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Master’s Thesis

Estimating the Potential Reduction of Transport-related Air Pollutants in Munich

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Air is the basic requirement for all living organisms. For human beings, clean air is related to health as it is the major substance that our bodies absorb at up to 30,000 liters per day. Therefore, it is important to take a brief look at the meaning of air quality. Air quality can be defined by the content of air pollutants that affect human health, ecosystems and the environment. Nitrogen oxide (NO_x) is one of the important air pollutants because of its contribution to the precursors of the ozone (O_3) and the particulate matters (PM). Therefore, this study particularly deals with nitrogen dioxide (NO_2), a part of NO_x.

NO_2 emissions are emitted from combustion processes as an undesirable secondary reaction. In Germany, the transport sector is responsible for approx. 40 % of these emissions. Thereof, diesel-powered vehicles are the main contributors at 91 % of the transport-related NO_2 emissions. This air pollutant causes reductions in lung function and is particularly fatal for asthmatics.

To protect human health, the European Union (EU) has determined thresholds of air pollutants, aligned with the World Health Organization (WHO). For NO_2, the hourly amount of emissions should not exceed 200 µg/m^3 for more than 18 times in a year, and the average annual mean value should be less than 40 µg/m^3. According to the Federal Environmental Agency (UBA) which collects and evaluates the emissions data from 650 monitoring stations across Germany, 46 % of the monitoring stations located near roads in urban areas exceeded the annual threshold in 2017. Among German cities, Munich reached the highest NO_2 emissions average annual mean value, at 78 µg/m^3. It is almost twice as high as the EU limit.

On August 2nd, 2017, Germany's carmakers and policymakers met at a 'diesel summit' and discussed measures to reduce NO_2 emissions of diesel-powered vehicles, which would lead to reducing the emissions by up to 6 % in German cities. However, this reduction potential is still not enough to meet the EU limit. According to the monitoring stations by the Bavarian Environmental Agency, NO_2 emissions tend to decline since 2007. However, with the steadily growing populations and respectively increasing traffic, the decline process will be decelerated. For Munich, it is urgent to find efficient strategies to meet the EU limit and protect the health of the inhabitants. This Master’s thesis will investigate the potential to reduce emissions by implementing measures in the Munich region.

The methodological approach for potential reduction is based on a case comparison technique. The amount of emissions is forecasted and compared in two different scenarios. The first scenario predicts emissions without any reduction measures implemented. For the second scenario, a strategy will be implemented, and emissions will be estimated. These two scenarios will be modeled with the Multi-Agent Transport Simulation (MATSim).

The student will present intermediate results to the mentor(s) (Nico Kühnel, Prof. Dr.-Ing Rolf Moeckel, Jan Schönig (Siemens AG)) in the fifth, tenth, 15th and 20th week. The student will submit one copy for each mentor plus one copy for the library of the Focus Area Mobility and Transport Systems. Furthermore, the student will provide a PDF file of the master thesis for the website of this research group. In exceptional cases (such as copyright restrictions do not allow publishing the thesis), the library copy will be stored without public access and the PDF will not be uploaded to the website.

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

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Nico Kühnel, Prof. Dr.-Ing. Rolf Moeckel Student’s signature

Abstract

With increasing concern about nitrogen dioxide impacts, particularly on human health, Munich, one of the German cities with the highest NO_2 concentration, and its surrounding communities have implemented various emission reduction measures to improve air quality. However, a decrease significant enough to meet the EU threshold of the average annual mean value at 40 µg/m^3 has not been successful until today.

NO_2 emissions are mainly produced by human activities. In Germany, the transport sector, particularly the road transport, is responsible for the greatest share of the emissions. As a vast majority of the German population live in urban areas with diverse human activities, they are particularly affected.

Germany set the objective to increase the number of electric vehicles to one million by 2020 and to six million vehicles by 2030. Therefore, in 2015, Munich decided to promote electric cars as the major emission reduction measure to reach the governmental objective. This thesis predicts the potential reduction in the transport-related NO_2 emissions to be reached by improving vehicle efficiency through vastly increasing the number of electric vehicles in the vehicle composition.

The emissions are estimated for an average one-day each of the years 2011, 2020 and 2030 for four scenarios: A business-as-usual scenario without any measures, the optimistic, and the pessimistic scenarios, a scenario averaging optimistic and pessimistic. The last three scenarios are differentiated by the achievement of the objective. The thesis predicts the potential reductions in the emissions by comparing these scenarios.

The results of the emission estimation determine that, compared to the business-as-usual scenario, the promotion of electric vehicles will see a reduction of up to 9 % by the first target year. Furthermore, if efforts to increase electric cars continue, a reduction of up to 42 % could be expected by the year 2030.

Acknowledgement

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List of Abbreviations

BAU *Business-as-usual*

BImSchG *Bundes-Immissionsschutzgesetz*

BImSchV *Bundes-Immisionsschutzverordnung*

CNG *Compressed Natural Gas*

CO *Carbon monoxide*

CO_2 *Carbon dioxide*

CyAM *City Air Management*

E-Plan München *Planung von Elektromobilität im Großraum München*

EU *European Union*

EV *Electric vehicles*

HBEFA *Handbook on Emission Factors for Road Transport*

HC *Hydrocarbons*

HDV *Heavy-duty vehicles*

HNO_3 *Nitric acid*

IHFEM *Integrierte Handlungsprogramme zur Förderung der Elektromobilität in München*

KBA *Kraftfahrt-Bundesamt*

LPG *Liquefied Petroleum Gas*

LÜB *Landesüberwachungssystem Bayern*

MATSim *Multi-Agent Transport Simulation*

MITO *Microscopic Transport Orchestrator*

MVV *Münchner Verkehrs- und Tarifverbund*

N *Nitrogen*

NH_3 *Ammonia*

NH_4NO_3 *Ammonium nitrate*

NMHC *Non-methane hydrocarbons*

NO_2 *Nitrogen dioxide*

NO_x *Nitrogen oxide*

O *Oxygen*

O_3 *Ozone*

OSM *Open Street Map*

PM *Particulate matter*

QSim *Queue simulation*

RAS-N *Richtlinie für die Anlage von Straßen - Netzgestaltung*

SILO *Simple Integrated Land Use Orchestrator*

SO_2 *Sulfur dioxide*

StMUGV *Bayerisches Staatsministerim für Umwelt, Gesundheit und Verbraucherschutz*, *Siehe*

TCO *Total Cost of Ownership*

UBA *Umweltbundesamt*

WHO *World Health Organization*

Content

1. Introduction

Air is a basic requirement for nearly all living organisms. For human beings, clean air is directly related to health as it is the major substance that our bodies absorb. Therefore, it is important to take a brief look at the meaning of air quality. Air quality can be defined by the content of air pollutants that affect human health, ecosystems and the environment. Nitrogen dioxide (NO_2), a part of nitrogen oxide (NO_x), is one of the most important air pollutants because of its contribution to the precursor of ozone (O_3) and particulate matter (PM). Furthermore, it causes a reduction in lung function, such as is found in respiratory, and cardiovascular diseases and in asthma aggravation (World Health Organization 2006).

NO_2 emissions are produced by natural sources, but the predominant source is human activities, in particular combustion processes (World Health Organization 2006). In Germany, the transport sector is responsible for the greatest share of the emissions. Of these, diesel-powered vehicles are the main contributors at 61 % of the transport-related NO_2 (Minkos et al. 2018; Pitz et al. 2015). 77 % of the German population live in urban areas with diverse human activities and so are particularly affected (Statistisches Bundesamt 2018b).

To protect human health, the European Union (EU) has developed thresholds of air pollutants, aligned with the World Health Organization (WHO). The hourly amount of the NO_2 emissions should not exceed 200 $\mu g/m^3$ more than 18 times in a year, and the average annual mean values should be less than 40 $\mu g/m^3$ (EU 2008). According to the Federal Environmental Agency (UBA – German abbreiviation) (Minkos et al. 2018), which collects and evaluates the emissions data from 650 monitoring stations across Germany, 46 % of the road side monitoring stations in urban areas exceeded the EU limit in 2017. Among German cities, Munich reached the highest average annual mean value of the NO_2 emissions, at 78 $\mu g/m^3$ (Umweltbundesamt 2018a). This is almost twice as high as the EU limit. Over the past decade, the concentration of NO_2 in Munich has shown a minor reduction (Bayerisches Landesamt für Umwelt 2017d). However, with the steadily growing population and respectively increasing traffic, this decline process is likely to decelerate. It is urgent that Munich find efficient strategies to meet the EU limit and protect the health of the inhabitants.

In addition to the thresholds, the member countries of the EU have agreed on developing an 'air quality plan' if an exceedance of emission is detected in any area. The plan should provide emission reduction measures to meet the EU limits (Bundesgesetz; EU 2008). In 2004, Munich developed its first air quality plan. In the meantime, Munich along with surrounding communities has developed six versions of the plan, and the seventh update is in process. As of the sixth update of the air quality plan, Munich began to promote electric vehicles as a major emission reduction measure to support the national governmental program *Elektromobilität* that provides guidelines to promote electric mobility (Bundesministerium für Wirtschaft und Technologie et al. 2011; Bayerisches Staatsministerium für Umwelt, Gesundheit und Verbraucherschutz 2015).

This thesis focuses on the transport-related NO_2 emissions in the Munich metropolitan area. It estimates an average one-day accumulation of the emissions for each of the years 2011, 2020 and 2030 for four scenarios. The first scenario predicts the emissions without any reduction measures implemented. For other scenarios, NO_2 is forecast with an implementation of the electromobility intervention, differentiated according to the achievement of the objective. These scenarios are modeled with the emission modelling tool integrated in Multi-Agent Transport Simulation (MATSim). This thesis predicts the possible reductions in the emissions by comparing the scenarios. It will help to realize the importance of reduction strategies for the Munich metropolitan area and to react for the future.

The thesis is structured as follows. Chapter 2 gives general information concerning NO_2 pollution. This includes the sources and the formation of NO_2 and their distribution in Munich. Chapter 3 then presents the emissions reduction measures that have been included in the air quality plans. Moreover, it covers an in-depth look at the recent governmental objective to increase electric vehicles. This is followed in Chapter 4 by a description of modelling approaches used in emission modelling. Chapter 5 depicts the simulation approach of the transport model MATSim and the methodology of the integrated emission modelling tool. In Chapter 6, the Munich metropolitan area as the study area is described and its road transport is discussed in more depth. Chapter 7 specifies and details the data that are necessary to model the emissions. Chapter 8 describes all the specifics taken into account for the four scenarios. In Chapter 9, the results for each scenario are presented and compared. Finally, Chapter 10 makes some concluding remarks.

2. Background information on Air Pollution

Air pollution, existing in the form of gas, liquid or solid phase, has impacts on the environment and on human health. Urban areas with diverse human activities, such as industry and transportation, are particularly affected. Such areas account for approx. 77 % of German population (Statistisches Bundesamt 2018b). Institutions such as environmental agencies have designated the air pollutants affecting air quality; these are sulfur dioxide (SO_2), PM, O_3 and NO_2, among others. Among these, NO_2 further plays a role as the precursor for other air pollutants, such as O_3 and PM (World Health Organization 2006). This chapter gives an overview of NO_2, such as its formation and its sources. Further, the situation of air pollution in Munich is discussed.

2.1 Nitrogen dioxide

Air pollutants can be classified based on their sources. Primary air pollutants are emitted in a direct way into the atmosphere, whereas secondary air pollutants are formed within the atmosphere itself. NO_x, various gaseous compounds structured with nitrogen (N) and oxygen (O), is emitted in NO and NO_2 as both primary and secondary pollutants. As a primary pollutant, N contained in fuels is converted to NO_x during the combustion processes in stationary sources (heating and power generation) and in mobile sources (internal combustion engines in vehicles and ships). Approximately 95 % of this NO_x is produced as primary NO and the rest is formed as primary NO_2. However, the resulting NO rapidly oxidizes with atmospheric O_3 to NO_2, which composes the major proportion of NO_2 (World Health Organization 2006). Based on this fact, NO_x emissions are often indicated as NO_2. Equation 1 shows the chemical reaction of secondary NO_2.

$$NO + O_3 \rightarrow NO_2 + O_2.$$

Equation 1: Chemical reaction of secondary NO2 formation

When it absorbs sunlight, NO_2 decomposes into NO and O, which further leads to a formation of ground level O_3 (World Health Organization 2006). These reactions are presented as follows.

$$NO_2 + hv \rightarrow NO + O$$

and

$$O + O_2 \rightarrow O_3,$$

Equation 2: Chemical reaction of NO2 decomposition

where:

- hv: light from solar radiation,
- h: Planck's constant,
- v: frequency of light.

Such O_3 and NO_2 are the main cause of photochemical smog. In addition, NO_2 is one of the major precursor gases for PM. Nitric acid (HNO_3) oxidized from NO_2 reacts with ammonia (NH_3) to form ammonium nitrate (NH_4NO_3), which leads to secondary particles (World Health Organization 2006).

$$HNO_3 + NH_3 \rightarrow NH_4NO_3.$$

Equation 3: Chemical reaction into secondary PM

Apart from combustion processes, NO_2 is produced from natural sources, such as stratospheric nitrogen oxides, bacterial and volcanic action, and lightning. However, the resulting emissions are rarely counted to the total amount. It builds the background atmospheric concentrations. The anthropogenic activities, particularly the combustion processes, remain as the central source (World Health Organization 2006). The emissions generated from the combustion processes are caused by incomplete combustion, and the amount depends on the composition of fuels (van Basshuysen 2010). In Germany, the major contributor to the emissions is the transport sector, at approx. 41 %, as shown in Figure 1. In particular, road transport is responsible for the majority of the transport-related emissions (Umweltbundesamt 2018b).

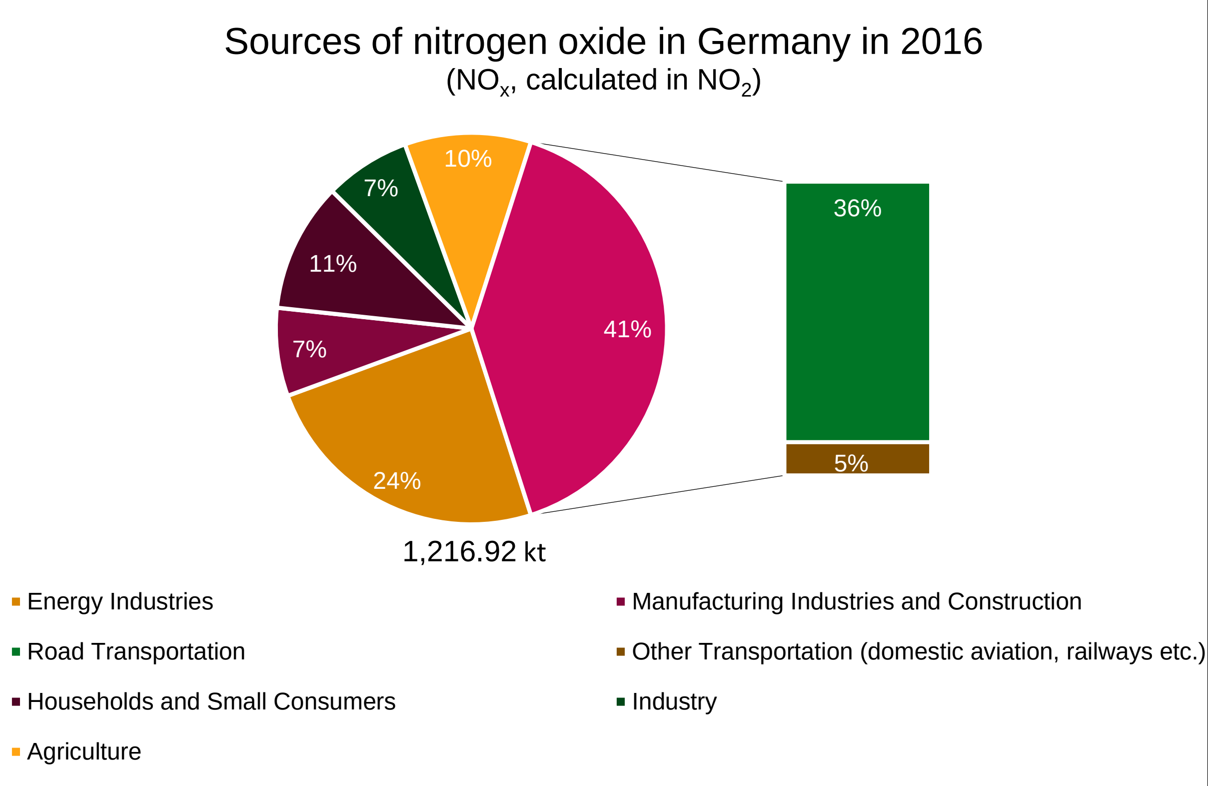

Figure 1: Sources of nitrogen oxide in Germany, adapted from Umweltbundesamt 2018b

NO_x, particularly NO_2, is the pollutant of far greater concern in relation to the environment and human health. In the ecological system, the emissions cause discoloring of plants to yellow, premature aging or declining growth. Moreover, significant intrusion of NO_2 into the ecosystem has an impact as overfertilization. Together with the Sulphur compounds, NO_2 contributes to an imbalanced acidity, which further changes living conditions for plants (Bayerisches Landesamt für Umwelt 2004). Concerning human health, NO_2 pollution causes a reduction in lung function, such as is found in respiratory, and cardiovascular diseases, and in asthma aggravation. In particular, it is fatal for children, elderly people and asthmatics (World Health Organization 2006). Moreover, according to the UBA (Schneider et al. 2018), the long-term exposure to such emissions leads to a reduction of a lifetime or even to a premature death. 6,000 premature deaths caused by cardiovascular diseases in Germany in 2014 were traced back to NO_2 emissions. Epidemiological studies including studies by the UBA have set a clear correlation between NO_2 and its impact on human health. However, it is strongly debated. Professor Dieter Köhler, a lung specialist and the former president of the German Pneumological Association, commented on those epidemiological studies that imply causality rather than correlation. A correlation builds a basis for a hypothesis, and it must be confirmed through further investigations, something that according to Köhler the studies lack by simply repeating studies of the same design continually. The UBA's study on the premature death emphasizes the dilemma of the epidemiological studies (Köhler 2018). In addition, pneumologists argue that the pollution caused by combustion processes is a mixture of hazardous substances. Restriction of its impact on human health to a single pollutant, such as NO_2, in experiments does not represent the overall exposure in reality (Bundesverband der Pneumologen, Schlaf- und Beatmungsmediziner 3/9/2018). The environmental medical experts such as Wolfgang Straff contradicted that a regulation of NO_2 serves as a prevention for the entire population, and not only for the healthy population (FOCUS Online 2018).

To protect human health, the European Union has implemented thresholds of air pollutants in the EU directive (2008/50/EC) aligned with the WHO, which is transferred to German law as 'the 8th Federal Pollution Control Act (BImSchG – German abbreviation)' and the more detailed, '39th ordinance for the implementation of the Federal Emission Control Act (39. BImSchV – German abbreviation)'. For NO_2, as of 2010, the hourly amount of emissions should not exceed 200 µg/m^3 for more than 18 times per year, and the average annual mean value should be less than 40 µg/m^3. If the emissions exceed the alert threshold at 400 µg/m^3 for three hours, short-term measures should be implemented immediately (EU 2008).

To provide comparable data throughout Europe, the EU directive gives a guideline for standardized methods and criteria (EU 2008). The directive prescribes that metropolitan areas with more than 250,000 inhabitants and areas with fewer inhabitants nevertheless specified by their national government should be monitored (EU 2008). In Germany, three pollution regimes are classified for emissions detection, namely, 'rural area', 'urban area', and 'urban traffic area'. Rural areas represent the background emissions, depicting areas that are not influenced by local emissions. Monitored pollution in urban areas characterize typical air quality in cities. Emissions produced from road transport are detected by the monitoring stations located on highly trafficked roads, which contribute to the urban traffic pollution (Minkos et al. 2018; Bundesrechtsverordnung 2010). The following figure schematically depicts the three pollution regimes. The amount in each regime is roughly presented.

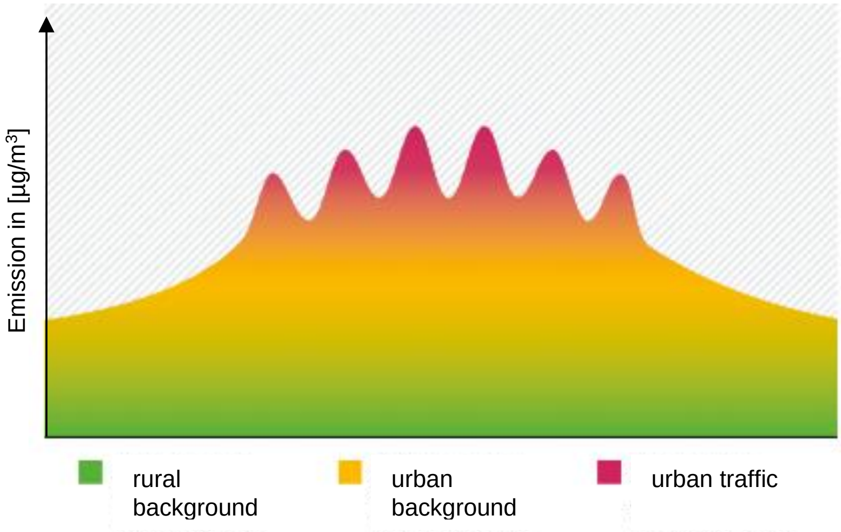

Figure 2: Schematic horizontal representation of the pollution regime for nitrogen dioxide, adapted from Minkos et al. 2018

These pollution regimes are observed daily by more than 650 monitoring stations across Germany. Five of these are located in Munich. One out of the five detects the highest pollution within the Munich metropolitan area, which is discussed further in the following section.

2.2 Air Pollution in Munich

Already in the 60s, the city Munich established a monitoring network, which was adopted in 1972 by the Bavarian monitoring system (LÜB – German abbreviation) which is integrated in the Bavarian Environmental Agency. To align with 39. BImschV, LÜB has relocated the measuring stations several times, thereby reducing from eight to five in the meantime. These are located in: Allach; Landshuter Allee; Johanneskirchen; Lothstraße and Stachus. Three of the stations detect pollution in the Munich urban background whereas two are responsible for the urban traffic areas. As a reference for pollution in the rural area, there is an additional station in Andechs, outside of the city (Bayerisches Landesamt für Umwelt 2017a; Bayerisches Staatsministerium für Umwelt, Gesundheit und Verbraucherschutz 2004). The locations of the monitoring stations and their area types are displayed in the following figure.

