva, Christopher et al. (2018). "VTOL Urban Air Mobility Concept Vehicles for Technology Development". In: *2018 Aviation Technology, Integration, and Operations Conference*. AIAA AVIATION Forum. American Institute of Aeronautics and Astronautics. DOI: 10.2514/6.2018-3847.

Sinha, Pranay et al. (2015). "Design and Testing of the Joby Lotus Multifunctional Rotor VTOL UAV". In: *15th AIAA Aviation Technology, Integration, and Operations Conference*. AIAA AVIATION Forum. American Institute of Aeronautics and Astronautics. DOI: doi:10.2514/6.2015-3336.

Skowron, A., D.S. Lee, and R.R. De León (2013). "The assessment of the impact of aviation NOx on ozone and other radiative forcing responses – The importance of representing cruise altitudes accurately". In: *Atmospheric Environment* 74, pp. 159–168. ISSN: 1352-2310. DOI: 10.1016/j.atmosenv.2013.03.034.

Smit, Robin and L. Ntziachristos (2013). "COPERT Australia: A new software to estimate vehicle emissions in Australia". In: *Australasian Transport Research Forum*. URL:

https://www.researchgate.net/publication/289154012_COPERT_Australia_A_new_software_to_estimate_vehicle_emissions_in_Australia.

Sokhi, Ranjeet S. (2011). *World Atlas of Atmospheric Pollution*. London: Anthem Press, p. 118. ISBN: 978-1-84331-289-5.

Stoll, Alex M (2015). "Comparison of CFD and Experimental Results of the LEAPTech Distributed Electric Propulsion Blown Wing". In: *15th AIAA Aviation Technology, Integration, and Operations Conference*. AIAA AVIATION Forum. American Institute of Aeronautics and Astronautics. DOI: 10.2514/6.2015-3188.

Stoll, Alex M, JoeBen Bevirt, et al. (2014). "Drag Reduction Through Distributed Electric Propulsion". In: *14th AIAA Aviation Technology, Integration, and Operations Conference*. AIAA AVIATION Forum. American Institute of Aeronautics and Astronautics. DOI: doi:10.2514/6.2014-2851.

Stoll, Alex M, Edward V Stilson, et al. (2013). "A Multifunctional Rotor Concept for Quiet and Efficient VTOL Aircraft". In: *2013 Aviation Technology, Integration, and Operations Conference*. AIAA AVIATION Forum. American Institute of Aeronautics and Astronautics. DOI: doi:10.2514/6.2013-4374.

Stoll, Alex M and Gregor Veble Mikic (2016). "Design Studies of Thin-Haul Commuter Aircraft with Distributed Electric Propulsion". In: *16th AIAA Aviation Technology, Integration, and Operations Conference*. AIAA AVIATION Forum. American Institute of Aeronautics and Astronautics. DOI: 10.2514/6.2016-3765.

Stoll, Alex M. et al. (2014). "Conceptual Design of the Joby S2 Electric VTOL PAV". In: *Aviation Technology, Integration, and Operations Conference, 16-20 June 2014, Atlanta, Georgia*. Atlants, Georgia, p. 6. URL: http://www.jobyaviation.com/S2ConceptualDesign(AIAA).pdf.

Struben, Jeroen and John Sterman (2008). "Transition Challenges for Alternative Fuel Vehicle and Transportation Systems". In: *Environment and Planning B: Planning and Design* 35.6, pp. 1070–1097. URL: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=881800.

SWM (2018). *SWM - At the forefront of the energy transition*. Tech. rep. Renewable Energies Expansion Campaign: Green energy & heating & cooling, p. 11.

Szczechowicz, Eva, Thomas Dederichs, and Armin Schnettler (2012). "Regional assessment of local emissions of electric vehicles using traffic simulations for a use case in Germany".

In: *The International Journal of Life Cycle Assessment* 17.9, pp. 1131–1141. ISSN: 1614-7502. DOI: 10.1007/s11367-012-0425-8.

Tahzib, Ing. Baryalai and Ing. Lenka Zvijáková (2012). "Environmental Impact of Land Transport". In: *Transfer inovácií* 24. URL: https://www.sjf.tuke.sk/transferinovacii/pages/archiv/transfer/24-2012/pdf/070-077.pdf.

The Council of the European Communities (1970). *Council Directive 70/220/EEC*. Tech. rep. Official Juornal of the European Communities, pp. 171–191. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:31970L0220%5C&from=EN.

— (1991). *Council Directive 91/441/EEC*. Tech. rep. Official Journal of the European Communities. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:31991L0441&from=EN.

— (1993). *Council Directive 93/59/EEC*. Tech. rep. Official Journal of the European Communities. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:31993L0059%7B%5C&%7Dfrom=EN.

— (2007). *Regulation (EC) No 715/2007 of the European Parliament and of the Council*. Tech. rep. Strasbourg: Official Journal of the European Union. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32007R0715%7B%5C&%7Dfrom=EN.

— (2014). *Commission Regulation (EU) No 136/2014*. Tech. rep. Brussels: Official Journal of the European Union. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32014R0136%7B%5C&%7Dqid=1545670972791%7B%5C&%7Dfrom=EN.

The Vertical Flight Society (2019). *Aurora PAV*. [Online; accessed December-2018]. URL: http://evtol.news/aircraft/aurora/.

Thipphavong, David P et al. (2018). "Urban Air Mobility Airspace Integration Concepts and Considerations". In: *2018 Aviation Technology, Integration, and Operations Conference*. AIAA AVIATION Forum. American Institute of Aeronautics and Astronautics. DOI: doi:10.2514/6.2018-3676.

TRIP, Transport Research Innovation Portal (2012). *Towards low carbon transport in Europe*. Tech. rep., p. 24. DOI: 10.1021/IC0201553.

Tzeng, Gwo-Hshiung, Cheng-Wei Lin, and Serafim Opricovic (2005). "Multi-criteria analysis of alternative-fuel buses for public transportation". In: *Energy Policy* 33.11, pp. 1373–1383. ISSN: 0301-4215. DOI: 10.1016/j.enpol.2003.12.014.

UBER (2016). *Fast-Forwarding to a Future of On-Demand Urban Air Transportation.* Tech. rep. UBER Elevate, p. 98.

Udaeta, Miguel Edgar Morales et al. (2015). "Electric Vehicles Analysis inside Electric Mobility Looking for Energy Efficient and Sustainable Metropolis". In: *Open Journal of Energy Efficiency* 04.01, pp. 1–14. ISSN: 2169-2637. DOI: 10.4236/ojee.2015.41001.

Umweltbundesamt (n.d.). *Handbuch für Emissions- faktoren des Strassen- verkehrs (HBEFA).* URL: http://www.hbefa.net/d/.

UNFCCC (2008). *KYOTO Protocol Reference manual on Accounting of Emissions and Assigned Amount.* UNFCCC. [Online; accessed April-2019], p. 127. ISBN: 92-9219-055-5. URL: https://unfccc.int/resource/docs/publications/08_unfccc_kp_ref_manual.pdf.

— (2015). *PARIS AGREEMENT.* UNFCCC. [Online; accessed April-2019], p. 25. URL: https://unfccc.int/sites/default/files/english_paris_agreement.pdf.

— (2018). *Report of the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement on the third part of its first session, held in Katowice from 2 to 15 December 2018.* FCCC/PA/CMA/2018/3, p. 8. URL: https://unfccc.int/sites/default/files/resource/cma2018_3%7B%5C%%7D28report%7B%5C%%7D29_advance.pdf.

United Nations (2014). *World Urbanisation Prospects. The 2014 revision.* [Online; accessed January-2019]. URL: https://esa.un.org/unpd/wup/publications/files/wup2014-highlights.pdf.

U.S. Department of Transnportation (2013). *Aviation Environmental Design Tool 2a – Uncertainty Quantification Executive Summary.* Tech. rep. Federal Aviation Administration, p. 6. URL: https://aedt.faa.gov/Documents/AEDT_2A_UQ_Executive_Summary%20v2.pdf.

Vahana (2018). *Vahana.* [Online; accessed January-2019]. URL: https://vahana.aero.