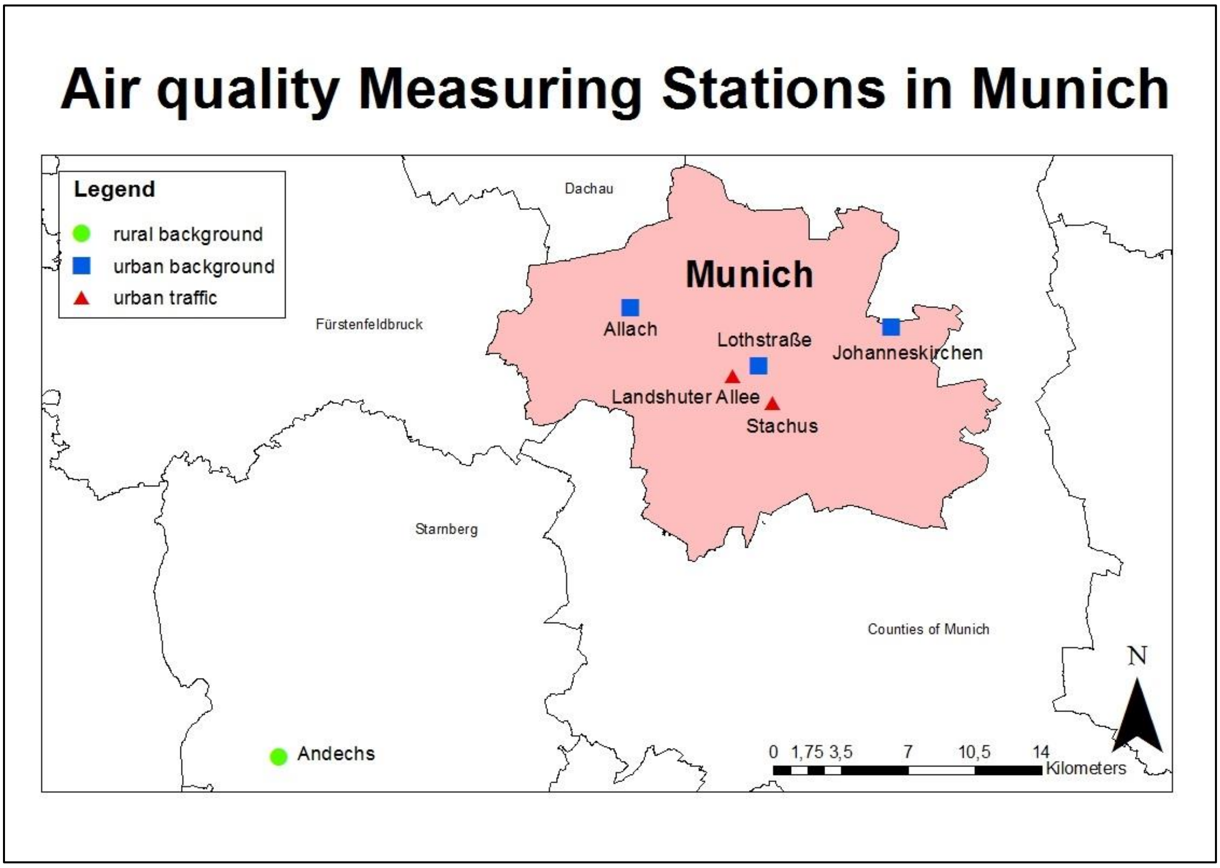

Figure 3: Air quality measuring stations in Munich, adapted from Bayerisches Landesamt für Umwelt 2018b

The emissions measured by the six stations are presented as the average annual mean value in Figure 4. The Andechs station, which is not influenced by the local emissions, detects the lowest value among other stations. During the presented period from 2005 to 2017, NO_2 has decreased slightly. Observing the urban area, the progressions of NO_2 in Munich have generally decreased since 2005. Two urban background stations, Johanneskirchen und Lothstraße, detected a decrease of the emissions in the first half of the period. In 2008, the average annual mean value detected by the Johanneskirchen station achieved to meet the threshold at 40 µg/m^3. From 2011 to 2017, together with the station in Allach, detected values are relatively constant. The air quality measuring stations located on high trafficked roads observed an increase of the emissions from 2005 to 2010. In 2010, NO_2 detected by the Landshuter Allee reached the highest amount at 99 µg/m^3. In the following period, the emissions fluctuate around 80 µg/m^3. In 2017, the Landshuter Allee station detected the highest NO_2 value among all German cities at 78 µg/m^3 (Umweltbundesamt 2018a; Bayerisches Landesamt für Umwelt 2018a). It is almost twice as high as the EU limit. To meet the EU threshold, NO_2 emissions should be reduced by at least 49 %.

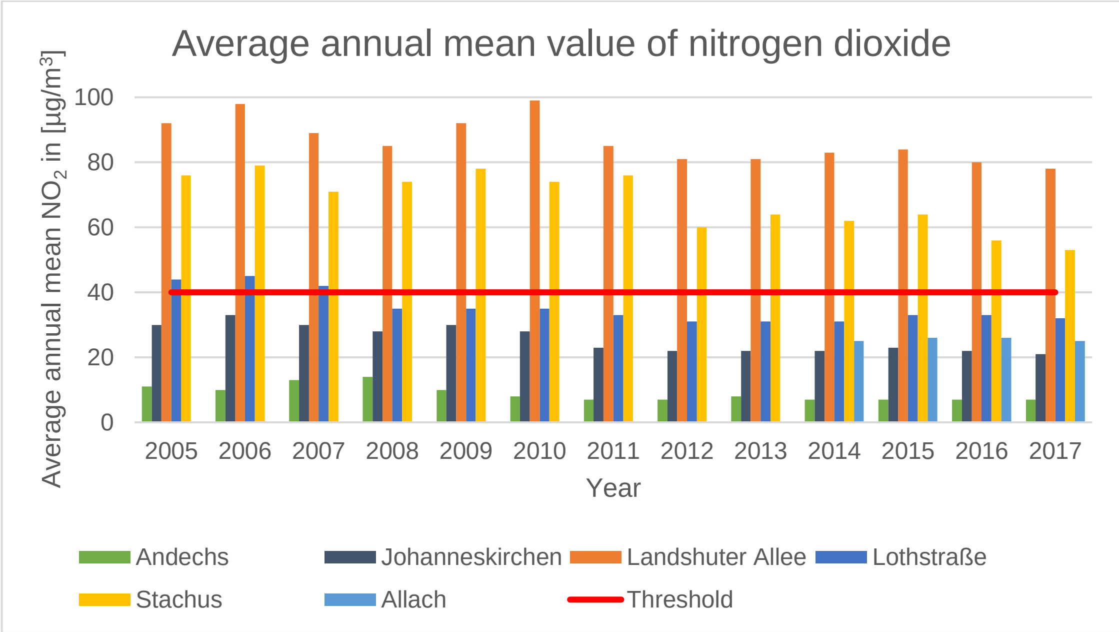

Figure 4: Average annual mean value of NO_2 2005 – 2017, adapted from Bayerisches Landesamt für Umwelt 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017b, 2018a

The two monitoring stations with the highest amount of emissions are in urban traffic areas. The Landshuter Allee, a so-called hotspot, was further investigated by the Bavarian State Ministry of Environment. It affirmed that the road transportation was responsible for approx. 56 % of the NO_2 emissions total in 2014. Of transport-related emissions, diesel vehicles are predominant source at 61 % (see Figure 5).

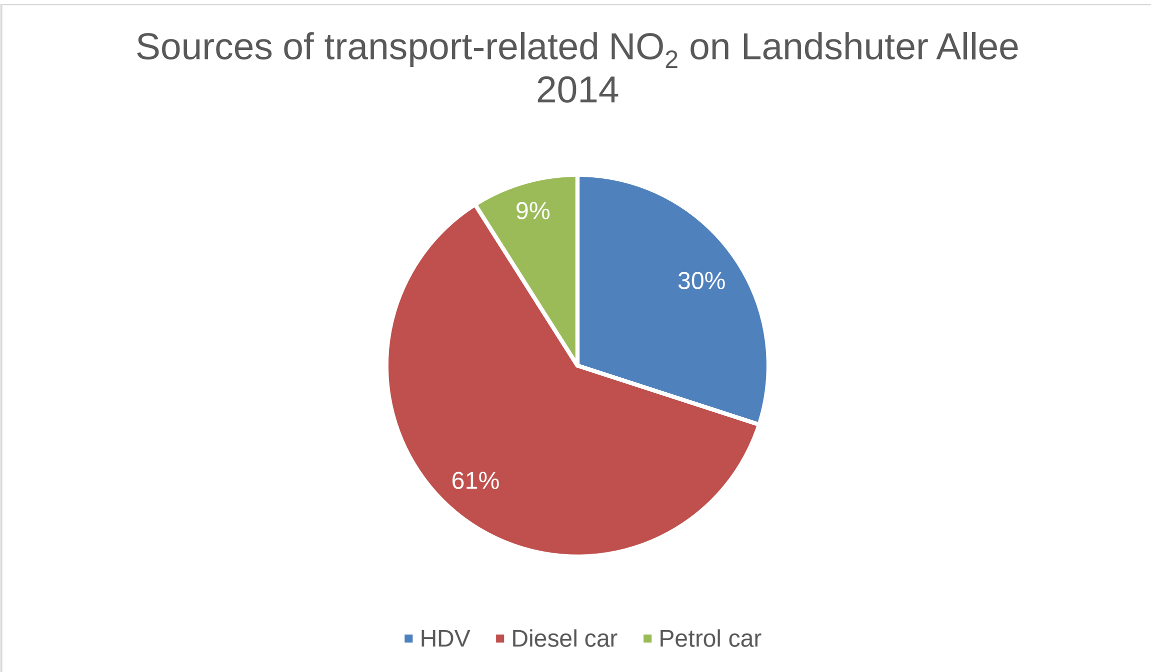

Figure 5: Sources of transport-related nitrogen dioxide on Landshuter Allee, adapted from Pitz et al. 2015

Although the number of the diesel vehicles driving on Landshuter Allee does not much differ from those of petrol's (diesel: 57,704; petrol: 63,270), a large difference in NO_x and NO_2 were observed in the study. The major share of both emissions was traced back to diesel cars. Diesel-powered vehicles were responsible for 43 % of NO_x and for 75 % of the total NO_2 emission, while petrol cars produced much less emissions (NO_x: 7 %; NO_2: 2 %). The reason for the high amount of NO_2 lies in the fact that up to 50 % of the NO_x emission produced from diesel vehicles occurs as primary NO_2, which contribute to the disproportional exposure of NO_2 (Pitz et al. 2015).

Munich has been attempting to improve the air quality. The following chapter discusses the measures that have been implemented so far and those planned.

3. Emissions Reduction Measures

According to §47 BImSchG (Bundesgesetz), all authorities in which the concentrations of one or more pollutants exceed the corresponding threshold along with the tolerance margin, should set up an ‘air quality plan’. For NO_2, the tolerance margin means a gradual reduction of 50 % from July 19th, 1999, and zero from 2010. Such a plan should guarantee long-term compliance with the air quality target values by:

- analyzing the situation of the emissions;
- examining all emissions reduction measures that come into question and defining the possible measure;
- organizing efforts by public administrations in their areas;
- binding all participating administrative areas.

Furthermore, the plan should be updated if the concentration of pollutants further exceeds the limit despite the introduced measures within two years. With the detected exceedances of NO_2 and PM in 2002, Munich had to develop the air quality plan (Bayerisches Staatsministerium für Umwelt, Gesundheit und Verbraucherschutz 2004). In the meantime, the plan has been updated six times, and the next update is in process. Today, PM has met its EU threshold whereas the average annual mean value of the NO_2 emissions still remain as the particular problem. This chapter presents the emission reduction measures that have been introduced in the air quality plans.

The measures implemented so far have been derived from the ‘Avoid-Shift-Improve’ strategies, which are the generalized concept for emission reduction strategies in urban planning. The avoid strategy aims at decreasing unnecessary trips or reducing travel times. The shift refers to switching to a more efficient transport mode. If these two concepts cannot be applied, the improve strategy allows increasing the vehicle efficiency of the motorized trips (Sustainable Urban Transport Project).

3.1 Implemented Measures

Air quality plan: a package of fundamental measures

In Bavaria, the limits for NO_2 and PM were exceeded in 2002. Therefore, the responsible authority for the air quality plan, the Bavarian State Ministry for Environment, Health and Consumer Protection (StMUGV – German abbreviation), assigned the local jurisdiction, Upper Bavaria, to create an air quality plan frame work for metropolitan Munich. In 2004, the air quality plan for Munich was developed by Upper Bavaria with the participation of the Bavarian Environmental Protection Agency and the city of Munich. In the air quality plan, Munich described measures that had been implemented before. For road transport, the city had attempted to shift car users to environmentally friendly modes by supporting bike and the public transportation. With the plan developed in 2004, the city introduced a package of measures encouraging all transport modes. It included establishing freight centers and city logistics for commercial transport, further supporting of the public transportation, expanding of the infrastructure, amongst others. The effects resulting from these measures are difficult to quantify due to complex contexts (Bayerisches Staatsministerium für Umwelt, Gesundheit und Verbraucherschutz 2004).

First update: redirection of heavy-duty vehicles

Given the potential of emission reductions from the package of measures integrated in the previous plan is predicted to be less, a significant high level of NO_2 and PM was detected in 2005. Therefore, the first updated plan in 2007 established the main measure for heavy-duty vehicles (HDV) passing through the city. All vehicles that weigh more than 3.5 t and do not have their destination in the city should be redirected to Autobahn A 99 instead of driving through the city (Bayerisches Staatsministerium für Umwelt, Gesundheit und Verbraucherschutz 2007). The city reported that freight transport within the city had been relieved since the implementation in February 1^{st}, 2008. From 2007 to 2009, a reduction of 18 % freight transport at the Landshuter Allee area was detected (Referat für Stadtplanung und Bauordnung 2010).

Second update: introduction of Environmental Zone

Four of seven air quality measuring stations detected exceedances of NO_2 and PM, including their tolerance values, in 2007. Therefore, the second update of the air quality plan was arranged, in which a reduction of emissions was targeted by an implementation of a new ‘environmental zone’. For this concept, all vehicle types such as passenger cars, trucks and buses are categorized according to the level of exhaust emissions in compliance with the identification ordinance of vehicles (35. BImSchV) (Bundesrechtsverordnung 2006), as follows:

- no plaque for pollution group 1: diesel vehicles with Euro I/1, or even worse, and petrol vehicles without regulated catalytic converters;
- red plaque for pollution group 2: diesel vehicles with Euro II/2 and diesel vehicles with Euro I/3 plus particulate filters;
- yellow plaque for pollution group 3: diesel vehicles with Euro III/3 and diesel vehicles with Euro II/2 with particulate filters;

- green plaque for pollution group 4: diesel vehicles with Euro IV/4, diesel vehicles with Euro III/3 with particulate filters and petrol vehicles with Euro 1 with regulated filters, or even better, such as vehicles without combustion engines.

As of October 1st, 2008, vehicles without plaque (pollution group 1) were no longer permitted to drive in the environmental zone. Such vehicles accounted for approx. 5 % in the whole city of Munich then. The environmental zone was applied within the middle ring area, not including the middle ring itself. This particular area counts approx. 15 % of the entire city area, shown in Figure 6. However, this second version of the plan predicted that NO_2 would still amount to more than the EU limit which would come into effect as of 2010 (Bayerisches Staatsministerium für Umwelt, Gesundheit und Verbraucherschutz 2008).

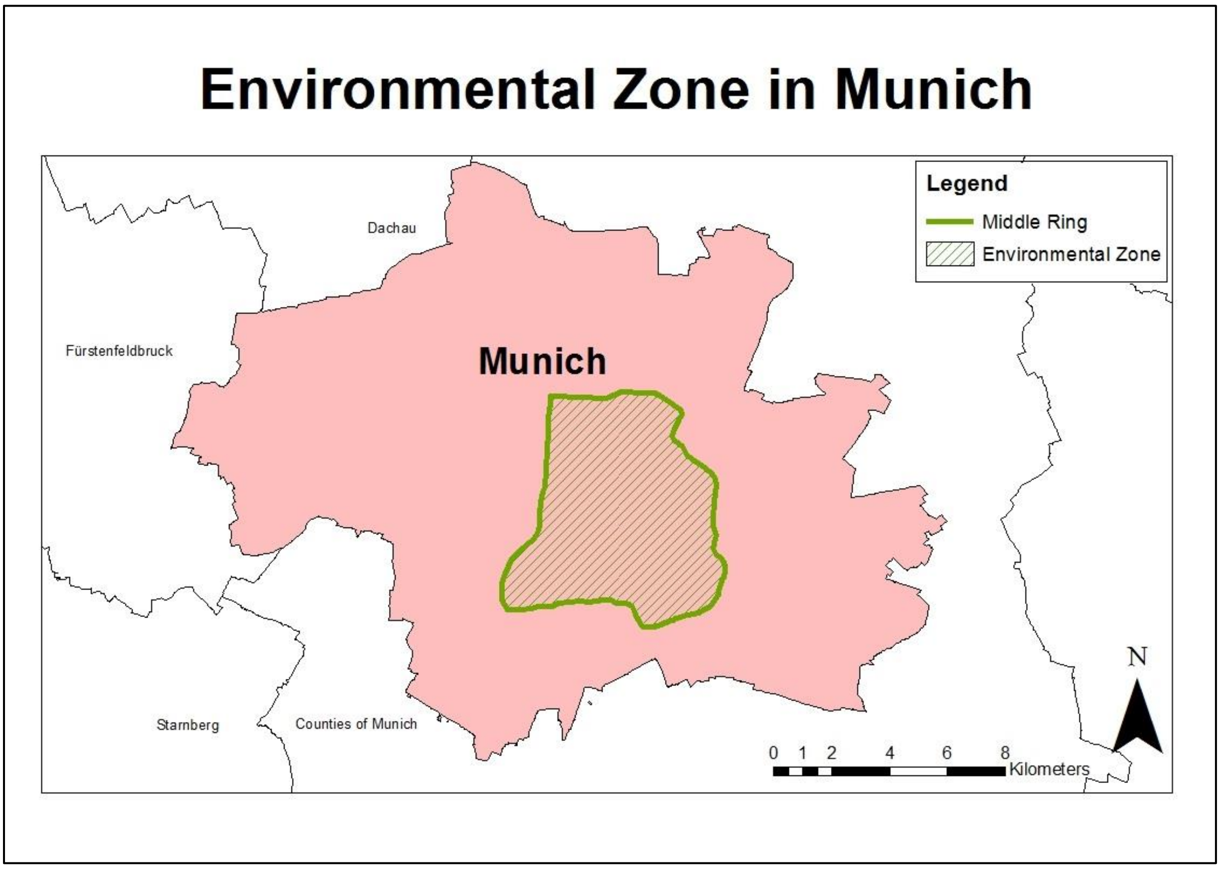

Figure 6: Environmental zone in Munich, adapted from (Bayerisches Staatsministerium für Umwelt, Gesundheit und Verbraucherschutz 2008)

Third update: participation of surrounding communities

The third update of the air quality plan aimed at cooperation with the surrounding communities, as high levels of air pollution within the city, particularly PM, are largely caused by commutes from surrounding areas Therefore, Munich in cooperation with the urban agglomeration, including 79 communities in 7 districts, targeted a comprehensive improvement of the regional air quality. However, since procedure steps were delayed due to extensive coordination processes, the third update was officially stated in 2012, after the fourth updated plan (Bayerisches Staatsministerium für Umwelt und Gesundheit 2012).

Fourth update: intensification of environmental zone

While the third update was in process, the Landshuter Allee station measured PM and multiple stations (Landshuter Allee, Stachus and Luise-Kiesselbach Platz – which does not exist today) measured a significantly high level of NO_2 emissions in 2008. Therefore, the Munich city council determined to tighten the environmental zone in the fourth update. Many approaches were discussed, such as expansion of the zone to include the middle ring or even the entire urban area. However, the restriction to such areas would have led to displacements into residential zones, main roads and surrounding communities. Implementation of limited access in other areas, such as the Altstadtring, was also discussed, but has been rejected due to its trivial potential for emissions reduction. Finally, the city council agreed on a graduated ban of passenger vehicles. As of October 1st, 2010, only vehicles with yellow and green plaques were allowed to drive in the zones. After two years, the regulation has become more stringent, so that only vehicles with green plaques have been allowed to drive in the environmental zone. This measure was expected to reduce NO_2 by 6 µg/m^3 (Bayerisches Staatsministerium für Umwelt und Gesundheit 2010).

In 2010, the NO_2 threshold at 40 µg/m^3 came into force. As Germany could not comply with the threshold throughout all highly trafficked areas, Munich along with numerous communities and cities requested a temporary extension for 57 areas, based on article 22 of the EU directive (2008/50/EC). According to this article, the member nations can allow the areas and metropolises which had set up their air quality plan to prolong the deadline by 5 years at most (EU 2008). On February 20th, 2013, the European Commission announced the approval of the extension for 22 areas. However, the commission had forecasted that NO_2 in 35 areas would still exceed the limit in spite of already implemented plus additional measures. Therefore, for such areas, including metropolitan Munich, the commission required these areas to implement stricter reduction measures in their air quality plan (European Commission, Commission Decision of 2/20/2013).

Fifth update: emissions reduction measures focusing on Landshuter Allee

For the first time, PM finally met the EU threshold both for the hourly and the annual average mean value in 2012. However, the long-term compliance for the pollutant was not guaranteed even with planned interventions. Furthermore, NO_2 continuously exceeded the limit from 2010 to 2013. In 2010, the Landshuter Allee station detected its maximum amount at 99 µg/m^3. Therefore, Upper Bavaria in cooperation with the city of Munich and the Environment Agency developed the fifth update on behalf of the StMUG, which came into force in 2014. The main focus of this version was to reduce emissions particularly on Landshuter Allee by setting a speed limit of 50 km/h. The potential reductions were predicted at 3 % of PM and 13 % of NO_2, which would still be insufficient to draw NO_2 under the limit (Nagel et al. 2012). Concerning the whole plan area, a package of measures consisting of new and once discussed actions has been established, which covered the whole spectrum of activities related to the objective of the air quality plan. One of the major actions within the package was the implementation of dynamic traffic control at the connection between the middle ring and the exit of two Autobahns A 95 and A 96 to improve traffic flow and the air quality respectively (Bayerisches Staatsministerium für Umwelt, Gesundheit und Verbraucherschutz 2014).

Although the overall NO_x level has decreased over the years, the NO_2 concentration was only slightly reduced in urban traffic areas. Therefore, within the fifth update, the major polluter was re-examined by the Bavarian State Ministry of the Environment. This investigation has determined that the transport sector still remains the most significant source, and diesel vehicles are responsible for the greatest share of the emission (see more details in Section 2.2) (Pitz et al. 2015). On August 2nd, 2017, Germany's carmakers and policymakers met at a 'diesel summit' and discussed measures to reduce NO_2 emissions of diesel-powered vehicles, and they decided on 'software updates', which improve shifting 5.3 million diesel vehicles to the higher vehicle efficiency, Euro 5 or 6. These would reduce up to 30 % of NO_x emissions generated by a vehicle. However, according to the examination by UBA, the software updates would reduce the emissions by up to 6 % in German cities, which is still not enough to meet the EU limit (Umweltbundesamt 2017; Bayerisches Landesamt für Umwelt 2017c). Today, the ban on diesel vehicles came into question as an immediate measure. Thereby, the ban includes all diesel-powered vehicles in Euro 1 to 5, which vary based on the implemented area. As the Federal Administrative Court allows a diesel ban in February 2018, this is now dependent on the courts in many German cities. Hamburg has already executed the ban. Berlin, Bonn and Cologne plan to implement it in 2019, and it is being discussed in other cities as well (Wo Diesel-Fahrverbote gelten oder drohen 2018). Munich has determined not to perform the traffic ban. The ban on Munich's main road would lead to a relocation of the traffic flow onto the receptive roads. Based on the preliminary investigation of the traffic ban in Munich, this concept is temporally or functionally inappropriate and not controllable. This intervention would lead to a grave displacement effect, and the problem areas would rather be shifted instead of being solved (Regierung von Oberbayern 2017). However, the possibility of executing the diesel ban remains, which would affect many car users, since 42 % of the traffic consists of diesel vehicles in Munich (Kraftfahrt-Bundesamt 2017c).