Vallamsundar, Suriya and Jane Lin (2011). "Overview of US EPA New Generation Emission Model: MOVES". In: *ACEE International Journal on Transportation and Urban Development* 1.1. DOI: 01.IJTUD.01.01.34.

Vascik, Parker D and R John Hansman (2017a). "Constraint Identification in On-Demand Mobility for Aviation through an Exploratory Case Study of Los Angeles". In: *17th AIAA Aviation Technology, Integration, and Operations Conference*. AIAA AVIATION Forum. American Institute of Aeronautics and Astronautics, p. 25. DOI: 10.2514/6.2017-3083.

— (2017b). *Systems-level analysis of on-demand mobility for aviation*. Tech. rep. 2. Atlanta, GA: MIT International Center for Air Transportation (ICAT) Department of Aeronautics & Astronautics Massachusetts Institute of Technology.

Weiss, Martin et al. (2012). "Will Euro 6 reduce the NOx emissions of new diesel cars? – Insights from on-road tests with Portable Emissions Measurement Systems (PEMS)". In: *Atmospheric Environment* 62, pp. 657–665. ISSN: 1352-2310. DOI: 10.1016/j.atmosenv.2012.08.056.

Westbrook, Michael H (2008). *The Electric Car: development and future of battery, hybrid and fuel-cell cars*. Vol. 38. London, Warrendale: IET Power and Energy Series, p. 216. ISBN: 9780852960134. DOI: 10.1049/PBPO038E.

Williams, Martin L. and David C. Carslaw (2011). "New Directions: Science and Policy - Out of step on NO_x and NO_2?" English. In: *Atmospheric Environment* 45.23, pp. 3911–3912. ISSN: 1352-2310. DOI: 10.1016/j.atmosenv.2011.04.067.

WORKHORSE Company (2019). *Sure Fly*. [Online; accessed January-2019]. URL: http://sureflyaero.com.

World Bank Group (n.d.). *CO2 emissions (metric tons per capita)*. URL: https://data.worldbank.org/indicator/EN.ATM.CO2E.PC?end=2014&locations=EU-DE&name_desc=true&start=1960&view=chart.

Wu, Xinkai et al. (2015). "Electric vehicles' energy consumption measurement and estimation". In: *Transportation Research Part D: Transport and Environment* 34, pp. 52–67. ISSN: 1361-9209. DOI: 10.1016/j.trd.2014.10.007.

Xie, Qi and Wagner, Armin (2010). *Electric Mobility. Perspectives and Recommended Reading and Links*. Tech. rep. July. GTZ, Transport Policy Advisory Servicies, Federal Ministry for Economic Cooperation and Development, p. 39. URL: https://www.sutp.org/files/contents/documents/resources/F_Reading-Lists/GIZ_SUTP_RL_Electro-Mobility_EN.pdf.

Yang, Fan, Bingbing Li, and Chris Yuan (2013). *Geographical Differences of Electricity Supply in Environmental Impact Assessment of Electric Vehicles*. Tech. rep. University of Wisconsin Milwaukee, pp. 13–18. DOI: 10.4271/2013-01-1280. URL: https://www.sae.org/publications/technical-papers/content/2013-01-1280/.

Yang, Liuhanzi et al. (2015). "Experimental Assessment of NOx Emissions from 73 Euro 6 Diesel Passenger Cars". In: *Environmental Science & Technology* 49.24. PMID: 26580818, pp. 14409–14415. DOI: 10.1021/acs.est.5b04242. eprint: https://doi.org/10.1021/acs.est.5b04242. URL: https://doi.org/10.1021/acs.est.5b04242.

Yu, Q, T Li, and H Li (2015). "Improving urban bus emission and fuel consumption modeling by incorporating passenger load factor for real world driving". In: *Applied Energy* 161, pp. 101–111. DOI: 10.1016/j.apenergy.2015.09.096.

Zhang, Shengyuan and Jimin Zhao (2018). "Low-carbon futures for Shenzhen's urban passenger transport: A human-based approach". In: *Transportation Research Part D: Transport and Environment* 62, pp. 236–255. ISSN: 1361-9209. DOI: 10.1016/j.trd.2018.02.001.