3.2 Promoting Electric Vehicles

In 2014, the amount of NO_2 emission at the hotspots still remained over the EU limit. Compared to the previous year, even higher amounts were detected at the Landshuter Allee station (83 µg/m^3). As a result, Munich was requested to develop an additional update for the air quality plan.

Promoting electric vehicles had been already included in the older versions and finally became the major emission reduction measure in the sixth update of the air quality plan. Supported by two projects – *Integrierte Handlungsprogramme zur Förderung der Elektromobilität in München* (IHFEM) and *Planung von Elektromobilität im Großraum München* (*E-Plan München)* – the electromobility will be introduced and promoted in Munich. An improvement of the vehicle efficiency of the motorized trips is expected through this measure (Bayerisches Staatsministerium für Umwelt, Gesundheit und Verbraucherschutz 2015).

Since 2007, Germany has seen electric cars as the future vehicle generation. Electromobility contributes to limiting climate change and improving air quality, as electric vehicles do not generate emission. Therefore, in 2011, the German cabinet adopted a governmental program, called *Regierungsprogramm Elektromobilität* that outlines promoting the electric mobility to reach a target of one million vehicles by 2020 and six million by 2030. Their definition of an electric vehicle covers not only the vehicles powered only by electricity, but also plug-in-hybrid vehicles (Bundesministerium für Wirtschaft und Technologie et al. 2011). In the following year, four regions including Bavaria together with Saxony were selected as the 'showcases' and have received subvention for further research and development (Schaufenster elektromobilität et al. 2017). Bavaria-Saxony designed further projects under the name of *ELEKTROMOBILITÄT VERBINDET* in which the city of Munich participates with *E-Plan München* with a focus on the charging infrastructure. E-Plan has investigated the distribution of the infrastructure and has contributed to developing a master plan. The resulting master plan was then included as one of the actions designed in IHFEM, which aims to improve of the air quality by supporting the governmental program. Moreover, a municipal funding was promised in IHFEM to promote electric vehicles or charging infrastructure. However, the potential impacts of such a measure on local emission is difficult to quantify, as it is correlated to the number of electric cars that in term strongly dependent on the end customers (Bayerisches Staatsministerium für Umwelt, Gesundheit und Verbraucherschutz 2015; Dronia 2016; Referat für Gesundheit und Umwelt, Beschluss des Umweltausschusses in der gemeinsamen Sitzung des Umweltausschusses, des Ausschusses für Stadtplanung und Bauordnung, des Ausschusses für Arbeit und Wirtschaft und des Kreisverwaltungsausschusses of 5/6/2015).

With the continued exceedance of NO_2 limits at the hotspots in 2017, an additional update is planned for the air quality plan. Until now, the concepts for the seventh update have been designed but not finished yet. The emissions reduction measures described in the concepts further underlines the importance of electric vehicle. Building on the governmental promotion, creating the charging infrastructure still remains one of the major focuses in the update. It covers both public and private charging points. The Bavarian funding program aims at providing 7,000 publicly accessible charging points by 2020 (Regierung von Oberbayern 2017).

Electric vehicles are known as ‘zero-emission’. However, the name only refers to the emissions produced locally. Concerning the overall processes, i.e. Well-to-wheel, the environmental benefit is highly dependent on the sources of the electricity whether the vehicle is powered by conventional or renewable energy. In 2017, renewable energy only amounted to approx. 33 % of the electricity supply in Germany (Arbeitsgemeinschaft Energiebilanzen e.V. 2018). For complete zero-emission vehicles, Germany must replace the remaining electricity produced from fossil fuels.

4. Modelling Approach

Modelling plays a vital role in engineering. It helps to assess the impact of measures before their implementation, and it leads to improved planning and decision-making (Ortúzar Salar and Willumsen 2011). To estimate the amount of emissions and to examine the potential reduction of emissions, this thesis applies a modelling approach which is discussed in-depth in this chapter. In the beginning, the general concept of a modelling approach is described, and how such an approach is applied in the emissions modelling. Finally, various investigations of emission modelling are presented.

4.1 Model

A model represents a part of the real world in a simplified way. It depicts the system of interest, depending on specific problems, from a particular point of view, i.e. various models can be derived and differentiated according to problems and viewpoints. This characteristic may lead to the limitation that a model is only realistic from a particular perspective (Ortúzar Salar and Willumsen 2011).

A model can be expressed in either physically or abstractly. Physical models are for designing architecture or fluid mechanics, whereas abstract models can be broadly defined from mental models to formal and abstract representations of systems. One of the important classes in abstract modelling is the mathematical model, which replicates the system of interest and its behavior with equations. Such a model might be very complex and require large amounts of data. One the other hand, the results are considered as a basis to discuss policies and enable unbiased examining of necessary compromises. Moreover, the behavior and internal workings of the system are transparent (Ortúzar Salar and Willumsen 2011).

Due to a problem-specific characteristic of a model, it is important to declare planning problems, which are presented here as a set of variables:

- endogenous variables are predictable by the model;
- exogenous variables are not predictable, possibly required as an input.

The exogenous variables can be further classified into variables that cannot be controlled by the modeler but depend on the plan, and into variables that are ignored in the theory behind the model (Wilson 1974). Given these distinctions of variables, the main use of models in planning is to forecast endogenous variables that are conditional on the given exogenous variable. Conditional forecasts work in two different ways, according to the relation to the variables:

- setting exogenous variables in relation to the controlled variables of a plan, such as policy variables, the impacts of the policy are tested with the model;
- setting exogenous variables in relation to other variables with assumed values, running may simulations.

In the second case, many simulation runs in the context of any particular planning problems generate a range of alternative plans and of possible assumptions in order to test the other variables (Wilson 1974; Ortúzar Salar and Willumsen 2011). Suppose the task of models is to give the 'best' advice to foster decision-making processes. Figure 7 presents the theory behind the model by mapping the reality into variables in the model.

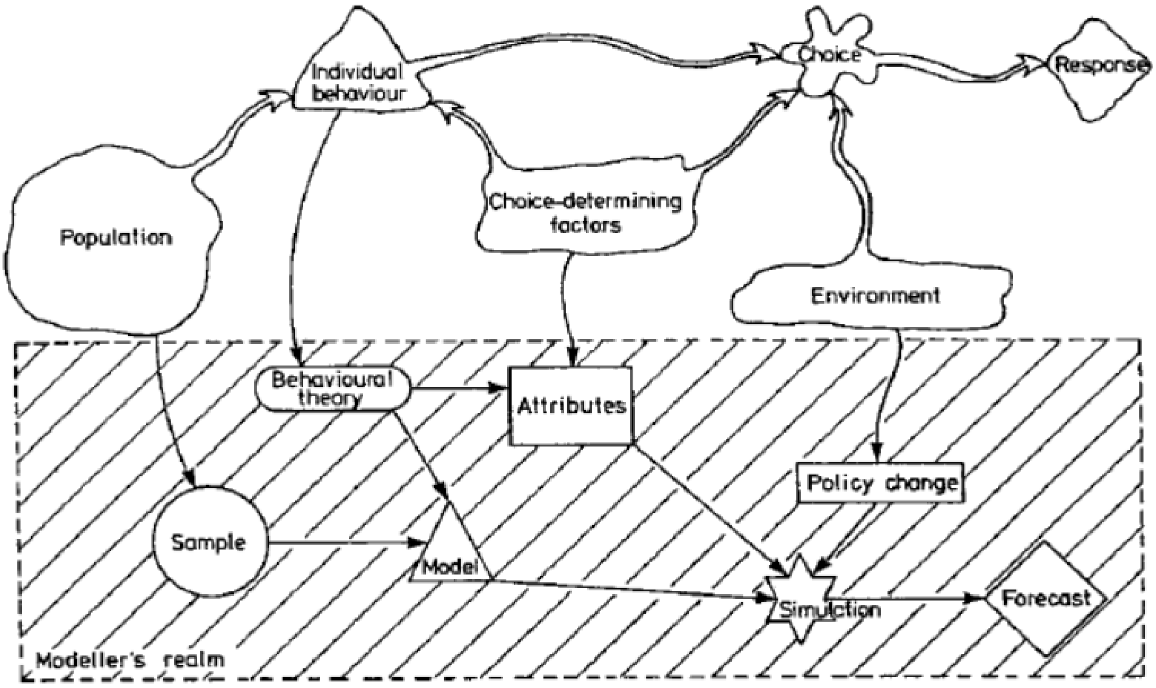

Figure 7: Reality and model (Ortúzar Salar and Willumsen 2011)

The modelling approach is crucial for estimating the emissions. It predicts the impacts of interventions by comparing models with various scenarios and helps to determine the most effective one to reach the target. The following section presents a specific model useful for emission modelling.

4.2 Emission Modelling

Emission inventory, one of the important tools in emissions modelling, compiles emissions from different sources across a geographical area and presents the resulting emissions. It plays a significant role in modelling air quality, monitoring emission trends and government managing of air quality (World Health Organization 2006).

To create inventories, the most common estimation approach is carried out by a mathematical model that combines the extent to which a human activity takes place, called activity, with coefficients quantifying the emissions per unit activity, called emission factor. The general formula is therefore:

$$E = AD * EF,$$

Equation 4: General formula for emissions calculations (European Environment Agency 2016)

where:

- E: emissions,
- AD: activity data of a source of emission,
- EF: emission factor related to that activity.

This equation for emissions modeling is very simple and straightforward. This general formula can be adjusted based on emission sources and the available inputs for activity and emission factors. For example, in road transportation, the definition of an activity component comprises energy demand, fuel consumption, distance traveled, amongst others. Emission factors present the average emissions rate for a given pollutant, and change relative to the respective activity (European Environment Agency 2016; World Health Organization 2006; Davison et al. 2011). In conducting calculations using Equation 4, there are three tiers of the methodology, based on the complexity level. Tier 1 methods use activity data from statistical information, such as traffic counts, population sizes, etc., and averaged emission factor. Tier 2 is more advanced, applying the same activity data as Tier 1 methods, but including emission factors with country-specific information. Tier 3 methods are most the advanced approaches, using tailored activity data and emission factors. The higher tier, the lower the uncertainty of the estimation. However, a high tier methodology may not be feasible for every category of emissions, as such a method requires extensive resources for data collection and calculation. Therefore, it is recommended that the major contributor to the overall inventory estimates be identified and that Tier 2 and 3 be prioritized (European Environment Agency 2016; Davison et al. 2011).

In the remainder of this section, emissions modelling that have been attempted so far are discussed briefly.

4.2.1 City Air Management

Siemens AG (Siemens AG) has developed an intelligent software ‘City Air Management (CyAM)’. It enables predicting the air quality and estimating the potential impacts of regulatory actions on the emission. Today, CyAM is operative in Nuremberg.

This air management tool forecasts the air quality for every hour up to five days in advance through an artificial neural network, which bases on historic air pollution, weather and traffic patterns together with the live monitored values from the local sensors. This artificial neural network allows the system improving itself over time. The results can be found in its forecasting system using recurrent neural networks, which make unavailable and hence unobserved information regarding the source of air pollution such as traffic, industries and agriculture visible in its internal dynamic model.

Through such a system, CyAM informs the cities on their air quality level and the risks of the exceedance. Furthermore, it can predict the potential reduction of emission against the expected air quality level so that the city leaders can make a right decision and can immediately react by implementing short-term measures.

CyAM indicated a relatively low error rate in its accuracy test. Forecasting five days in advance showed less than 28 % of the error rate, and forecasting for shorter period showed an even lower error rate. There are possibilities to improve its accuracy by providing more data.

The main focus of CyAM is on short-term measures. However, the cities can address their long-term air pollution by building upon the resulting expertise from CyAM. Such possibilities give cities the chance to assess the impact of medium and long-term measures and the city leaders can make better longer-term decisions.

However, CyAM has several limitations. It has difficulties modelling the locations with the highest level of the pollution, so-called hotspots. Furthermore, as the system applies the data such as weather, the resulting prognosis is strongly dependent upon the quality of the data. Also, the statistical data stored in the system play a crucial role as it is the basis of the prediction of the potential impacts of measure. The quality for such data should be guaranteed particularly (Schönig 11/21/2018).

4.2.2 Other approaches

Apart from City Air Management, there have been investigations using various modelling tools to map air pollution in transportation science as this is drawing increasing attention. To model transport-related emissions, models that integrate traffic and vehicular emission are necessary. Such integrated models differ depending on the combination of traffic and emission models. Macroscopic traffic flow models consider the average behavior of traffic flow in the network, whereas microscopic traffic models are based on the dynamics of individual vehicles. The categorization of emission models is similar. Macroscopic emission models consider aggregated emissions, whereas microscopic emission models are based on instantaneous variables of individual vehicles. This section introduces various models integrating different types of traffic and emission models.

Karin Hirschmann et al. (September 2010) proposed a tool linking the microscopic traffic flow simulator VISSIM with the instantaneous emission model PHEM. The developed model calculates emissions by matching dynamics of each vehicle to the transient load change emission factor, and it is able to analyze the impact generated by different traffic signal controls on emission and fuel consumptions. However, due to the microscopic focuses of both integrated models, this tool may not be feasible for large-scale scenarios.

Csikós et al. (2015) introduced a framework combining the macroscopic traffic model described by the Network Fundamental Diagram with the emission model COPERT IV, based on average speed. The resulting framework indicated relatively low error in the accuracy analysis, using the microscopic model Versit+Micro as reference. In contrast to the previous model based on microscopic-scale, this approach is more feasible for larger-scale scenarios. However, as this framework applies aggregated traffic variables representing the whole network, the emission is calculated for the network, but not by links.

Gerdien Klunder et al. (2013) combined the macroscopic traffic model RBV with the macroscopic emission model, which still incorporates microscopic characteristics of vehicles. The emission module consists of emission rate curves considering various intersection types, sizes and speed limit, which are gained from the microscopic traffic model VISSIM and the microscopic emission model VERSIT+. Therefore, this developed model can consider dynamic behavior of vehicles, in spite of macroscopic characteristics of the system. However, its practical applications are limited, as the emission module contains values that had been simulated with the microscopic models. If a new situation occurs, the emission rate is either covered by interpolated values from similar traffic situations, or the new rate is added by performing more simulations.

Zegeye et al. (2013) developed a general framework VT-macro, which considers the macroscopic traffic model METANET and the microscopic emission and fuel consumption model VT-micro. To balance between macroscopic and microscopic models, vehicle characteristics derived for a group of vehicles are approximated for individual vehicles by averaging speed and acceleration over the number of vehicles in order to match to the corresponding microscopic emission and fuel factors. Due to such an approximation, this model shows uncertainties.

The following chapter presents the emission modelling tool within MATSim, applied in this thesis, which incorporates large-scale scenarios and dynamic characteristics of vehicles.

5. Methodology: MATSim

A further attempt to model large-scale scenarios was undertaken by Friederike Hülsmann (2014), using a multi-agent based transport model combined with the emission model from Handbook on Emission Factors for Road Transport (HBEFA), which considers driving dynamics of individual vehicles. This developed tool is able to represent an entire urban area, such as the Munich metropolitan region, and assesses the changes of individuals resulting from measures in transport policies.

To estimate the more precise potential emissions reduction brought about by measures in the study area, this thesis applies the emission modelling tool developed by Hülsmann. This chapter depicts the simulation approach of the integrated transport model MATSim and the methodology of the emission modelling tool. All information on MATSim in this chapter is based on the Handbook *The Multi-Agent Transport Simulation MATSim* (Horni et al. 2016).

5.1 MATSim

MATSim is a transport model, developed by Swiss Federal Institute of Technology in Zurich (ETH Zürich) and Berlin Institute of Technology (TU Berlin). This transport model enables modelling the daily activity plans of an individual person for a single day, who is referred to as an agent in an activity-based model. The approach is carried out in a number of iterative steps, like the cycle shown in the following figure. In Section 5.1, it should be noted that the word 'activity' in MATSim does not mean the same as the activity in the emission modeling (see 4.2). Activity in transport modeling refers to functional areas of social life such as living, working, education and recreation (Wulfhorst 2014).

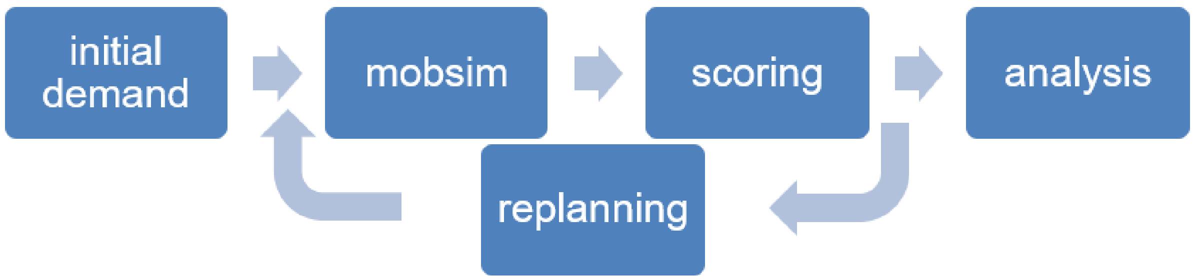

Figure 8: MATSim cycle (Horni et al. 2016)

The MATSim cycle starts with an initial demand reflecting the from daily activity chains of the population in the study area, which are usually based on empirical data. In this step, each agent generates their own daily plans to fulfill their desired activities during a day and the transport models to reach the activity locations.

'Mobsim' stands for the mobility simulation or simulation of the traffic flow in MATSim. It executes all plans of the agents simultaneously in a simulation of the physical world and enables creating the synthetic reality. The default implementation of mobsim is the queue simulation (QSim), which is described in Section 5.1.1..

In the scoring step, the 'performance' of the plan in the synthetic reality is measured to calculate a score for each executed plan by using a utility function, the Charypar-Nagel function. In this function, utility and penalties are given and accumulated throughout the day of an agent. Positive utility is given for performing activities, while travelling results in negative utility. Penalties are attributed in case of late arrivals, early departures, waiting times.

The replanning step allows encapsulating the learning and adaptation of the agents with the following steps:

- Choice set reduction and plans removal: If the maximum number of plans is exceeded or there are bad plans, the plans will be removed.
- Choice set extension, innovation: A plan is selected, copied, modified and used for the next iterations to support the generation of good plans.
- Choice set: All of the other agents select between their plans.

In the analysis step, an event after every action of the simulation is generated as an output component. Each event contains a timestamp, a type, and additional attributes describing the actions, such as vehicle or link ID, and an activity type. Event handler functions are necessary to interpret and evaluate these events for further analysis. Finally, the events can be visualized in the application Via.

The MATSim cycle, particularly the three stages mobsim, scoring and replanning, repeats the iterations that enable the agents to modify their plans by adopting the plans and behavior of the other agents. This iteration process is executed until the system has reached the stabilization of scores.

The following section explains the approach of the MATSim traffic flow model in-depth.

5.1.1 Queue Simulation

QSim, short for queue simulation, is the default implementation for private transport. It is very useful for large scale scenarios as it is computationally efficient. The queue-based approach is used for physical simulation on the network and models a vehicle entering a link from an intersection. Thereby, the first-in-first-out queue concept is applied onto network links.

QSim is defined by its two main parameters, the flow capacity and the storage capacity. The storage capacity characterizes the number of vehicles fitting onto a network link. This can be computed by taking the length of a link, divided by the length of the vehicles, and multiplied by the number of permanent lanes. The storage capacity is given as number of vehicles. The flow capacity describes the outflow capacity of a link, i.e. the maximum number of vehicles that can leave a link per time unit. However, QSim does not define inflow capacity for a link. This has the effect that congestions do not form at the beginning of merging links, as in reality, but rather at the end of the low capacity link. It occurs if more demand increases on the previous link. Figure 9 gives an overview of the queue-based traffic flow model.

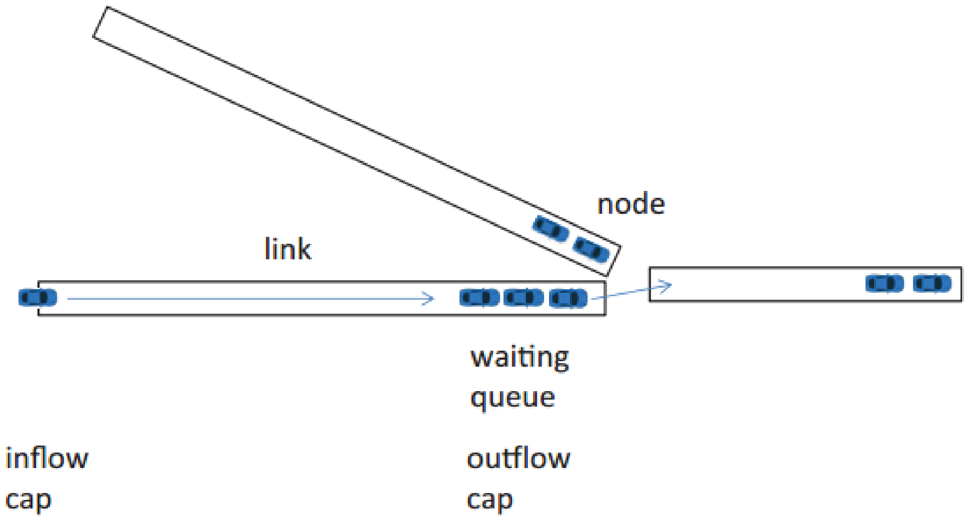

Figure 9: Traffic flow model (Horni et al. 2016)

Several criteria must be met for a vehicle to move on to the next link as following:

- the vehicle is at the head of the queue and stays for at least the time needed to travel across the link with free speed;
- the flow capacity of the current link must allow the vehicle to leave in the particular time step;
- the storage capacity of the following link must not be full.

Apart from the traffic modelling, MATSim provides some extensions, so-called contributions. One of the contributions is the emission modelling tool, which will be described in the following section.

5.2 Emission Modelling in MATSim

The emissions modelling tool of MATSim allows users to calculate emissions such as carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (HC), non-methane hydrocarbons

(NMHC), SO_2, PM, NO_x and NO_2. This thesis looks deeply into NO_2 emissions, but the methodology for all emission types remains the same except for minor aspects.

In general, MATSim computes emissions based on the general formula (see Equation 4), which leads to a methodology with two steps. First, the activity component of the general formula is derived for every transport user from the simulation. Based on this information, respective emission factors from the HBEFA are extracted in combination with vehicle characteristics. The calculation follows the Tier 3 methodology, as it is well-suited to calculations for individual person and the emission factors tailed to each agent.

Emission resulting from road traffic is produced in form of the abrasion emission, the evaporative emission and the exhaust emission. However, MATSim's emission contribution only considers the exhaust emission, for which MATSim can derive information from the simulation. There are two sources of air pollution from the transport-related exhaust gas emissions: Warm emissions are emitted during driving and consequently depend on the traffic states; cold-start emissions occur during the warm-up phase and hinge on the ambient temperature (Davison et al. 2011). Both these emission types are integrated in the emission modeling tool of MATSim. Further subcategories are aligned with the HBEFA methodology, since the emission factors applied in the tool based on the HBEFA database. Figure 10 gives an overview of the emission types with their subcategories included in the modelling tool.

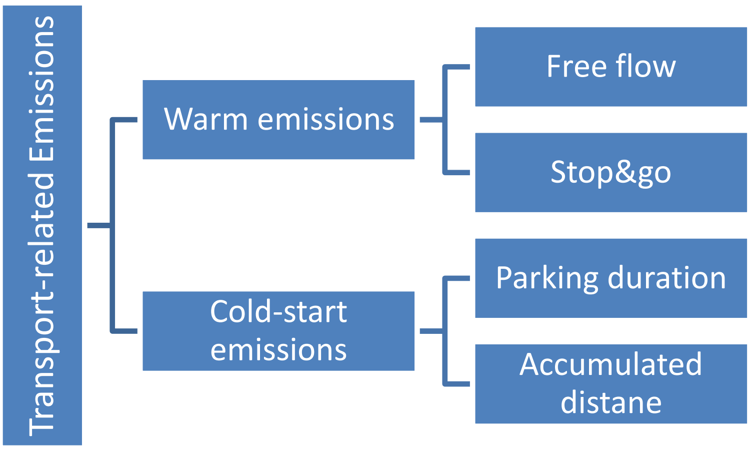

Figure 10: Overview of transport-related emissions, adapted from Horni et al. 2016

Derivation processes for warm emissions and cold-start emissions differ slightly. Thus, the calculation approaches for these two air pollution sources are outlined in-depth in the remainder of this section.

5.2.1 Warm Emission

Within warm emissions, there are differentiations with respect to: driving speed, acceleration/deceleration, stop duration, road gradient, and vehicle characteristics. However, in MATSim, road gradient is assumed to be 0 % for all links. Warm emissions change in proportion to the trip distance, which is modified according to the traffic state. Therefore, the emission calculation tool of MATSim applies to more than one traffic state. This section shows how the traffic states are integrated in the calculation tool.

Activity

In the traffic flow simulation, MATSim collects kinematic characteristics for warm emissions, such as driving speed and stop duration. MATSim's queuing model (see 5.1.1) helps to extract the agent's travel times and the average speed on a link. Based on the resulting time-velocity profile, traffic states on this link can be defined and matched to HBEFA traffic states. HBEFA has defined four traffic states, namely 'free flow', 'heavy', 'saturated' and 'stop&go'. From these, the emission tool of MATSim only considers two driving cycles: free flow and stop&go. MATSim additionally considers the mixed situation of these two traffic states. First, an assumption is made that vehicles are in the free flow state. As soon as they have to wait in a queue, the traffic state is changed to the stop&go state. The following criteria help users to define the traffic states.

(1) Only free flow on link, if average speed minus free flow speed equals to or is greater than -1.0
(2) Only stop&go on link, if average speed minus stop&go speed equals to or is less than 0
(3) Otherwise, there is an intermediate state between free flow and stop&go

After the driving cycle is determined, the trip distance as activity should be calculated. If the link shows a clear traffic state such as free flow or stop&go by fulfilling the criteria (1) and (2), the travel distance is equal to the length of the link (see Equation 5 and Equation 6). Otherwise, the travel distance for both traffic types should be calculated by using Equation 7. Since the intermediate traffic state is MATSim's own definition, the emissions are deduced by combining the free flow and stop&go states in order to align with HBEFA. This is described later in this section.

$$l_f = l$$

Equation 5: Travel distance in only free flow state, adapted from Multi-Agent Transport Simulation

$$l_s = l$$

Equation 6: Travel distance in only stop&go state, adapted from Multi-Agent Transport Simulation

$$l_s = \frac{l * v_s(v_f - v)}{v(v_f - v_s)}$$

$$l_f = l - l_s,$$

Equation 7: Travel distance in the intermediate traffic state (Kickhöfer 2014)

where:

- l: link length in $[km]$,
- l_s: distance in stop&go state in $[km]$,
- l_f: distance in free flow state in $[km]$,
- v: average speed of an agent on link l in $[\frac{km}{h}]$,
- v_s: stop & go speed in $[\frac{km}{h}]$,
- v_f: free flow speed in $[\frac{km}{h}]$.

The resulting activity must be applied in the general formula (see Equation 4). The identified traffic states are further used to extract emissions factors.

Emission Factor

The emission calculation tool applies the emissions factors taken from HBEFA (version 3.1). This emission factor model has been developed by the company INFRAS on behalf of the Federal Environment Agency of Switzerland, Austria, Sweden, France and Germany. The database of HBEFA provides country-specific emission factors for various levels of detail that vary by pollutants, vehicle type, fuel type, road category, speed limits and traffic states. Regarding the characteristics of NO_2 (see Section 2.1), the emission factors are defined according to share of NO_x emissions. The HBEFA database implemented in the modeling tool provides the emission factors only for passenger cars and heavy goods vehicles (Keller et al. 2017b).

As the second step of the calculation, the emission factors are assigned to an agent by mapping the defined traffic states with vehicle characteristics on to the HBEFA database. In case there is no detailed information on vehicle characteristics, the country-specific fleet average is applied. The categories of emission factors for the average case in the HBEFA database are simplified in the following figure. The figure shows the emission factors only for the passenger vehicles, but HBEFA provides it for the heavy-duty vehicle as well. It is just not depicted in the figure. If detailed vehicle characteristics are available, the categorization is extended according to vehicle type, fuel type, cubic capacity and European Emission Standard Class.

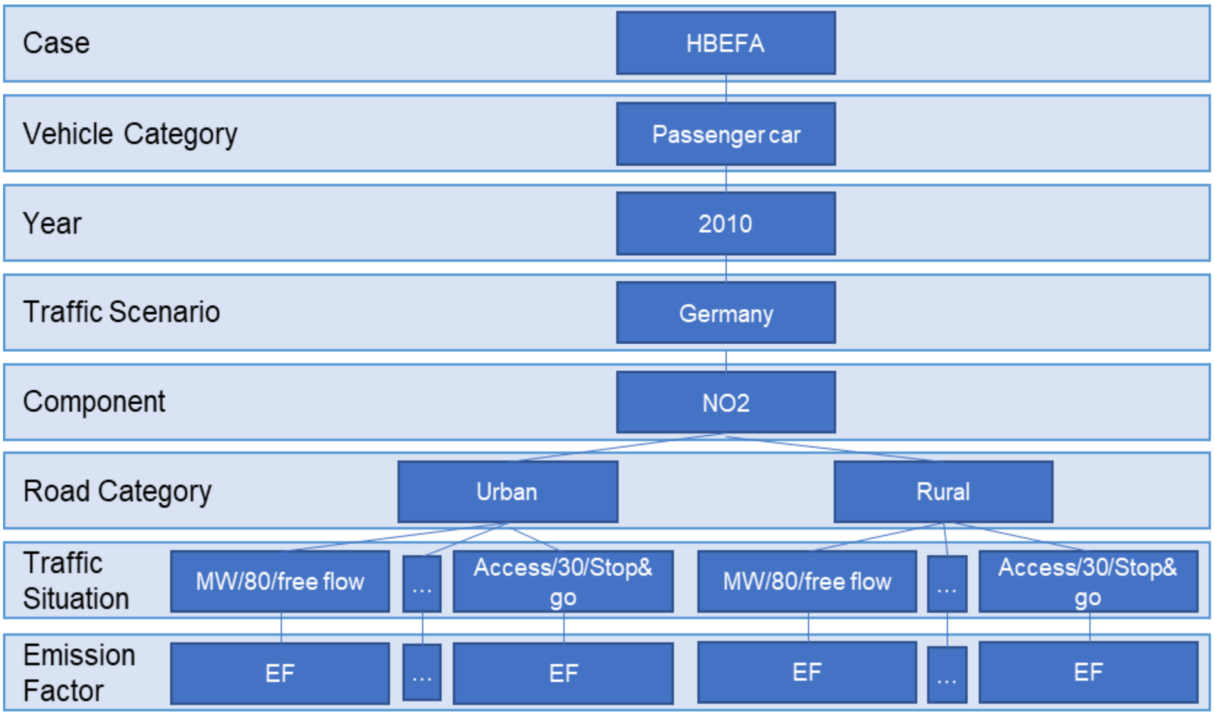

Figure 11: Overview of the HBEFA database for warm emissions, adapted from Multi-Agent Transport Simulation

The unit of the emission factors is given as $[\frac{g\ NO_2}{Person-km}]$. As MATSim models a vehicle for an agent, $1\ Person-kilometer$ can be assumed to be $1\ kilometer$.

In the traffic situation presented in Figure 11, the mixed situation between free flow and stop&go is not included in the HBEFA database. For intermediate traffic state, the emission factors from both driving cycles are extracted and combined in the further calculation step.

Warm Emissions

As the last step, the warm emissions are calculated by multiplying the value of the activity and the respective emission factor. The following equations are adjusted according to the general formula (see Equation 4). As already mentioned in the previous part, emissions for the mixed traffic state are calculated by combining the two traffic situations.

$$E_f = l * EF_f$$

Equation 8: Total warm emissions for free flow state, adapted from Multi-Agent Transport Simulation

$$E_s = l * EF_s$$

Equation 9: Total warm emissions for stop&go state, adapted from Multi-Agent Transport Simulation

$$E_{inter} = \left(l_f * EF_f\right) + (l_s * EF_s),$$

Equation 10: Total warm emissions for the intermediate traffic state, adapted from Multi-Agent Transport Simulation where:

- E_f: emissions in free flow state in [$g\ NO_2$],
- E_s: emissions in stop&go state in [$g\ NO_2$],
- E_{inter}: emissions in intermediate state in [$g\ NO_2$],
- EF_f: emission factor in free flow state in [$\frac{g\ NO_2}{Person-km}$],
- EF_s: emission factor in stop&go state in [$\frac{g\ NO_2}{Person-km}$].

This methodology is repeated for every agent and every link that is driven. In the final step, MATSim generates the emission events containing the calculated warm emissions with information about the agent and the link.

Assumptions

To calculate warm emissions, the following assumptions are made:

- only for passenger vehicles and heavy goods vehicles;
- one agent per a vehicle;
- only three traffic states in network;
- road gradient 0 %;
- one vehicle per agent.

Transport-related emissions include a further air pollution source. Influencing factors as well as the calculation methodology of cold-start emissions are described in the following section.

5.2.2 Cold-start Emissions

The emissions produced during the warm-up phase of an engine cannot be neglected, especially in the urban areas, where a high level of short distance trips is performed. The amount of cold-start emissions can be influenced by driving speed, vehicle characteristics and the 'pattern of ambient conditions', which consists of ambient temperature, distance traveled after a cold-start and the parking duration before the start (Keller et al. 2017b). This ambient condition pattern is particularly considered in MATSim, with the ambient temperature is assumed to be average value. This section discusses the calculation approach for cold-start emissions in-depth.

Activity

As an agent turns on their vehicle and enters the traffic, cold-start emissions start to be produced. These are further generated until the engine is completely warmed up, so the warm emissions start to be produced. Thus, this vehicle's start is regarded as the activity component of the general formula (see Equation 4) in this subsection. To compute the emissions, one start must be applied in the general formula for every agent who travels with their own vehicle. The key element differentiating the size of the activity is the accumulated distance, which is the summed distance driven in the warm-up phase.

HBEFA differentiates the cold-start emissions according to the trip length, categorized into short trips for less than 1 kilometer and longer trips for equals to or greater than 1 kilometer (Keller et al. 2017b). Aligned with the HBEFA, MATSim implements this concept in its calculation. In case of short trips, the emissions are mapped to the link where the agent starts its vehicle. If the agent travels longer with the vehicle, further emissions are added onto those of the short trip. In reality, such emissions are produced along the route. However, in MATSim, these are assigned to the link where the accumulated distance reaches 1 kilometer. With 2 kilometers of the accumulated distance, HBEFA made an assumption that the production of such emissions is terminated. The following figure illustrates the concept of the calculation for cold-start emissions.

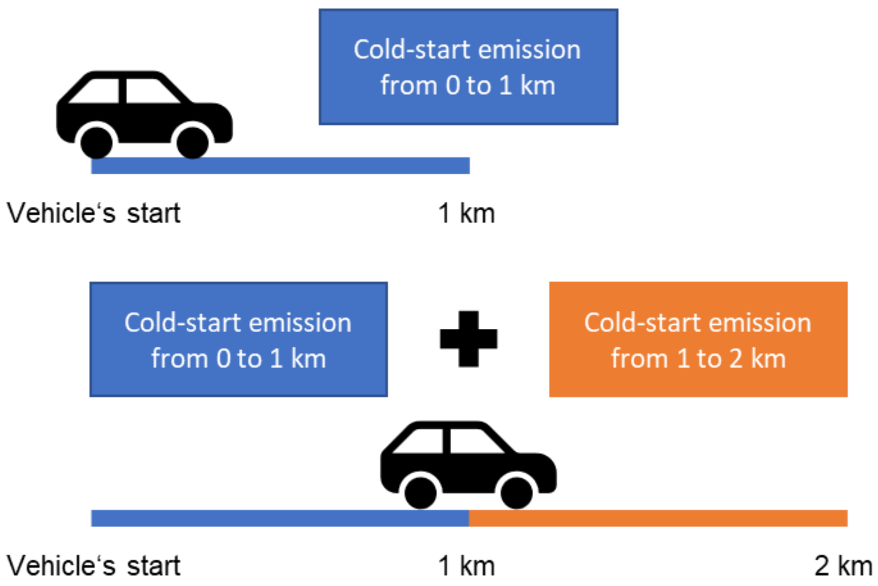

Figure 12: The concept of calculating the cold-start emissions in MATSim, adapted from Horni et al. 2016 and Keller et al. 2017b

As the vehicle is partially warmed up after the first kilometer, it produces less cold-start emissions compared to that of the short trip. To map this concept into the calculation, MATSim made an assumption that the vehicle makes one additional start as soon as the trip distance exceeds the first kilometer, which allows assigning another emission factor for the partly heated vehicle. The emissions are calculated as the vehicle reaches 2 km. The activity considered in the cold-start emissions can be summarized as follows.

$$S_{0-1} = \begin{cases} 1, if\ 0 \leq l_{acc} < 1 \\ 0, else \end{cases}$$

Equation 11: Activity data for the short-distanced trips, adapted from Multi-Agent Transport Simulation and Horni et al. 2016

$$S_{1-2} = \begin{cases} 1, if\ 1 \leq l_{acc} < 2 \\ 0, else \end{cases}$$

Equation 12: Activity data for the long-distanced trips, adapted from Multi-Agent Transport Simulation and Horni et al. 2016

where:

- S: an engine' start in [$1\ start$],
- l_{acc}: accumulated distance in [km].

A further element differentiating the amount in cold-start emissions is the emission factor, which is described in more details in the next part.

Emission Factor

As well as for the warm emissions, HBEFA is applied for cold-start emissions. It provides the emission factors for passenger cars and light goods vehicles only.

MATSim derives the ambient condition patterns, such as parking time and accumulated distance, from the simulation. The combination of these two aspects characterizes the emission factors, which leads to a differentiation in the amount of emissions. HBEFA provides emission factors for the duration that a vehicle is not moved, shown by the one-hour steps. Thereby, an assumption is made that a vehicle has been completely cooled down after 12 hours of parking; therefore, a constant emission factor is applied for such vehicles (Keller et al. 2017b).

As the ambient condition patterns are defined, the respective emission factors can be extracted from the HBEFA database. Figure 13 shows a simplified overview of emission factors for cold-start emissions. As well as for warm emissions, if there are detailed vehicle characteristics, the categorization is extended.

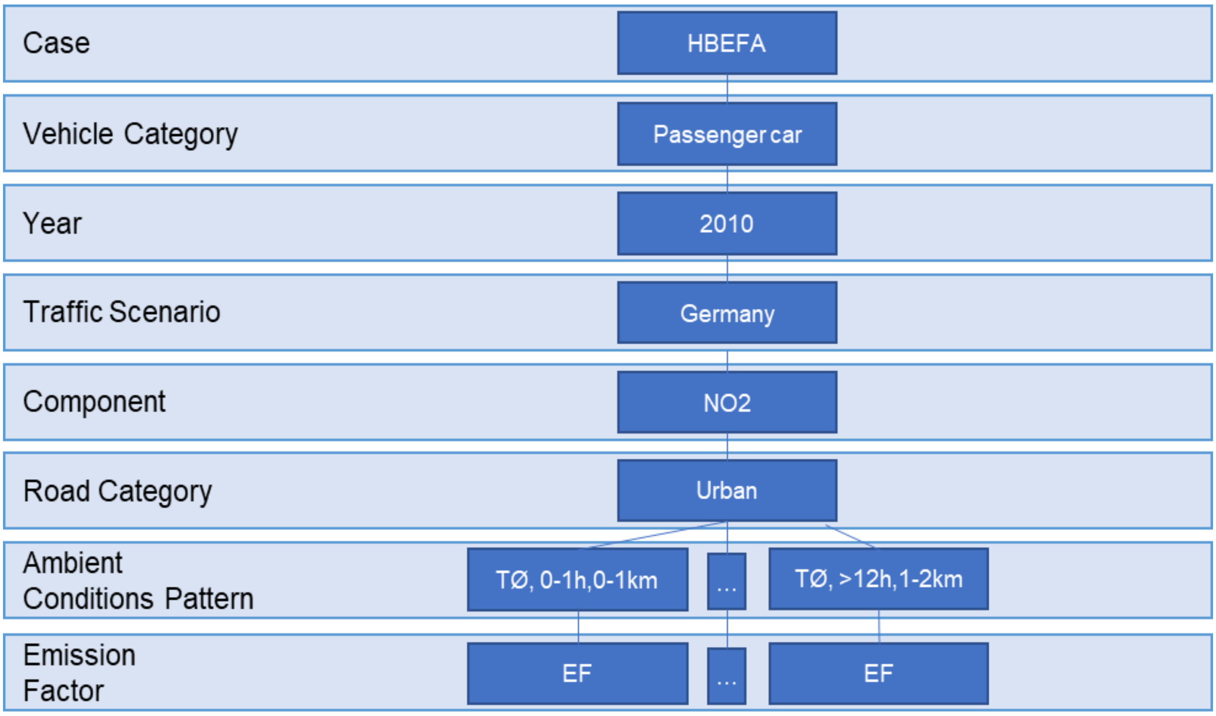

Figure 13: Overview of the HBEFA database for cold-start emissions, adapted from Multi-Agent Transport Simulation

In general, emission factors rise with parking time. The unit of emission factors is given as $[\frac{g\ NO_2}{start}]$ (Keller et al. 2017b).

Such cold-start emissions are complementary to the warm emissions. Generally, an engine generates more emission during the cold-start phase. However, this does not apply for NO_x generated by diesel-powered vehicles. Those emissions are produced mainly after the engine has been completely warmed up. To compensate this exception, the NO_x factors produced from diesel vehicles are negative and the emission factors for NO_2 are negative respectively (Keller et al. 2017a).

Cold-start emissions

To compute cold-start emissions, Equation 4 is adjusted, as presented below.

$$E_{cold} = S_{0-1} * EF_{0-1} + S_{1-2} * EF_{1-2},$$

Equation 13: Total cold-start emissions, adapted from Multi-Agent Transport Simulation

where:

- E_{cold}: emissions resulting from cold-start emissions in $[g\ NO_2]$,
- $EF_{l_{acc}}$: emission factor for cold-start emissions in $[\frac{g\ NO_2}{start}]$.

This approach for cold-start emissions is repeated for every vehicle's start. The results are recorded in the emissions events, along with the warm emissions with information about vehicle and link.

Assumptions

To calculate cold-start emissions, the following assumptions are made:

- two separate vehicle's start for long-distance trips;
- average ambient temperature;
- only for passenger vehicles;
- completely cooled after 12 hours parking.

The following chapter presents the study area in which the transport and finally emissions are modeled by means of MATSim.

6. Munich Metropolitan Region

Wide areas of southern Bavaria around the planning region with the provincial capital Munich as its center, form one of the eleven metropolitan areas in Germany. It holds a high importance for social, economic and cultural developments. This chapter provides a brief insight into the geographical, demographical and economical structures in the Munich region. Furthermore, an overview of the transportation in this region is provided.

6.1 Geography

As the most southern metropolitan region in Germany, the Munich area covers a wide area of administrative districts in Upper Bavaria, part of Lower Bavaria and Schwabia and consists of 6 cities and 27 districts (see Appendix 1). This area is 25,548 km^2 and counts for approx. 36 % of Bavaria and 7.2 % of Germany (Metropolregion München).

6.2 Demography

Home to 7 % of Germany's entire population (ca. 6 million inhabitants in 2016), metropolitan Munich's the number of inhabitants has increased by 20 % compared to 1990. Today, the population density is 236 inhabitants/km^2, which is comparable to that of Germany (231 inhabitants/km^2). Regarding the urban-rural distribution, approx. 31 % of the total population live in the cities – Munich, Augsburg, Ingolstadt, Kaufbeuren, Landshut and Rosenheim – whereas the remaining 66 % live in other districts. The region is anticipated further to grow to approx. 6.6 million inhabitants by 2036 (Metropolregion München; Bayerisches Landesamt für Statistik 2018; Statistisches Bundesamt 2018a).

6.3 Economy

As one of the more successful and innovative economic regions of Germany – 7 DAX companies, approx. 100,000 craft businesses, approx. 525,000 companies with emphasis of industries, trade and services – the Munich metropolitan region shows a high GDP per capita at a value of 82,696 €, which is 21 % above the average value in Germany. The economic attractiveness is also reflected by its employment growth rate, with an increase of 23.4 % in the last ten years, during which the rate increased by 16 % in Germany (Metropolregion München).

6.4 Transportation

Mobility provides opportunities for people to change locations via transportation to meet their needs. It plays a crucial role both for humans and goods. However, such opportunities are limited, depending on factors such as time, destination choices and transport offers. This section gives an overview of the travelling purposes and mode share within the metropolitan region. Furthermore, an insight into the road transport is provided.

The study *Mobility in Germany* offers a specific section concentrating on Munich and gives a summary of daily traffic. A survey was done within the Munich public transportation authority (MVV – German abbreviation), which includes rural areas surrounding Munich. The purposes of journeys are not very different between the urban and rural areas. The majority of the inhabitants perform their trips for recreation and shopping, 32 % and 20 % on average. The trips for business, education and work make up 27 % on average (Landeshauptstadt München and Münchner Verkehrs- und Tarifverbund 2010).