Ziemke, Dominik, Kai Nagel, and Rolf Moeckel (2016). "Towards an Agent-based, Integrated Land-use Transport Modeling System". In: *Procedia Computer Science* 83. The 7th International Conference on Ambient Systems, Networks and Technologies (ANT 2016) / The 6th International Conference on Sustainable Energy Information Technology (SEIT-2016) / Affiliated Workshops, pp. 958–963. ISSN: 1877-0509. DOI: 10.1016/j.procs.2016.04.192.

Zuev, Dennis, David Tyfield, and John Urry (2018). "Where is the politics? E-bike mobility in urban China and civilizational government". In: *Environmental Innovation and Societal Transitions* 30.July. ISSN: 22104224. DOI: 10.1016/j.eist.2018.07.002.

List of Figures

List of Tables

Appendices

A Appendix: Power plants within the Bavarian region

Provider	Unit name	Source of electricity	Capacity, MWh
RWE Generation	Gundremmingen C	uranium	1,288.0
Uniper	Franken I Block 2 + GT	gas	440.0
Uniper	Irsching 4	gas	561.0
Uniper	Ingolstadt 4	oil	386.0
E.ON Energy Projects GmbH	Kraftwerk-Plattling-DT	gas	40.0
PreussenElektra GmbH	Isar 2	uranium	1,410.0
SWM Services GmbH	SWM HKW Süd GuD2 GT62	gas	136.0
SWM Services GmbH	SWM HKW Freimann GT12	gas	50.0
VERBUND AG	Jochenstein-DE	run-of-the-river	66.0
VERBUND AG	Passau-Ingling-DE	run-of-the-river	43.2
VERBUND AG	Schaerding-Neuhaus-DE	run-of-the-river	48.0
VERBUND AG	Egglfing-DE	run-of-the-river	42.0
VERBUND AG	Ering-DE	run-of-the-river	36.3
VERBUND AG	Braunau-Simbach-DE	run-of-the-river	50.0
VERBUND AG	Stammham	run-of-the-river	23.2
VERBUND AG	Perach	run-of-the-river	19.4
VERBUND AG	Neuötting	run-of-the-river	26.1
VERBUND AG	Töging	run-of-the-river	85.3

Provider	Unit name	Source of electricity	Capacity, MWh
Wacker Chemie AG	GuD-Block	gas	130.0
VERBUND AG	Oberaudorf-Ebbs-DE	run-of-the-river	30.0
VERBUND AG	Nussdorf-DE	run-of-the-river	36.7
VERBUND AG	Rosenheim	run-of-the-river	35.1
VERBUND AG	Feldkirchen	run-of-the-river	38.2
VERBUND AG	Wassserburg	run-of-the-river	24.1
VERBUND AG	Teufelsbruck	run-of-the-river	25.0
VERBUND AG	Gars	run-of-the-river	25.0
ENGIE Deutschland AG	DEZOLLI 1	coal	472.0
SWM Services GmbH	SWM HKW Nord Block 2	coal	333.0
N-ERGIE Aktiengesellschaft	HKW Sandreuth Block 2	gas	75.0
SWM Services GmbH	PSW Leitzach M22	pumped storage	22.0
N-ERGIE Aktiengesellschaft	HKW Sandreuth Block 3	waste	25.0
SWM Services GmbH	HKW Nord Block 3 T30	waste	22.0
Total			6,043.6

Fraunhofer ISE 2019

B Appendix: BaU Scenario Results

Current Technology

Public Transport		LDV		Sum	
CO2, tonn	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*
266.05	1.71	11,570.46	21.33	11,836.51	23.04

Scenario 1 - 50 % of EV

Public Transport		LDV		Sum	
CO2, tonn	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*
266.05	1.71	7,427.10	14.47	7,693.14	16.17

Scenario 2 - 100 % of EV

Public Transport		LDV		Sum	
CO2, tonn	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*
266.05	1.71	3,283.73	7.60	3,549.77	9.31