However, rural-urban differences are shown in the mode share. In general, private vehicles including drivers and passengers form the dominant mode. This mode even makes up 62 % of the total mode share in rural districts. The second most used mode is active modes, i.e. walking and cycling, for the journey. Up to 21 % of the urban population and less than 10 % of the rural used public transportation services (Landeshauptstadt München and Münchner Verkehrs- und Tarifverbund 2010). Results leave no doubt that the share of public transportation use goes down in rural districts that offer limited possibilities.

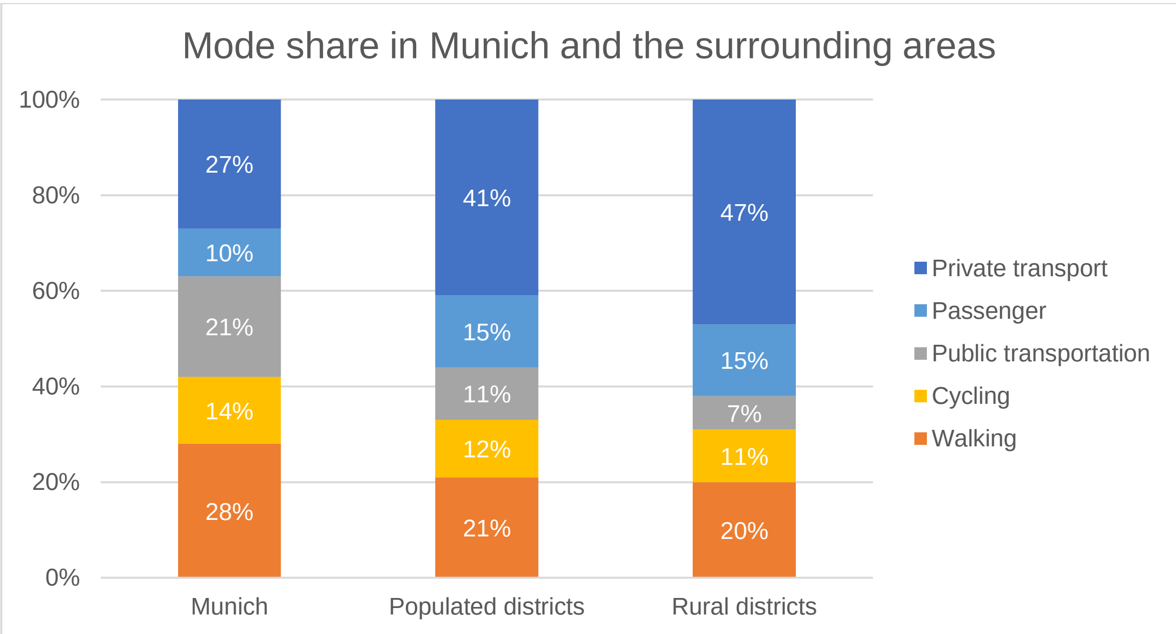

Figure 14: Mode share in Munich, adapted from Landeshauptstadt München and Münchner Verkehrs- und Tarifverbund 2010

That private transport is the dominant mode can be explained by its accessibility throughout the area. The following two figures present the various accessibilities to the nearest regional center by duration and by different modes. The depicted regional centers in this investigation are: Augsburg, Ingolstadt, Landshut, Rosenheim and Munich. Kaufbeuren, one of the cities located in the metropolitan region, is not represented as it does not fulfill the regional planning specification as a regional center. To present the significant difference between the private vehicle and the public transportation, Figure 16 used the same temporal classes. Comparing the accessibilities with two different modes, the average travel time with the public transportation amounts to 90 minutes, whereas for the private vehicles it averaged only 30 minutes. Particularly rural districts which have difficulties in financing an efficient public transportation show a high level of deficiency (Technische Universität München et al. 2010).

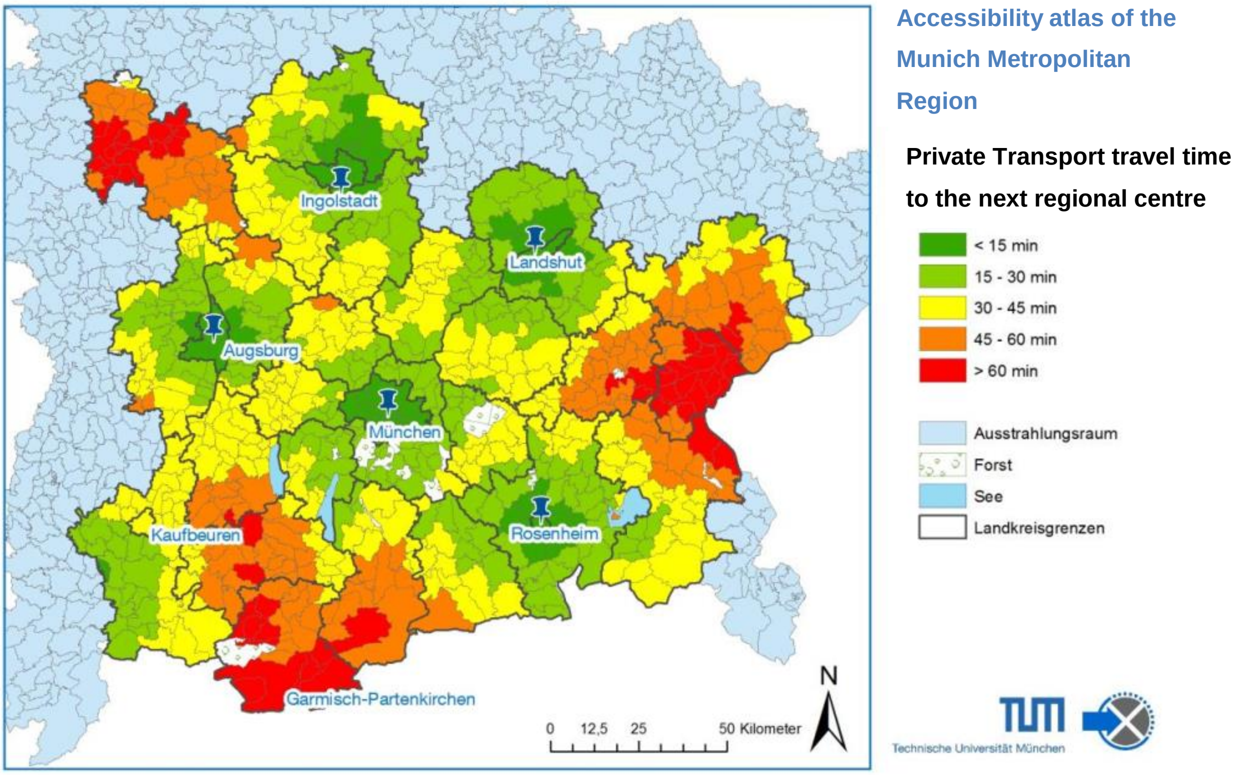

Figure 15: Travel time to the nearest regional center by private transport (Technische Universität München et al. 2010)

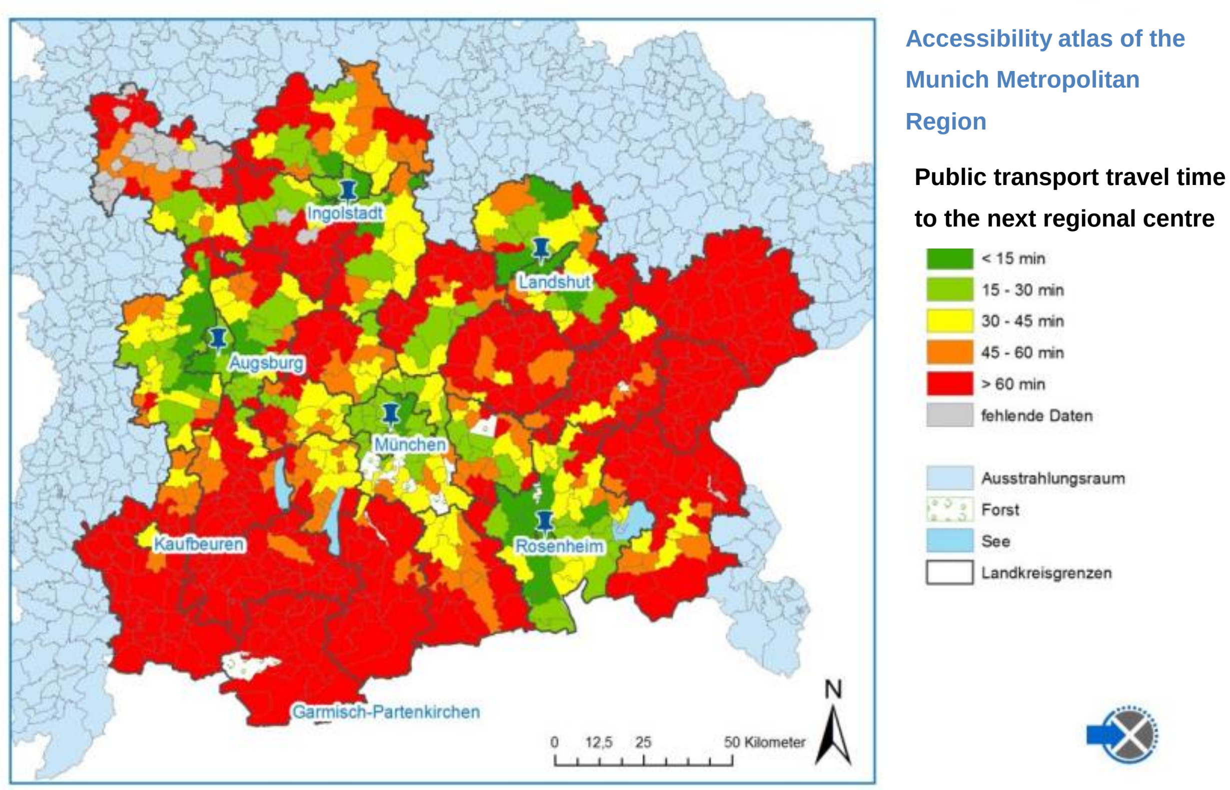

Figure 16: Travel time to the nearest regional center by public transportation (Technische Universität München et al. 2010)

The following subsection discusses the road transport in more depth. It discusses the road network and the private vehicles in the Munich region.

6.4.1 Road Transport

The major connection within the member cities and the districts of the metropolitan area is established by four transport axes: A8, A9, A96/A93 and A99. A8 builds an important east-west network in Central Europe, which goes from Perl to Bad Reichenhall via Stuttgart, Augsburg, Rosenheim and Munich. The second major axis, A9, starts from Munich and ends in Berlin via Ingolstadt and Nuremberg. A96/A93 link Lindau, Munich and Regensburg. The Munich outer ring road, A99, connects several motorways leading to Munich at locations outside of the city, which allows long-distance traffic to make bypasses instead of driving through the city.

The number of private vehicles is constantly rising. Between 2009 and 2018, the number of registered private vehicles grew from 3,049,426 to 3,580,981, an increase of 17 %. The growth in this region is 5 % higher than that of Germany as a whole (Kraftfahrt-Bundesamt 2009b, 2018b). The exact numbers of vehicles pertaining to the cities and districts of the Munich region are presented in Appendix 1.

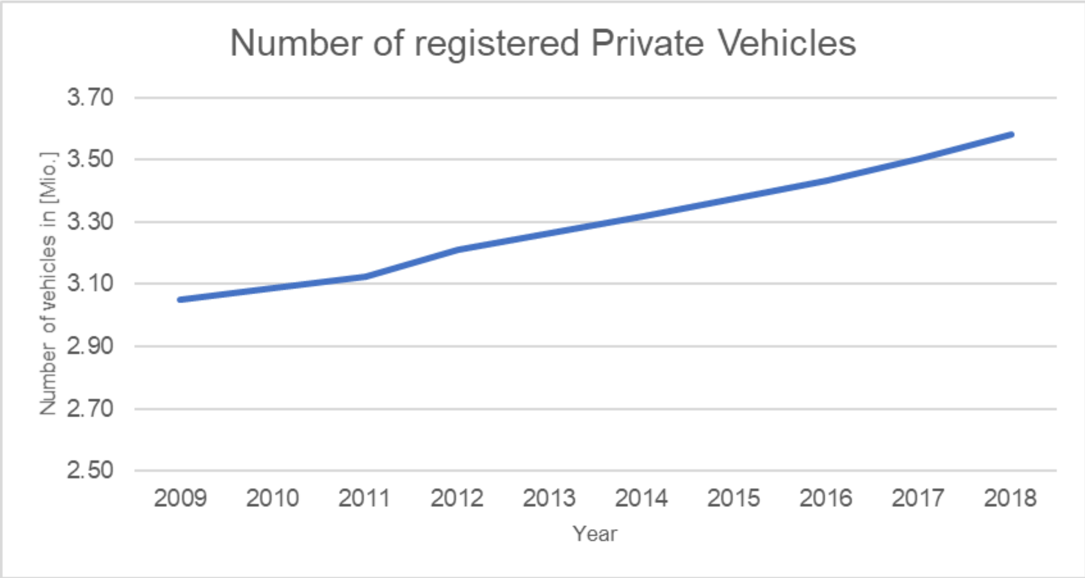

Figure 17: Number of registered private vehicles in Munich metropolitan region, adapted from Kraftfahrt-Bundesamt 2009b, 2010b, 2011b, 2012b, 2013b, 2014b, 2015b, 2016b, 2017b, 2018b

With the private vehicles increasing over the years, the trend of the fuel types has been changed. Figure 18 displays the changes in Bavaria from 2009 to 2018. The proportion of using petrol has continuously decreased, but it still remains as the dominant fuel type. The number of vehicles powered by diesel has increased by approx. 27 % from 2009 to 2018. The alternative fuel types total makes up only a minor proportion over the years.

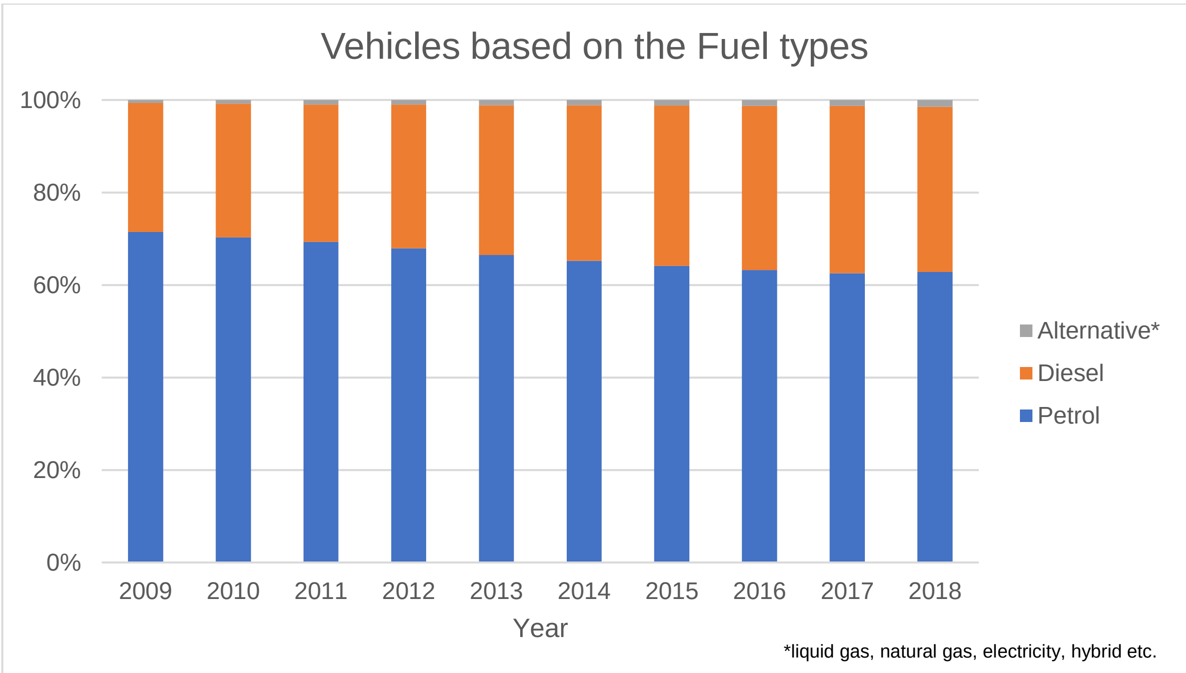

Figure 18: Vehicles based on the fuel types in Bavaria, adapted from Kraftfahrt-Bundesamt 2009a, 2010a, 2011a, 2012a, 2013a, 2014a, 2015a, 2016a, 2017a, 2018a

Among the alternative fuel, the majority of the vehicles is powered by the liquid gas (LPG). However, the proportion of the LPG is continuously decreasing since 2012. The second most used alternative fuel was the natural gas (CNG) until the number of hybrid vehicles has increased strongly as of 2012. From 2009 to 2018, its proportion grew from 0.3 % to 43.1 % of the total vehicles with the alternative drive systems. The market share with the alternative fuel that has grown most is the electric vehicles, which has increased by almost 4,000 % in 9 years.

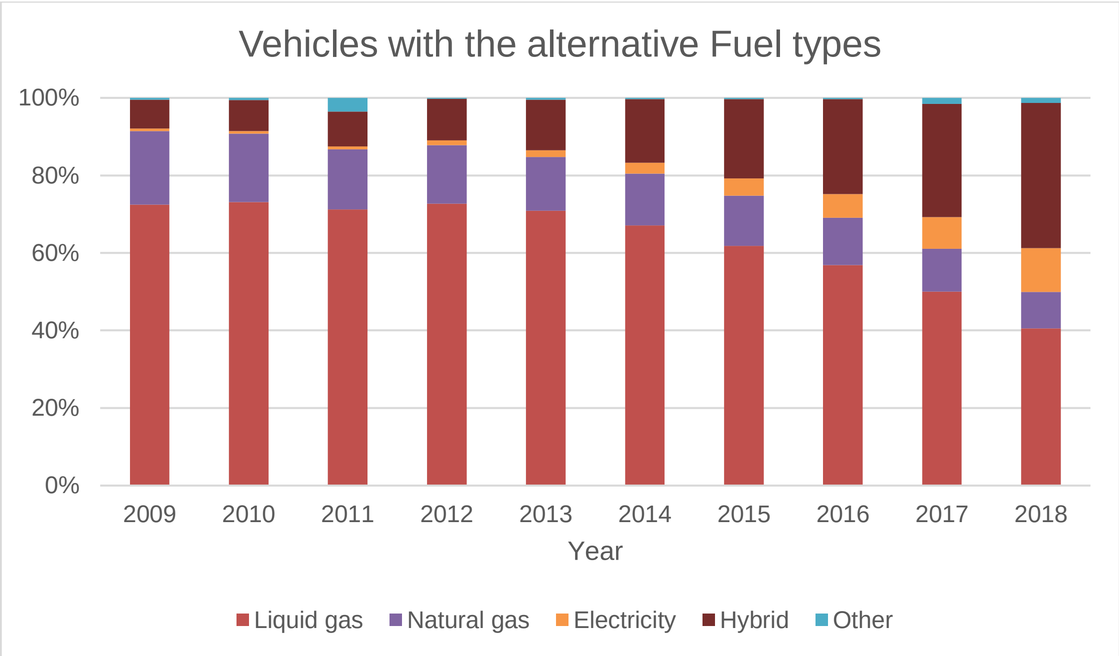

Figure 19: Vehicles with the alternative fuel types in Bavaria, adapted from Kraftfahrt-Bundesamt 2009a, 2010a, 2011a, 2012a, 2013a, 2014a, 2015a, 2016a, 2017a, 2018a

The next chapter discusses how such information described in this section is mapped onto the model for the emission calculation using MATSim.

7. Data Preparation

MATSim needs three files, at the very minimum, to simulate. These are configuration, network and population files. The configuration file builds a connection between the user and the transport model by its list of settings that dictate how the simulation should behave. It means everything from network, plans, output directories and number of iterations, amongst many others. The network file represents the infrastructure consisting of nodes and links on which the agents travel. The links depicted in the network file contain attributes describing traffic-related characteristics such as the length, the maximum travel speed permitted on the link, the number of lanes, the allowed modes and the flow capacity. The population, alternatively called the plans file, comprises information on the travel demand described by the agent's day plans. It is made up of a list of persons. Each person has a list of plans. Each plan contains a list of activity chains and a transport mode to travel between the activity locations, the so-called leg (Horni et al. 2016). To establish a model on the Munich metropolitan area, the Professorship for Modeling Spatial Mobility at the Technical University of Munich provided these minimum data.

The Professorship works on a research project that integrates land-use and transport models. A combination of the three microscopic models – the land-use model 'Simple Integrated Land Use Orchestrator (SILO)', the travel demand model 'Microscopic Transport Orchestrator (MITO)' and the transport model, MATSim – allows an extraction of feedbacks between land-use and transport at a microscopic level. The processes are carried out with the following steps: SILO retrieves the home and work zones with the given demographical structures; MITO generates lists of trips for every population that results from SILO, with a transport mode and a departure time; MATSim selects the one travel option for the agent with the highest benefit throughout the agent's experiences. Finally, every MATSim agent is assigned with the activities and the locations (Professur für Modellierung räumlicher Mobilität; Ziemke et al. 2016). The detailed integrating steps between these three models are illustrated in the following figure.

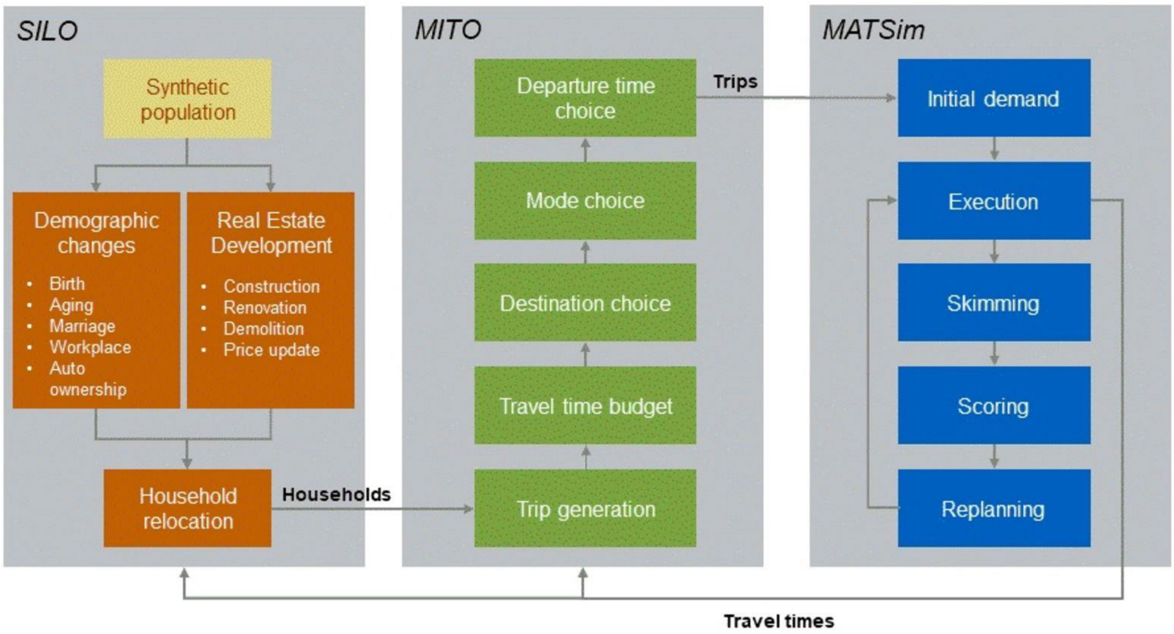

Figure 20: Integration of SILO, MITO and MATSim (Professur für Modellierung räumlicher Mobilität)

The provided configuration file presents how the plans files have resulted from this integrated model. In the last stage of the integration, MATSim executed 50 iterations, in which every agent tried out various travel options. For the Munich metropolitan region, the following types of activities are designed and assigned with the typical durations. The transport mode to travel between these activity locations is limited to a private vehicle at the moment.

Table 1: Provided activity types and their durations

Activity type	Typical duration
home	12 hours
work	8 hours
education	8 hours
shopping	1 hour
other	1 hour

The typical duration for each activity results in a positive utility while penalties are given for performing such activities within a shorter duration (see 5.1). While the plans of the agent were carried out and scored, MATSim selected a plan with the higher scores. Thereby, the plans with the worst scores were removed one by one whenever the agent had more plans than allowed, which was set here as four. As the number of iterations reached 80 % of the total, the scores remained constant. Based on the described settings, the Professorship provided the three resulting population files representing the years 2011, 2020 and 2030. These consist of the population and their daily activity-leg chains, which correspond to approx. 5 % of the trips performed on a normal working day in the Munich region (2011: 156,430 trips, 2020: 173,887 trips, 2030: 189,391 trips).

The given network file contains the infrastructure within the highlighted areas presented in Figure 21. The presented area does not exactly match with the Munich metropolitan region. However, as it covers the majority of this region, it is considered as a whole. The modeled network consists of 212,772 nodes and 499,435 links, each link containing its maximum permitted speed and the road type defined by the Open Street Map (OSM).

Figure 21: Modeled study area in the network file (Professur für Modellierung räumlicher Mobilität)

The emission modelling tool linked to MATSim requires several files in addition to the minimum input data. These are:

- HBEFA emission factor lookup tables;
- network assigned with the traffic situation;
- vehicles aligned to the population;
- new configuration file.

These are either provided, created or modified based on the provided input data. The remainder of this chapter discusses how the required files are developed.

7.1 Emission Factors

The MATSim's contribution, the emission modelling tool, already provides the HBEFA emission factors given as four lookup tables, which are based on two emission sources, each containing averaged and detailed vehicle characteristics. However, as it uses an older (HBEFA 3.1 with the reference year 2005) and limited version of the database, the Professorship provided the most recent version (HBEFA 3.3) of the fee-required HBEFA database. It reflects the year 2010 and was filtered for German-specific values. The number of tables and their categorization remained constant while the number of available emission factors is extended in the fee-required version.

7.2 Network

The infrastructure plays a significant role in differentiating the emission factors especially for warm emissions in HBEFA. The database provides the category 'traffic situation' for the warm emission, which are divided into four levels: the urban types, the road types, the traffic states and the speed limit (see Section 5.2). Thereof, the traffic states are the only element that are derived from the MATSim traffic simulation. The remaining characteristics should be assigned to the existing network file. The following table gives an overview of the dimensions of the traffic situations.

Table 2: Categories of the HBEFA traffic situations (Keller et al. 2017b)

			Speed limit [km/h]											
Area	Road type	Levels of service*	30	40	50	60	70	80	90	100	110	120	130	>130
Rural	Motorway-Nat.	4 levels of service												
	Semi-Motorway	4 levels of service												
	TrunkRoad/Primary-Nat.	4 levels of service												
	Distributor/Secondary	4 levels of service												
	Distributor/Secondary (sinuous)	4 levels of service												
	Local/Collector	4 levels of service												
	Local/Collector (sinuous)	4 levels of service												
	Access-residential	4 levels of service												
Urban	Motorway-Nat.	4 levels of service												
	Motorway-City	4 levels of service												
	TrunkRoad/Primary-Nat.	4 levels of service												
	TrunkRoad/Primary-City	4 levels of service												
	Distributor/Secondary	4 levels of service												
	Local/Collector	4 levels of service												
	Access-residential	4 levels of service												

* free flow, heavy, saturated, stop&go

To extract the emission factor aligned to the traffic situation in which the agent is located, it is necessary to add the road characteristics onto the links. Hereby, the two categories road types and speed limits are mainly considered. Following processes perform the allocation:

(1) matching the HBEFA road type with the OSM road type;
(2) allocating the maximum allowed speed in each range.

The provided network already contains the road types defined by OSM. However, since the definitions of OSM and HBEFA differ from each other, the OSM should be reallocated to accord with those of HBEFA.

The further process requires defining ranges for the speed limit. The given network file provides the maximum speed for every link, which is called freespeed in MATSim. However, as varying freespeeds are assigned across the entire network, and as their distribution is quite broad, these are aggregated into a certain range that is determined with a simple assumption adapted from the German guideline on road categories (RAS-N – German abbreviation). Table 3 shows the allocating of the OSM road type and the freespeed to align with the HBEFA. The speed limits stated in the following table present the maximum. Further categories are available by 10 km steps. Within each urban type, the HBEFA road types are assigned in order, based on the level of the road type.

Table 3: Road mapping based on the road types and the speed limit

Urban type	HBEFA road type	OSM Road type	Speed limit
Rural	Access	residential, service, living_street	up to 50 km/h
	Local	tertiary	up to 60 km/h
	Distributor	secondary	60 - 80 km/h
	Trunk	primary, trunk	up to 110 km/h
	Motorway	motorway, motorway_link	80 - 130 km/h
Urban	Access	residential, service, living_street	up to 30 km/h
	Local	tertiary	up to 50 km/h
	Distributor	secondary	up to 60 km/h
	Trunk-City	primary, trunk	up to 80 km/h
	Motorway-City	motorway, motorway_link	up to 80 km/h

During allocation of the new road types onto each link, two kinds of exceptions occur. One appears when the link does not fulfill both road type and speed limit criteria, for example, a link defined as ‘residential’ with the freespeed of 100 km/h or a secondary link with 30 km/h. Such an exception appears mainly with the OSM road types ‘residential’, ‘tertiary’ and ‘secondary’. In this case, the link is reallocated, based primarily on its freespeed. Its OSM road type constitute only a starting point in the HBEFA road type to which the freespeed belongs. As the freespeed does not fit within the speed limit range, the link is then compared to the next level of HBEFA road type. Such a comparing process is made within the urban area. If it fails, the link is further compared with the same HBEFA road type in rural area. These steps are repeated until the link finds a range in which its freespeed fits. As an example, a tertiary link with 70 km/h will allocated to the distributor road in the rural area. The second type of exception occurs with the link defined as the OSM type ‘unclassified’. These exceptions are allocated only based on their freespeed, as presented below.

Table 4: Road mapping for the unclassified links

freespeed in [$\frac{km}{h}$]	HBEFA Road type
0-30	URB/Access/30
30-40	RUR/Access/40
40-50	RUR/Access/50
50-60	URB/Distributor/60
60-70	URB/Trunk-City/70
70-80	URB/Trunk-City/80
80-90	RUR/Trunk/90
90-100	RUR/Trunk/100
100-110	RUR/Trunk/110
110-120	RUR/Motorway/120
120-130	RUR/Motorway/130

Once the allocating criteria are defined, a new network file can be generated, based on the provided network file with the road characteristics described in this section.

7.3 Vehicles

The given population file only represents the individual trips that are traveled by car, but it does not provide any further information on the vehicle characteristics. Such information is necessary to extract the emission factors from the HBEFA lookup tables. Thus, the additional file containing the vehicle attributes should be developed in alignment with the population file, particularly the agents included in the file. This holds true for both warm and cold-start emissions (see 5.2).

First of all, for every vehicle’s identification number equivalent to the agent’s identification number is generated. Such identification leads to better understanding of journey and the travel time. Then, all available vehicle types with their descriptions should be defined and stored in the ‘vehicles container’, which contains all the relevant data of the vehicle types in MATSim. A vehicle can be identified by three characteristics; these are the fuel types, the cubic capacities and the European Emission Standard Classes. The combination of the three results in 30 different types of the vehicles.

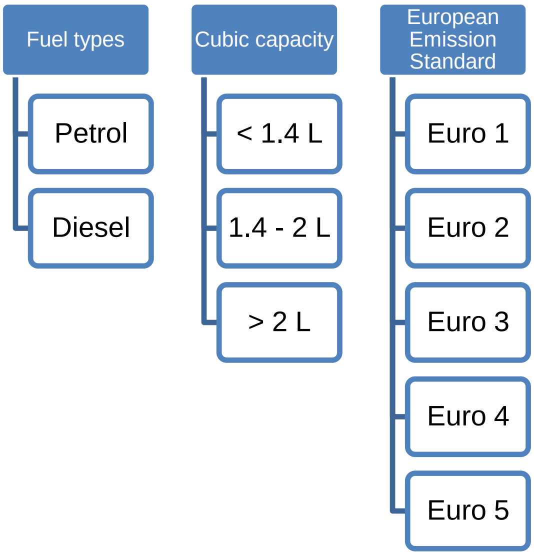

Figure 22: Three characteristics of a vehicle, adapted from Keller et al. 2017b

There is a further vehicle type whose characteristics can be neglected because it does not generate emission. This is defined as the zero-emission car in MATSim. After the vehicles container has stored all the relevant types, the attributes are assigned to each vehicle. The distribution of the vehicle types is made based on the fleet composition. In this thesis, the fleet composition is taken from the annual statistical data of the Federal Motor Transport Authority (KBA – German abbreviation). Although KBA provides only vehicle composition Germany-wide, its proportional distribution is assumed to be equivalent in the Munich metropolitan area. The precise proportion of each vehicle types is further discussed in Chapter 8. If such information were not available, the vehicles would be assigned with an average attribute. In such a case, HBEFA would take the averaged emission factor for this vehicle.

7.4 Configuration

Apart from the given configuration file, a new one is necessary to provide a link between the given files and the generated files. The following figure gives an overview of the relationship between the original files, the newly generated and the new configuration files.

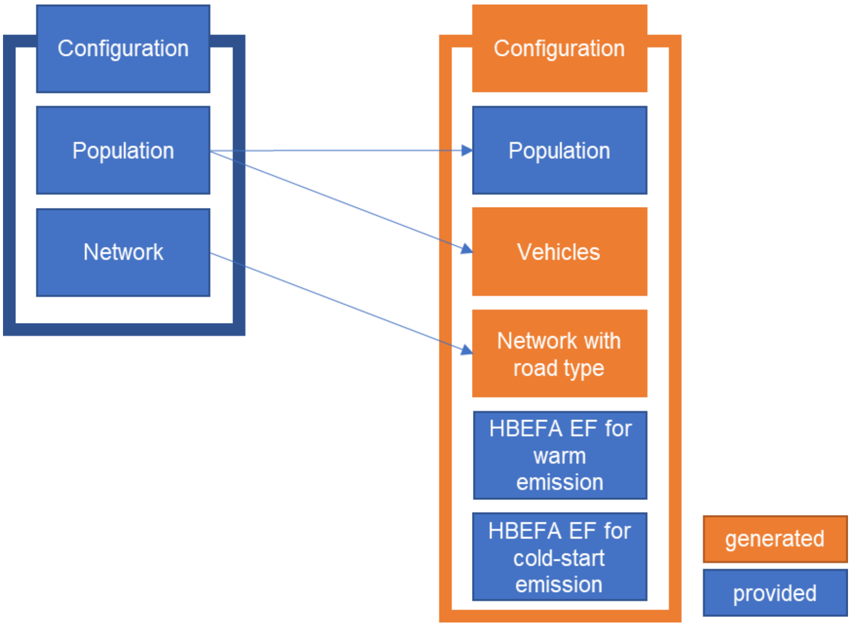

Figure 23: Overview of the provided and the generated configuration files

The generated configuration file further establishes a connection between the files presented in Figure 23 and the emission modelling tool. It enables application of the activity component and the emission factor for each agent in the emission calculation.

Setting the number of the iterations in the created configuration file has minor meaning, since the population file is a result of 50 iterations, and the agents have already set their activity parameters and their daily activity-leg chain. Although the types of the activities as well as their typical durations have been outlined in the given configuration file, these should be re-identified in the new file, as it is a basic information component that should be included in the configuration file. Therefore, information on the activity parameters are inserted without any changes (see Table 1).

The files described in this chapter should be generated if the given data have been updated due to the changes in the reality. Such changes occur at different paces. The changes in infrastructure occur over longer-term, whereas the population number and its travel demand can be changed easily. Mapping such information onto the emission model, the network file remains constant once the road characteristics are assigned. The vehicles files are created for every population file provided for the years 2011, 2020 and 2030. Moreover, further vehicles files are necessary to build intervention scenarios, which are described in the following chapter. These files should be re-linked by the configuration files that are developed respective to the newly generated files.

8. Scenarios

This thesis compares different scenarios to create visualizations of the NO_2 emissions and the potential impacts of implementing the emissions reduction measure. The estimation begins with establishing a baseline. This is a non-intervention scenario, used as a base in the analysis of all the intervention scenarios.

A system boundary should be set for the emission inventory. The baseline year is 2011, as this is the base year of the integrated model by the Professorship. The emissions are estimated for 2020, when the first stage of the German target goals should be one million electric vehicles, and 2030 when the second stage goal targets six million. The spatial domain is Germany and the spatial resolution is the Munich metropolitan area. The calculated emissions in this estimation are measured in NO_2.

Following this, the emission projections will forecast the NO_2 emissions for four scenarios. The first scenario is the 'business-as-usual (BAU)' scenario, where calculations are made with no measures implemented. The remaining scenarios consider an emission reduction measure. For a reduction measure, the intention to expand the percentage of electric vehicles is applied in this study. The difference within the three scenarios is the achievement of the measure. This chapter discusses the scope of each scenario.

8.1 Business-as-usual Scenario

The BAU scenario considers the development of the emissions without any reduction measures. This means that the proportion of electric cars from the year 2011 remains constant during the whole investigating period.

In 2011, with petrol the dominant fuel type (71.9 %), the second most used fuel for German drivers was diesel, which made up 26.8 %. Furthermore, only 1.3 % used alternative fuels such as LPG, CNG, hybrid mixes and electricity, amongst others. Thereof, the proportion of electric and hybrid cars amounts to only 0.09 % (see Figure 18 and Figure 19) (Kraftfahrt-Bundesamt 2011a). By illustrating such information onto the model, following assumptions are made due to limitations of HBEFA:

- all vehicles with alternative fuels belong to the zero-emission car category;
- for petrol and diesel cars, the categories unknown cubic capacity are categorized along with vehicles of more than 2 liters of cubic capacity;
- the Euro 6 vehicles are classified with Euro 5.

The following table displays the cars registered in Germany, categorized in more detail.

Table 5: The proportion of vehicle types in 2011, adapted from Kraftfahrt-Bundesamt 2011a

		EURO1	EURO2	EURO3	EURO4	EURO5	Total in the fleet
Petrol	< 1.4 L	8%	20%	12%	52%	8%	71.9%
	1.4 - 2 L	9%	32%	16%	39%	4%	
	> 2 L	12%	32%	18%	35%	4%	
Diesel	< 1.4 L	1%	2%	32%	61%	4%	26.8%
	1.4 - 2 L	2%	10%	28%	47%	13%	
	> 2 L	4%	25%	34%	27%	9%	
Zero-Emission							1.3%

For the BAU scenario, the above data is used to forecast the total emissions for the years 2011 to 2030. Moreover, it serves as basis for the intervention scenarios as well. The following section describes the further scenarios modelling the development of emissions with an intervention.

8.2 Intervention Scenarios

As Germany introduced the objective to increase the number of electric vehicles to one million by 2020, the Fraunhofer Institute has developed a model to estimate the potential resulting impacts in the German vehicle market in its study *Markthochlaufszenarien für Elektrofahrzeuge*. The intervention scenarios investigated in this work are based on this study.

The model developed by the Fraunhofer Institute integrates three calculation phases. The first step calculates the Total Cost of Ownership (TCO) for each individual driving unit, based on the vehicle data and the technical analysis, including several thousand different driving profiles of the vehicles. The subsequent phase builds on the resulting TCO in terms of advanced customer behavior, which depends on the price of charging infrastructure, limited availability of electric car offers and willingness to pay higher costs for innovative technologies. Finally, these aspects are projected onto the German vehicle market, and the trends of electric vehicles are forecast for 2020. Within the forecasting, the institute has established three different scenarios because of the uncertainties resulting from the price development of other fuels, the electricity and the battery. The ‘Pro electric vehicles (EV)’ assumes an optimistic condition for the electric vehicle with a high price for other fuels and low costs for the electricity and the battery, whereas the ‘Contra EV’ makes a contrary pessimistic assumption. The ‘Middle EV’ takes the average circumstance from both scenarios. The forecasts of the three scenarios are shown in the figure below. Each scenario shows a range that results from uncertainties given the limited sample of the driving profiles. Considering all the factors, the Pro EV expects approx. 1 to 1.4 million electric vehicles, the Middle EV 400,000 to 700,000 and the Contra EV 50,000 to 300,000 (Plötz et al. 2013).

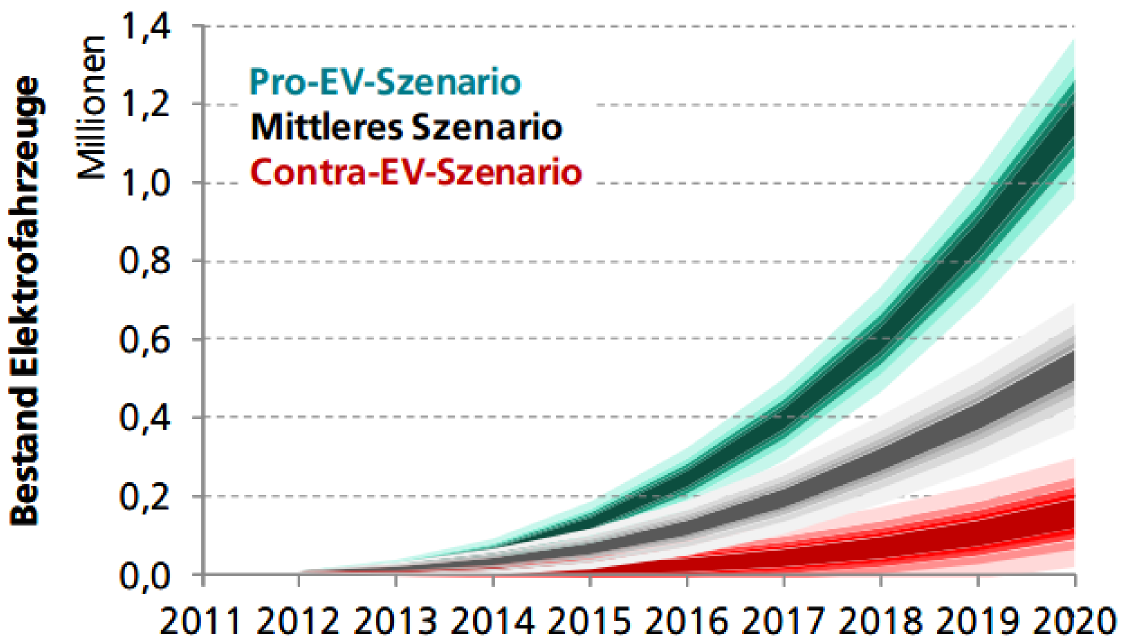

Figure 24: Estimated trends of electric vehicle until 2020 (Plötz et al. 2013)

These forecasts build a basis for the intervention scenarios with some extensions. Instead of observing the ranges, each scenario selects its average value for the year 2020. As Fraunhofer's study outlines the trends only up to 2020, a further 10 years will be projected to display the potential impacts of six million electric vehicles. For this, the following assumptions are established:

- the proportional achievements of the three scenarios are projected for six million electric vehicles by 2030;
- the number of the vehicles in Germany is forecasted with a linear extrapolation to 2030 based on the KBA's annual inventories from 2009 to 2018;
- the resulting proportional shares are applied in the study area;
- the percentage of diesel cars decreases in direct proportion to electric cars increase;
- the emissions class and the cubic capacity compositions within petrol and diesel car categories remain constant;
- the percentage of vehicles with other alternative fuels remain constant and allocated to the zero-emission cars.

With the average values within the ranges, the three scenarios would reach the target of one million electric vehicles at 120 %, 55 % and 18% respectively. These proportional achievements are applied to the target for 2030, and the numbers of electric vehicles assumed for each scenario are depicted in the table below.

Table 6: Targeted volumes in the intervention scenarios referring Germany

	2020	**2030**
Pro EV	1,200,000	7,200,000
Middle EV	550,000	3,300,000
Contra EV	175,000	1,050,000

These scenarios should be indicated as the share in the vehicle types in the emission calculation. To compute such the share, the volumes of the vehicles in Germany is required for both modelling years. These are forecast with a linear extrapolation based on the KBA's annual vehicle inventories from 2009 to 2018 (see Appendix 1) and result in 47,417,080 cars for 2020 and 53,085,995 for 2030. In addition to the percentage of electric cars, vehicles powered by other fuel types should be further considered by adding 1.17 %. Based on these aspects, the following proportions are reached in each scenario.

Table 7: The proportion of electric cars in the intervention scenarios

	2020	**2030**
Pro EV	3.7%	14.7%
Middle EV	2.3%	7.4%
Contra EV	1.5%	3.1%

As the estimations stated in Table 7 refer to that of Germany, the scenarios should be adjusted to the study area. Thereby, a simple assumption is made that the fleet composition of Germany is projected to the Munich metropolitan area.

As electric vehicles expand, the percentage of other vehicle types decreases respectively. In the intervention scenarios, the growth rates of electric vehicles are assumed to be the decreasing rate of diesel-powered vehicles, as these have high risk of a ban in cities. However, the shares of the categories within each fuel type remain constant. The following chapter presents the resulting emission trends applying these scenarios.

9. Results

Emissions can be computed based on the vehicle composition defined in the previous chapter. The results are recorded in ‘events’, which can be visualized by means of Via.

This chapter presents the results of each scenario. First, the BAU scenario is described for each of the years 2011, 2020 and 2030. Further, the results of the intervention scenarios are presented. As mentioned previously, the number of trips modeled in this estimation comprises only 5 % of the total. Therefore, the total emissions forecasted in this chapter also reflect 5 % of the trips.

9.1 Business-as-usual Scenario

Table 8 presents the one-day accumulation of NO_2 predicted for the BAU scenario. The growth in the number of trips and any changes in vehicle composition yield an emission increase of 14 % from 2011 to 2030.

Table 8: Total NO_2 in the BAU scenario

Total emission in $[g\ NO_2]$	2011	2020	2030
BAU	185,988.20	199,660.02	211,595.25

Base year 2011

The scenario in the base year visualizes the NO_2 emissions produced from 156,430 trips. First, the one-day model of NO_2 emissions are presented as the following figures. These present the emissions in the network, classified in the following ranges.