Scenario 3 - 50 % of electricity from renewable sources

Public Transport		LDV		Sum	
CO2, tonn	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*
237.83	1.63	11,570.46	21.33	11,808.30	22.96

Scenario 4 - 100 % of electricity from renewable sources

Public Transport		LDV		Sum	
CO2, tonn	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*
200.75	1.58	11,570.46	21.33	11,771.21	22.91

Scenario 5 - public bus fleet improvement by 50 %

Public Transport		LDV		Sum	
CO2, tonn	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*
169.19	0.94	11,570.46	21.33	11,739.65	22.27

C Appendix: Vehicle emissions

CO_2 and NO_x released per kilometer travelled from different transportation modes depending on the distance

	MC Heavy		EV		CV (diesel)		CV (gasoline)	
Distance, km	*CO2, g/km*	*NOx, g/km*	*CO2, g/km*	*NOx, g/km*	*CO2, g/km*	*NOx, g/km*	*CO2, g/km*	*NOx, g/km*
5	655.76	1.52	50.59	0.12	160.04	0.75	185.30	0.17
10	430.09	1.00	50.59	0.12	160.04	0.75	185.30	0.17
15	355.57	0.82	50.59	0.12	160.04	0.75	185.30	0.17
20	318.78	0.74	50.59	0.12	160.04	0.75	185.30	0.17
25	297.04	0.69	50.59	0.12	160.04	0.75	185.30	0.17
30	282.78	0.65	50.59	0.12	160.04	0.75	185.30	0.17
35	272.60	0.63	50.59	0.12	160.04	0.75	185.30	0.17
40	264.97	0.61	50.59	0.12	160.04	0.75	185.30	0.17
45	259.03	0.60	50.59	0.12	160.04	0.75	185.30	0.17
47.5	255.06	0.59	50.59	0.12	160.04	0.75	185.30	0.17

CO_2 and NO_x released per kilometer considering different electricity mixes

	50 % of electricity from renewable sources				100 % of electricity from renewable sources			
	MC Heavy		EV		MC Heavy		EV	
Distance, km	*CO2, g/km*	*NOx, g/km*	*CO2, g/km*	*NOx, g/km*	*CO2, g/km*	*NOx, g/km*	*CO2, g/km*	*NOx, g/km*
5	399.94	1.01	30.85	0.08	63.71	0.35	4.91	0.03
10	262.30	0.66	30.85	0.08	41.78	0.23	4.91	0.03
15	216.86	0.55	30.85	0.08	34.54	0.19	4.91	0.03
20	194.42	0.49	30.85	0.08	30.97	0.17	4.91	0.03
25	181.16	0.46	30.85	0.08	28.86	0.16	4.91	0.03
30	172.46	0.44	30.85	0.08	27.47	0.15	4.91	0.03
35	166.25	0.42	30.85	0.08	26.48	0.15	4.91	0.03
40	161.60	0.41	30.85	0.08	25.74	0.14	4.91	0.03
45	157.97	0.40	30.85	0.08	25.16	0.14	4.91	0.03
47.5	155.55	0.39	30.85	0.08	24.78	0.14	4.91	0.03

D Appendix: UAM Scenario Results

Current Technology

Public Transport		LDV		UAM		Sum	
CO2, tonn	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*
265.83	1.71	11,571.13	21.34	24.26	0.06	11,861.23	23.10

Scenario 1 - 50 % of EV

Public Transport		LDV		UAM		Sum	
CO2, tonn	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*
265.83	1.71	7,427.53	14.47	24.26	0.06	7,717.62	16.23

Scenario 2 - 100 % of EV

Public Transport		LDV		UAM		Sum	
CO2, tonn	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*
265.83	1.71	3,283.92	7.60	24.26	0.06	3,574.01	9.36

Scenario 3 - 50 % of electricity from renewable sources

Public Transport		LDV		UAM		Sum	
CO2, tonn	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*
237.66	1.63	11,571.13	21.34	14.80	0.04	11,823.59	23.00

Scenario 4 - 100 % of electricity from renewable sources

Public Transport		LDV		UAM		Sum	
CO2, tonn	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*
200.64	1.58	11,571.13	21.34	2.35	0.01	11,774.13	22.93