Table 9: Daily NO_2 categorization

Categorization	NO_2 range in $[g]$
1.0	less than 1.0
10.0	from 1.0 to 10.0
20.0	from 10.0 to 20.0
30.0	from 20.0 to 30.0
50.0	from 30.0 to 50.0
51.0	greater than 50.0

The highest level of the emissions is shown along the major transport axes connecting the cities. The cities Munich, Rosenheim, Augsburg, Landshut, Ingolstadt can be easily identified by the accumulated middle level of the emissions between 10 to 30, particularly the Munich area. The emissions are concentrated in the Southwest as well. The links with the highest-level amount to 332, which make up approx. 0.07 % of the network.

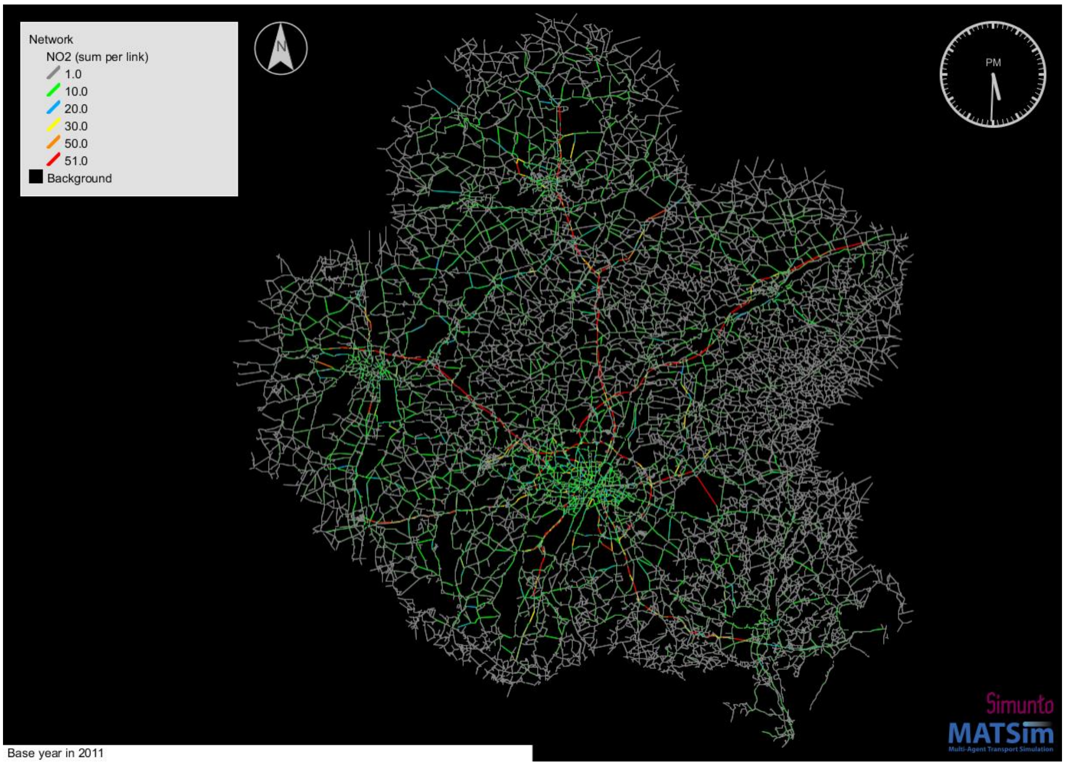

Figure 25: One-day model of NO_2 (Base year in 2011)

A closer look at the city of Munich, indicates nearly all links higher emission level. A majority of the links shown in green. Even higher level in yellow, orange and red can be found within the city.

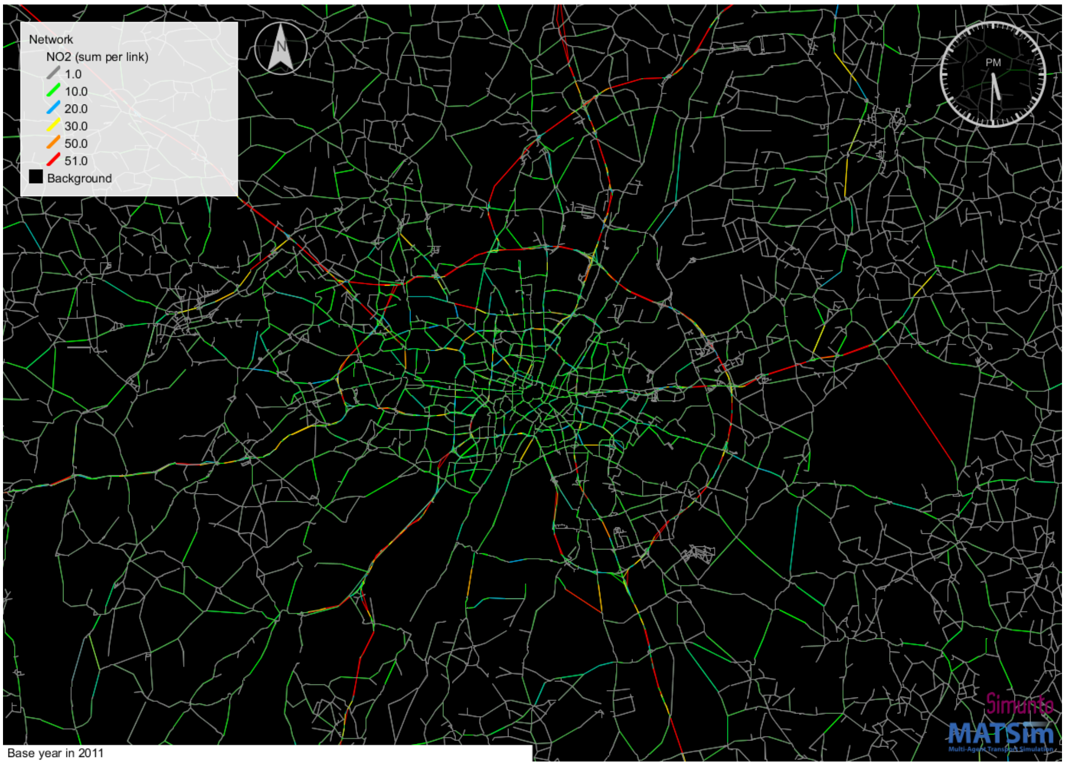

Figure 26: One-day model of NO_2 in Munich (Base year in 2011)

Via further enables presentation of the emissions at the hourly level. To picture the situations during which traffic is at its highest, the emissions are displayed for the morning peak at 9 and for the evening peak at 17:30. The ranges for the hourly emissions are adjusted as presented in Table 10.

Table 10: Hourly NO_2 categorization

Categorization	NO_2 range in $[g]$
0.01	less than 0.01
0.5	from 0.01 to 0.5
1.0	from 0.5 to 1.0
10.0	from 1.0 to 10.0
11.0	greater than 10.0

The trends in the morning and evening peaks depicted in Figure 27 and Figure 28 are very similar. Also similar to the daily accumulation of NO_2, the hourly emissions show the highest level along the major transport axes, particularly the axes connecting Munich – Augsburg and Munich – Landshut. Moreover, the links with higher levels are concentrated in the cities. NO_2 in the evening peak shows slightly higher emission levels than in the morning peak. The links along the axes Munich – Landshut, Munich – Ingolstadt and Munich – Rosenheim show this difference.

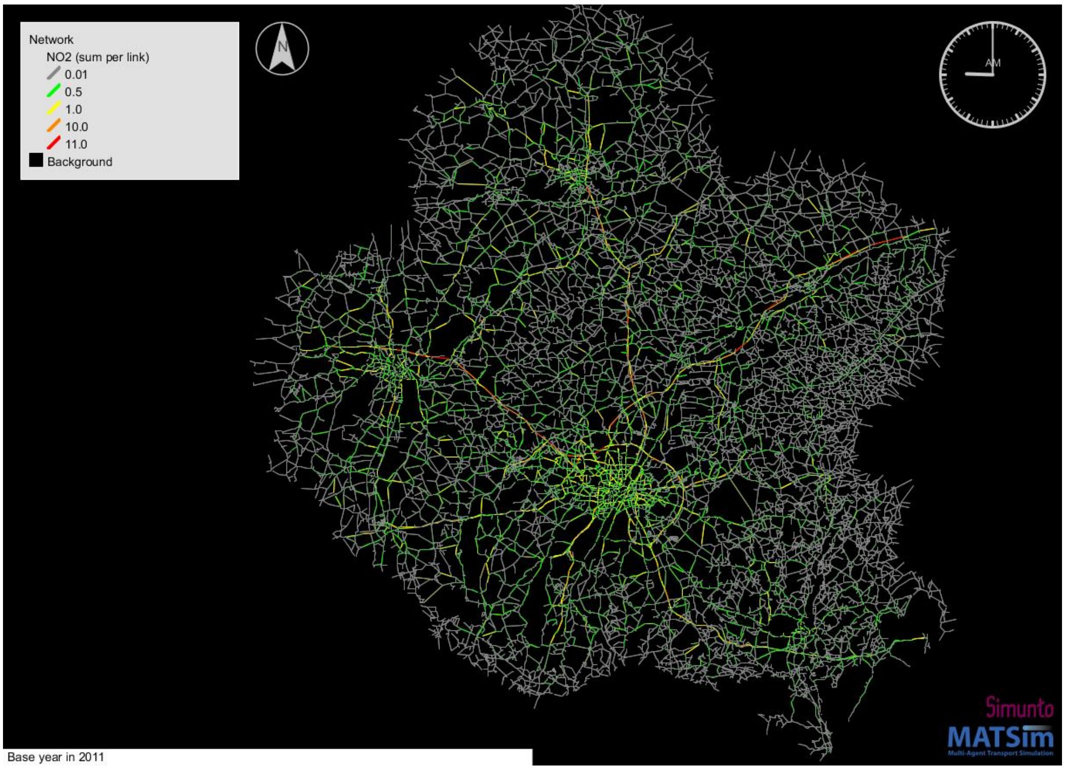

Figure 27: One-hour model of NO_2 during the morning peak (Base year in 2011)

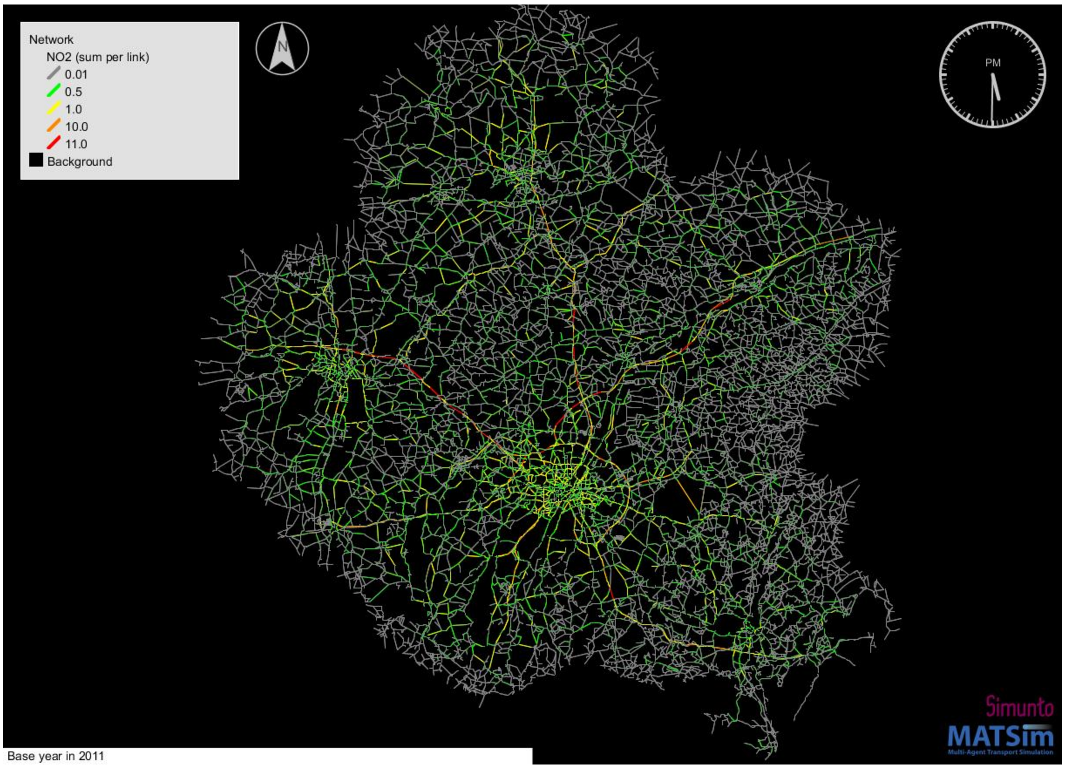

Figure 28: One-hour model of NO_2 during the evening peak (Base year in 2011)

Much like the previous comparison, the trends in both peaks of the Munich area show a very similar picture. Comparing the one-hour model, the emissions during the evening peak show slightly higher levels.

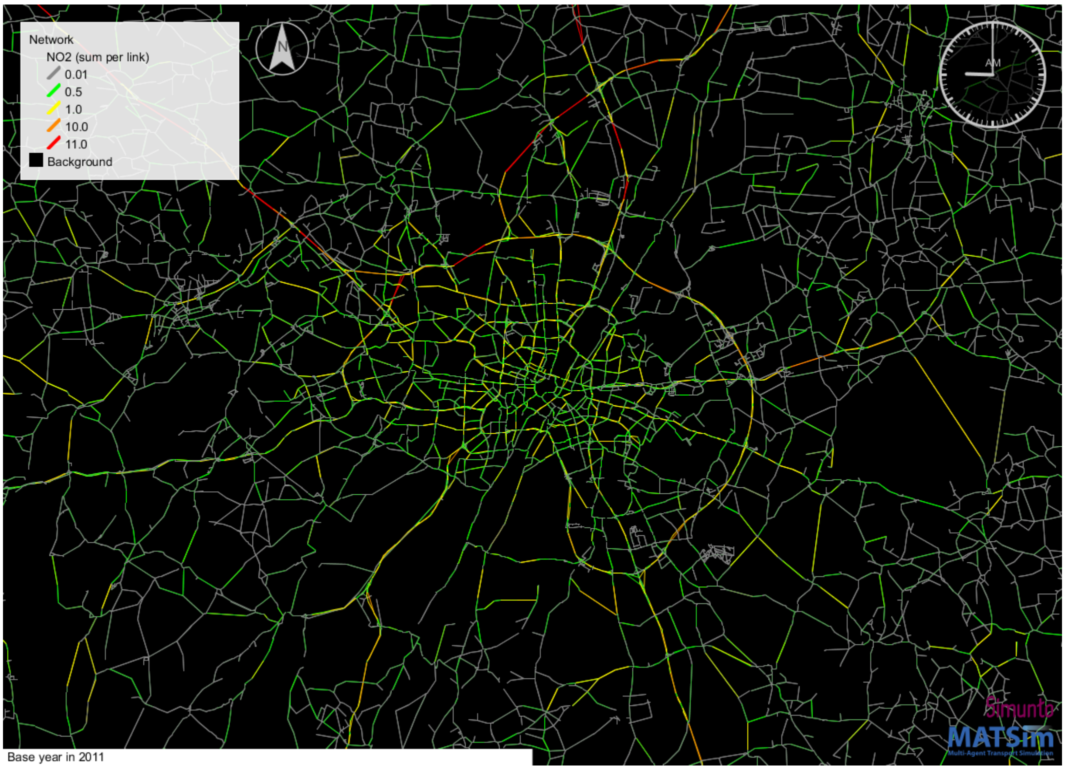

Figure 29: One-hour model of NO_2 in Munich during the morning peak (Base year in 2011)

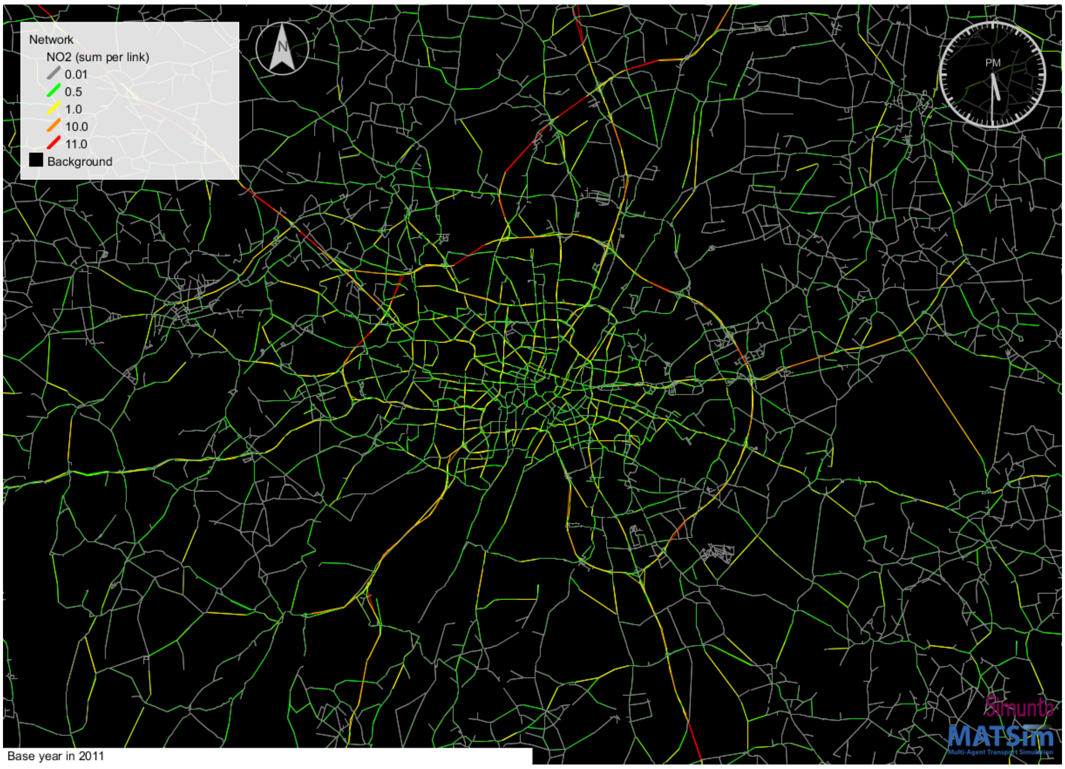

Figure 30: One-hour model of NO_2 in Munich during the evening peak (Base year in 2011)

The roads in the network consists of multiple links. For example, one section of the road contains the total number of lanes in both directions. To quantify the amount of the emissions in the two hotspots Landshuter Allee and Stachus, the resulting one-day accumulation of

NO_2 emissions are aggregated from the links depicted in the following figures. The marked sections consist of 31 links in Landshuter Allee and 12 links in Stachus.

Figure 31: Aggregated links on Landshuter Allee, adapted from OpenStreetMap

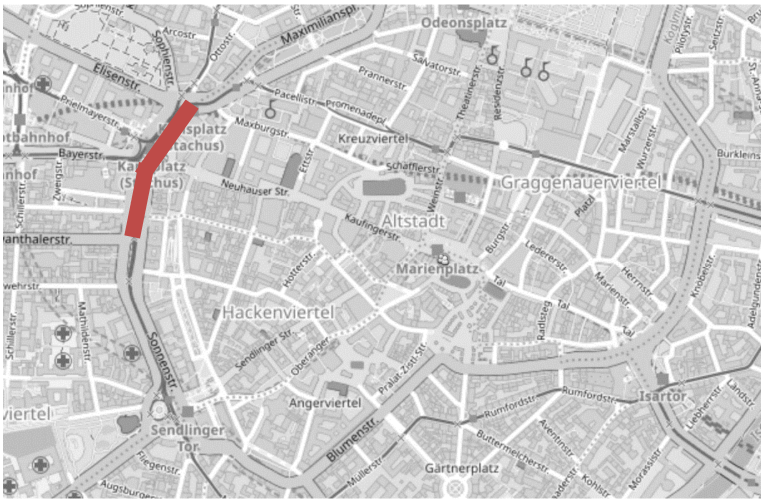

Figure 32: Aggregated links at Stachus, adapted from OpenStreetMap

Aggregating these emissions results in 150 g NO_2 on Landshuter Allee and 37 g at Stachus. To model the emissions during a day, a link with the highest amount of emissions is selected for each area and presented in the following charts. The maximum on Landshuter Allee amounts to 3.04 g at 16:00. Its average value is 1.0 g NO_2. At Stachus, lower emissions are detected with the maximum amount at 0.66 g and the average at 0.26 g NO_2. The morning and evening peaks are clear on Landshuter Allee, whereas these are difficult to identify at Stachus.