Scenario 5 - public bus fleet improvement by 50 %

Public Transport		LDV		UAM		Sum	
CO2, tonn	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*
169.02	0.94	11,571.13	21.34	24.26	0.06	11,764.42	22.33

E Appendix: BaU and UAM scenarios results. Only agents using UAM

Current Technology

BaU Scenario							
Public Transport		LDV		UAM		Sum	
CO2, tonn	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*
0.22	0.001	12.71	0.018	-	-	12.92	0.019
UAM Scenario							
Public Transport		LDV		UAM		Sum	
CO2, tonn	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*
0.17	0.001	4.53	0.008	24.26	0.06	28.97	0.066

50 % of EV

BaU Scenario							
Public Transport		LDV		UAM		Sum	
CO2, tonn	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*
0.22	0.001	8.16	0.016	-	-	8.37	0.017
UAM Scenario							
Public Transport		LDV		UAM		Sum	
CO2, tonn	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*
0.17	0.001	2.91	0.006	24.26	0.06	27.34	0.063

100 % of EV

BaU Scenario							
Public Transport		LDV		UAM		Sum	
CO2, tonn	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*
0.22	0.001	3.61	0.008	-	-	3.82	0.009
UAM Scenario							
Public Transport		LDV		UAM		Sum	
CO2, tonn	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*
0.17	0.001	1.29	0.003	24.26	0.06	25.72	0.060

50 % of electricity from renewable sources

BaU Scenario

Public Transport		LDV		UAM		Sum	
CO2, tonn	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*
0.17	0.001	12.71	0.018	-	-	12.89	0.019

UAM Scenario

Public Transport		LDV		UAM		Sum	
CO2, tonn	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*
0.15	0.001	4.54	0.008	14.80	0.038	19.49	0.046

100 % of electricity from renewable sources

BaU Scenario

Public Transport		LDV		UAM		Sum	
CO2, tonn	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*
0.11	0.0009	8.16	0.018	-	-	8.27	0.019

UAM Scenario

Public Transport		LDV		UAM		Sum	
CO2, tonn	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*
0.14	0.001	2.91	0.006	2.35	0.013	5.41	0.021

Public bus fleet improvement by 50 %

BaU Scenario

Public Transport		LDV		UAM		Sum	
CO2, tonn	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*
0.16	0.0006	12.71	0.018	-	-	12.87	0.019

UAM Scenario

Public Transport		LDV		UAM		Sum	
CO2, tonn	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*
0.10	0.0006	4.54	0.008	24.26	0.056	28.90	0.065

F Appendix: BaU and UAM scenarios results for different trip distances

UAM trip distance < 10 km

BaU Scenario							
Public Transport		LDV		UAM		Sum	
CO2, tonn	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*
0.010	0.00003	0.703	0.00101	-	-	0.713	0.00103
UAM Scenario							
Public Transport		LDV		UAM		Sum	
CO2, tonn	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*
0.026	0.00016	0.253	0.00047	1.229	0.00284	1.509	0.00347

10 km < UAM trip distance < 20 km

BaU Scenario							
Public Transport		LDV		UAM		Sum	
CO2, tonn	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*
0.169	0.00097	9.535	0.01365	-	-	9.704	0.01462
UAM Scenario							
Public Transport		LDV		UAM		Sum	
CO2, tonn	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*
0.069	0.00043	3.376	0.00622	18.136	0.04196	21.580	0.4861

20 km < UAM trip distance < 30 km

BaU Scenario							
Public Transport		LDV		UAM		Sum	
CO2, tonn	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*
0.036	0.00008	1.785	0.00256	-	-	1.821	0.00264
UAM Scenario							
CO2, tonn	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*
0.050	0.00039	0.621	0.00114	3.542	0.00820	4.214	0.00973

30 km < UAM trip distance < 40 km

BaU Scenario							
CO2, tonn	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*
-	-	0.682	0.00098	-	-	0.682	0.00098
UAM Scenario							
CO2, tonn	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*	*CO2, tonn*	*NOx, tonn*
0.021	0.00017	0.288	0.00053	1.357	0.00314	1.666	0.00384