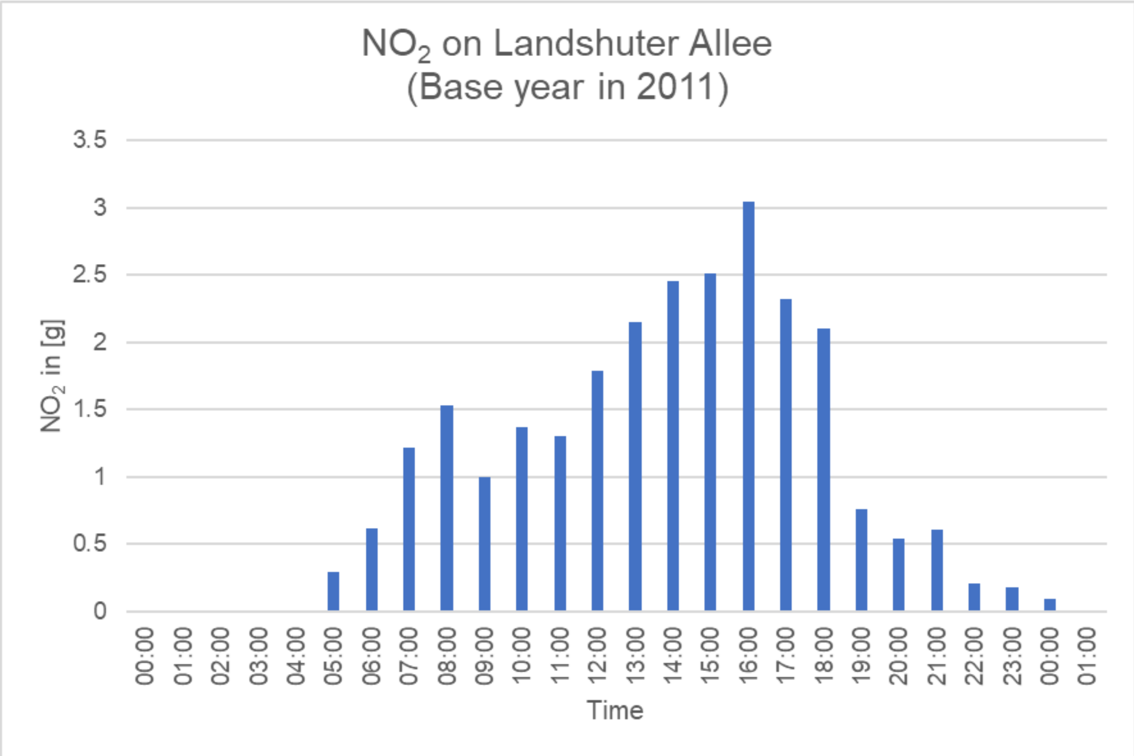

Figure 33: One-day course of NO_2 on Landshuter Allee

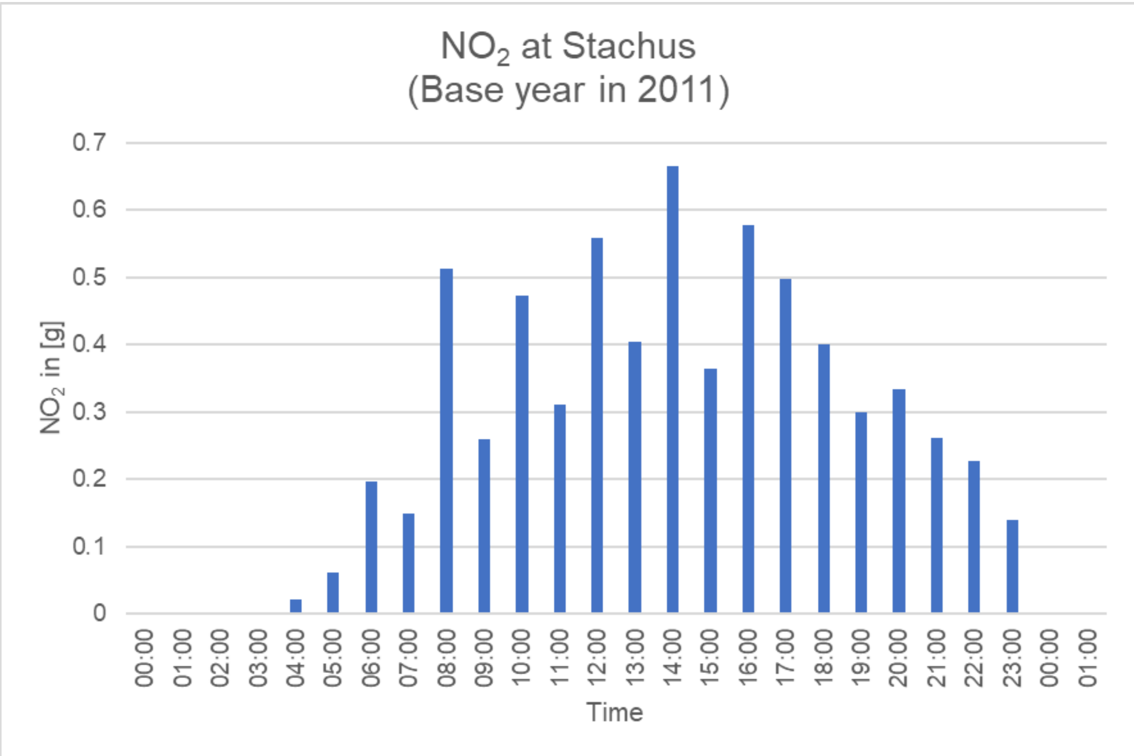

Figure 34: One-day course of NO_2 at Stachus

These results for the base year 2011 apply not only for the BAU scenario, but also serve as the basis for the intervention scenarios.

BAU scenario for 2020

The BAU scenario for 2020 examines the unchanged vehicle composition with increased trip numbers of 173,887. This results in an increased amount of the emissions, 199,660 g NO_2 in total. It is a growth of 7 % compared to the base year. When the trend presented in Figure 35 is compared to that of the base year, a slight increase in the emission level can be found in the rural area on the northwest side. The number of links in the emission levels 10 and 30 have increased by 5 %. The number of links with the highest-range has even increased by 8 % compared to the previous observation year.

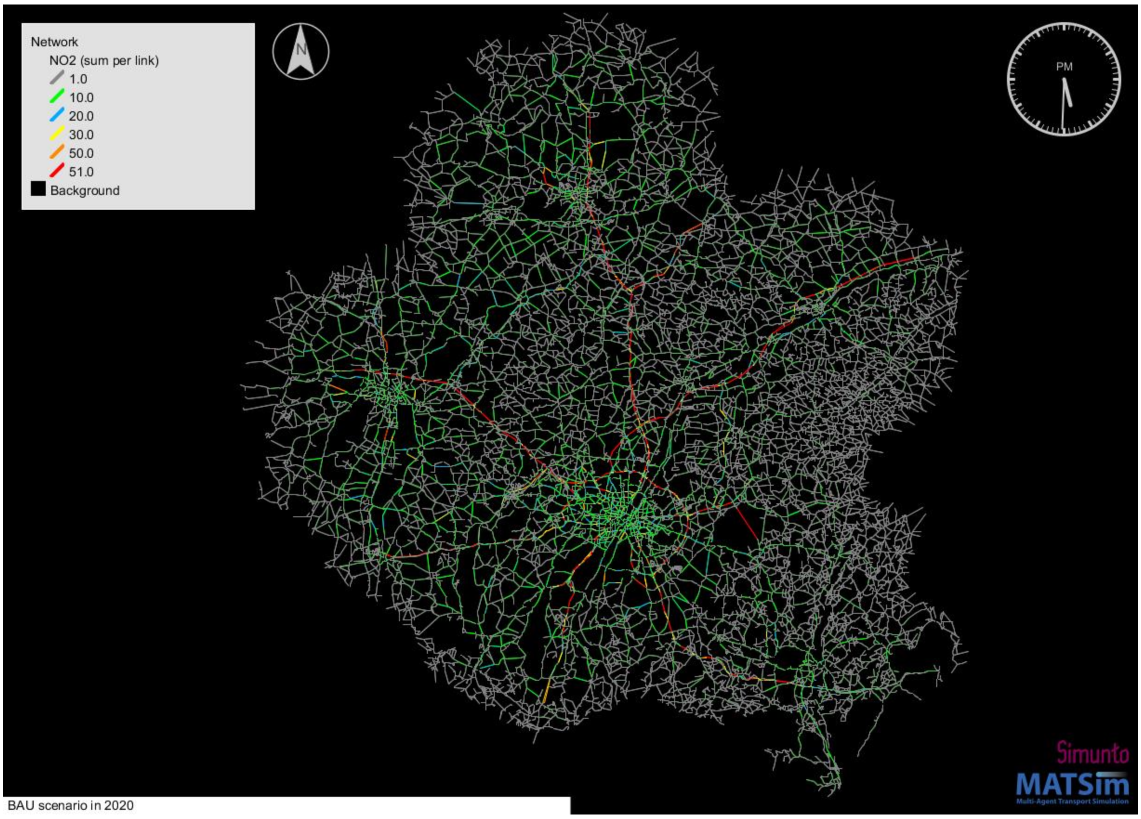

Figure 35: One-day model of NO_2 (BAU scenario in 2020)

This increase in the highest emissions level can be detected within the city of Munich respectively.

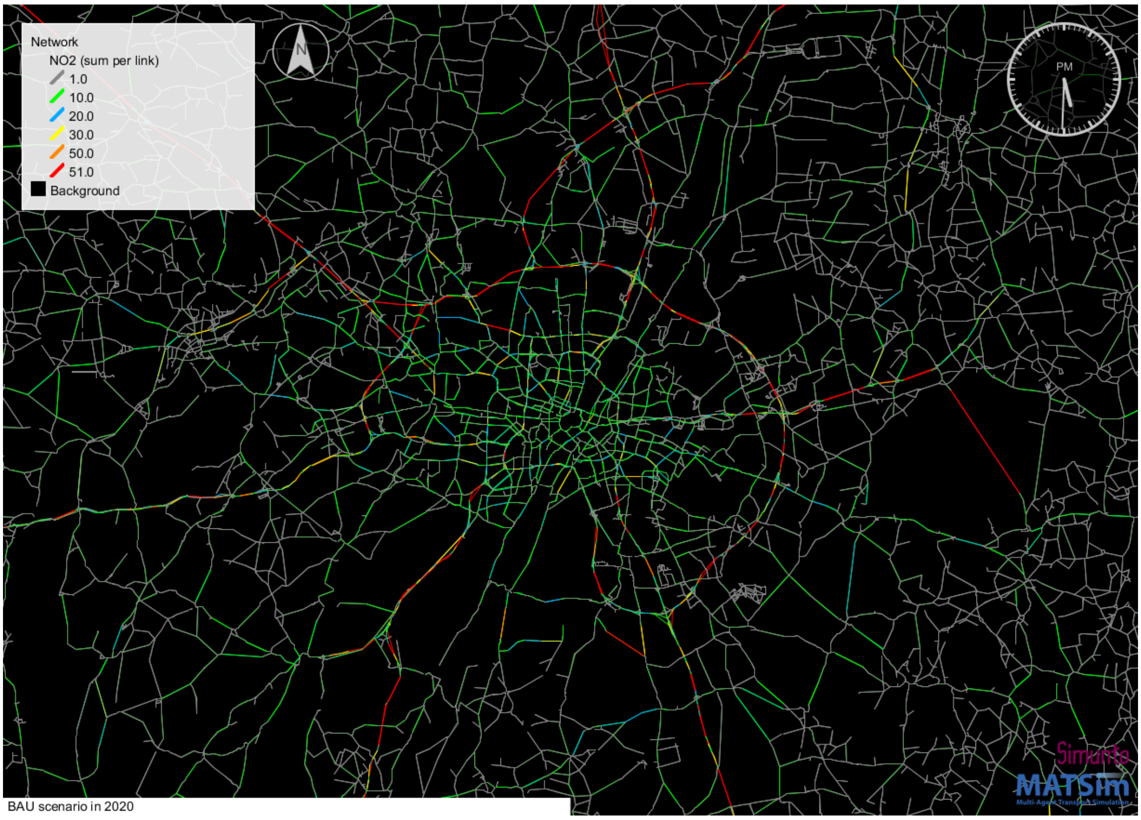

Figure 36: One-day model of NO_2 in Munich (BAU Scenario in 2020)

The following figures present the one-hour model during the morning and evening peak hours. When the trend presented in the figures below compared to those of the base year, slightly higher emission levels can be seen. In particular, the emissions during the evening peak hour indicate higher levels on the major transport axes.

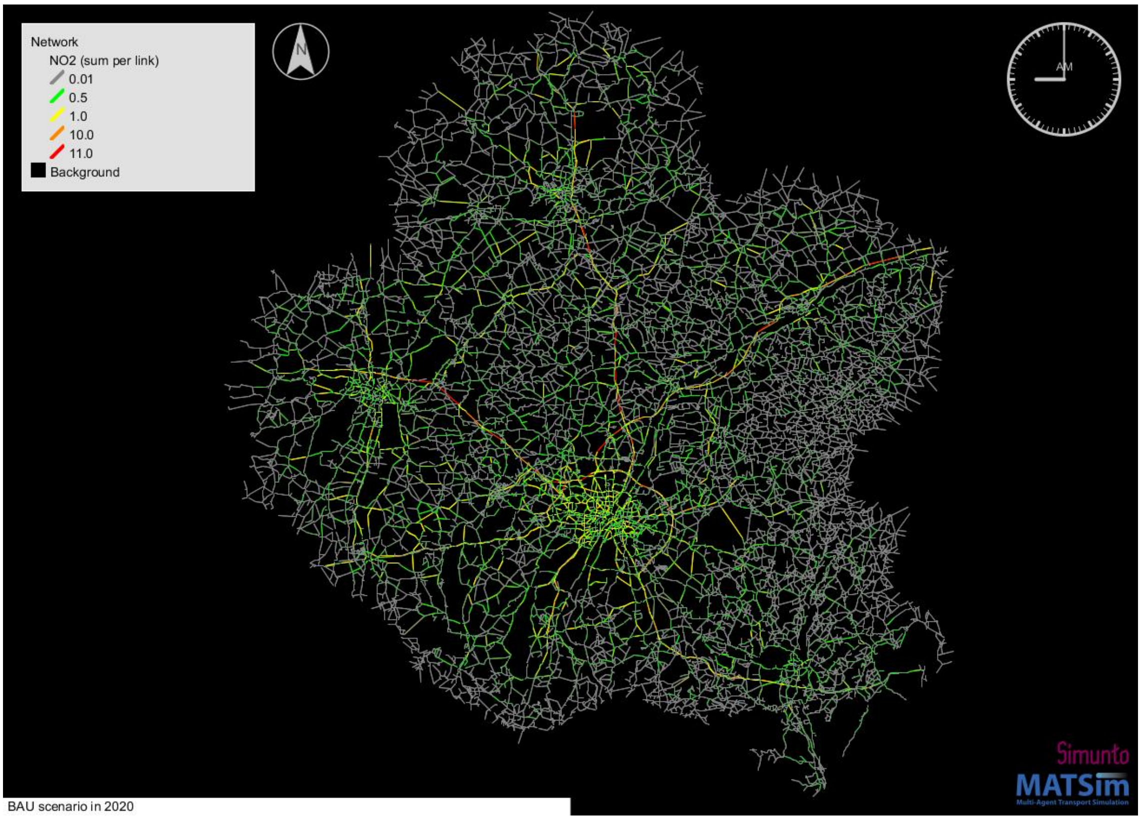

Figure 37: One-hour model of NO_2 during the morning peak (BAU scenario in 2020)

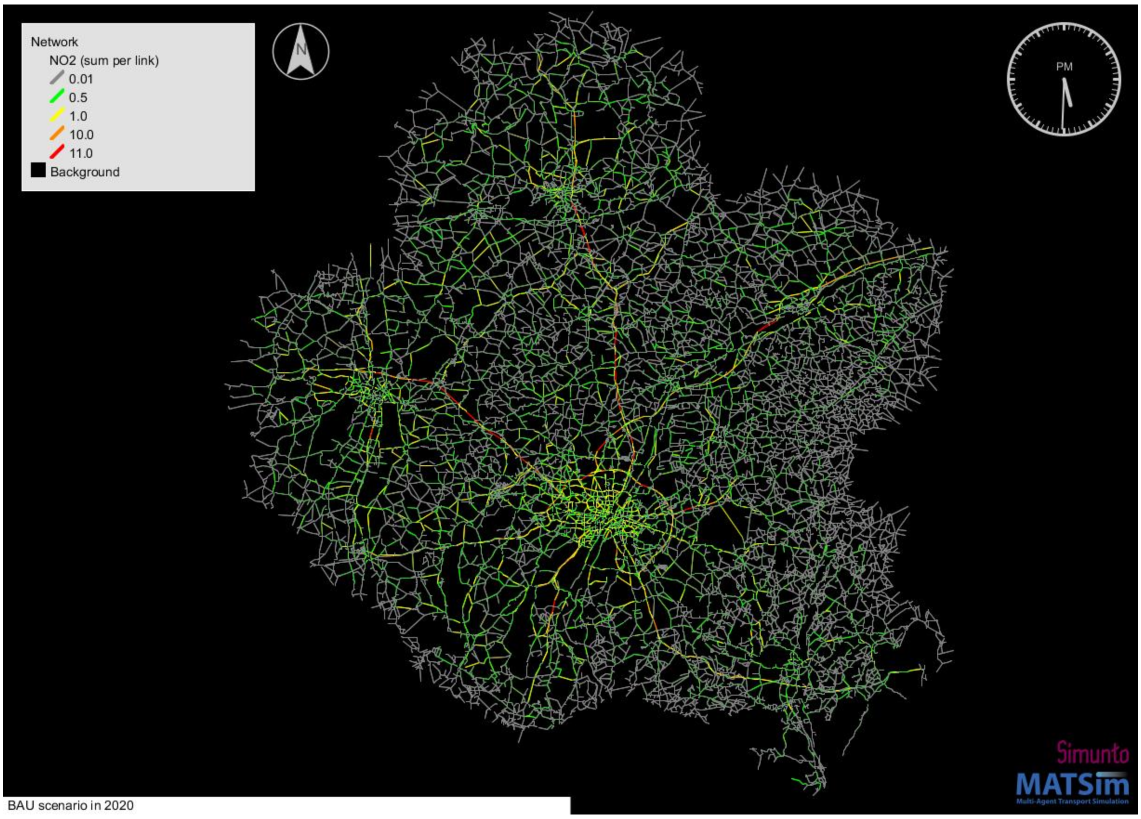

Figure 38: One-hour model of NO_2 during the evening peak (BAU scenario in 2020)

In Figure 39 and Figure 40, there is recognizable increase in the emission level from 0.5 to 1.0 or even to 10.0 in the both peak hours.

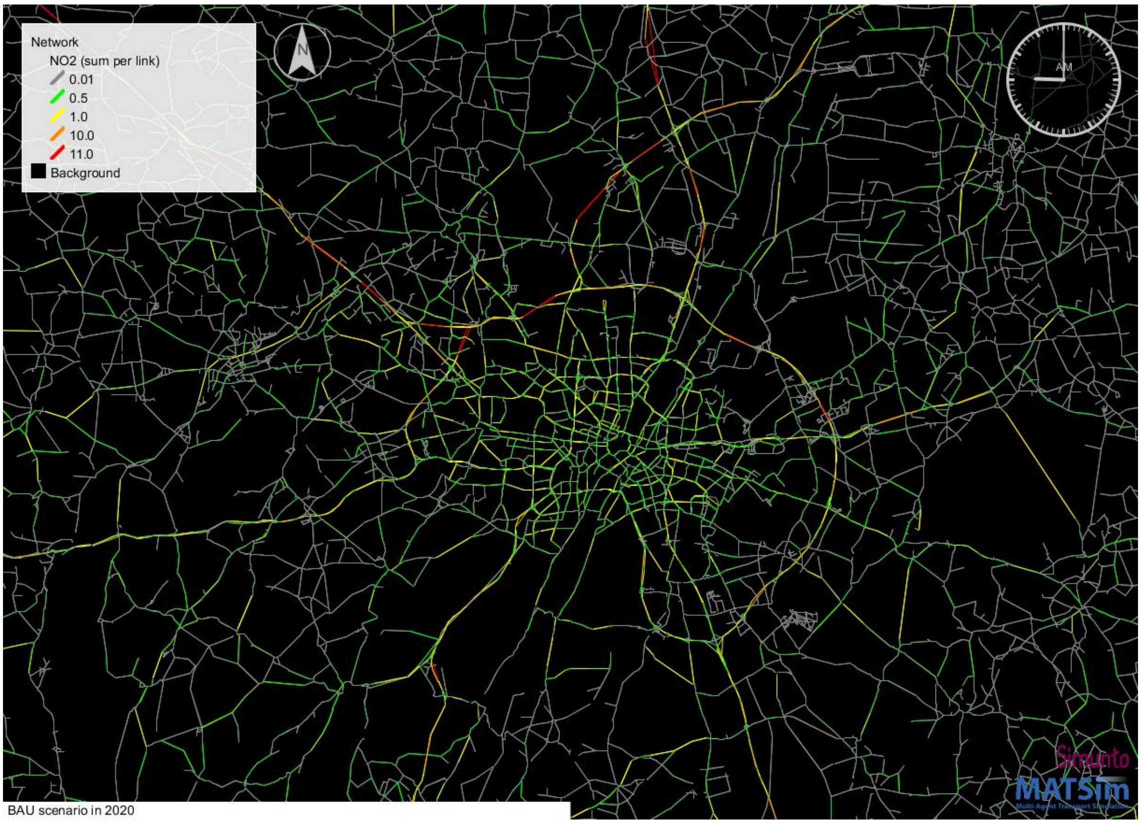

Figure 39: One-hour model of NO_2 in Munich during the morning peak (BAU scenario in 2020)

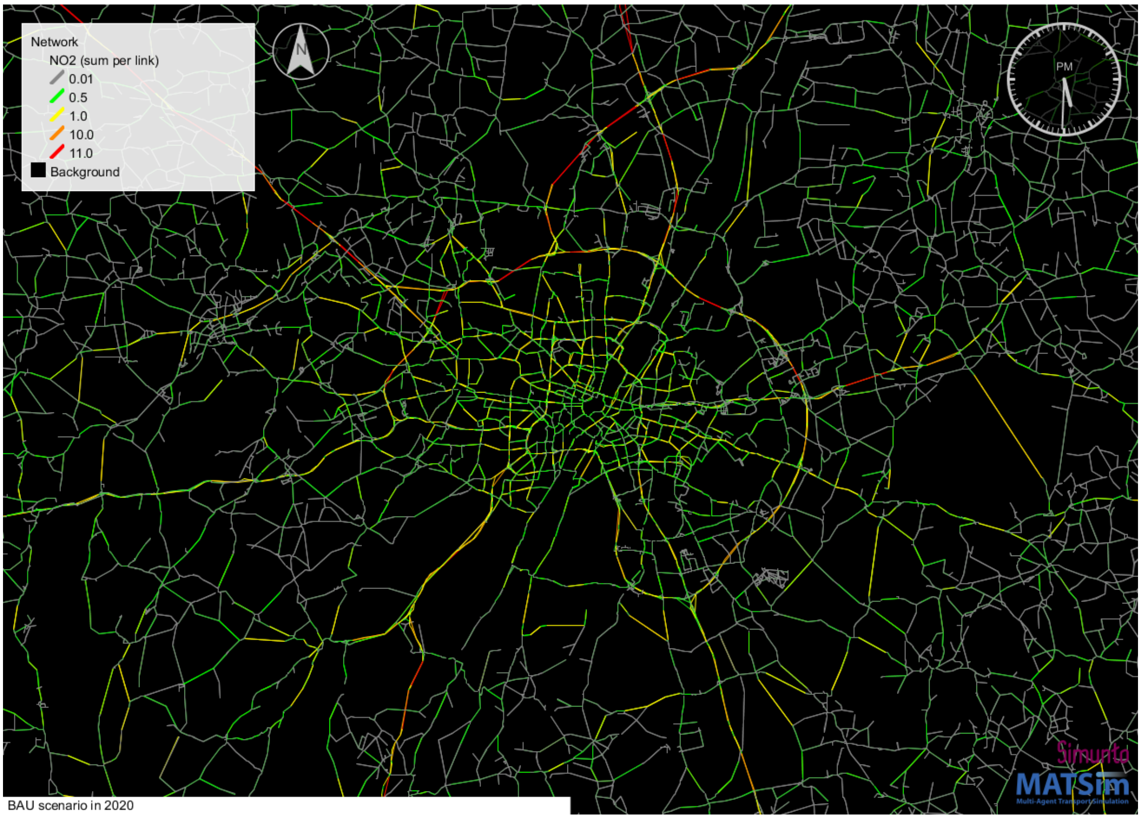

Figure 40: One-hour model of NO_2 in Munich during the evening peak (BAU scenario in 2020)

The hotspots indicate a growth of the emissions as well. The total amounts modeled for Landshuter Allee are 156 g NO_2 and at Stachus 40 g, with a respective increase of 4 % and

8 %. The maximum and average emissions at Stachus will probably grow by 18 % and 23 %. On Landshuter Allee, the average emissions amount to 1.1 g and the maximum emissions are 2.9 g. At Stachus, the average NO_2 is 0.3 g and the maximum NO_2 is 0.8 g.

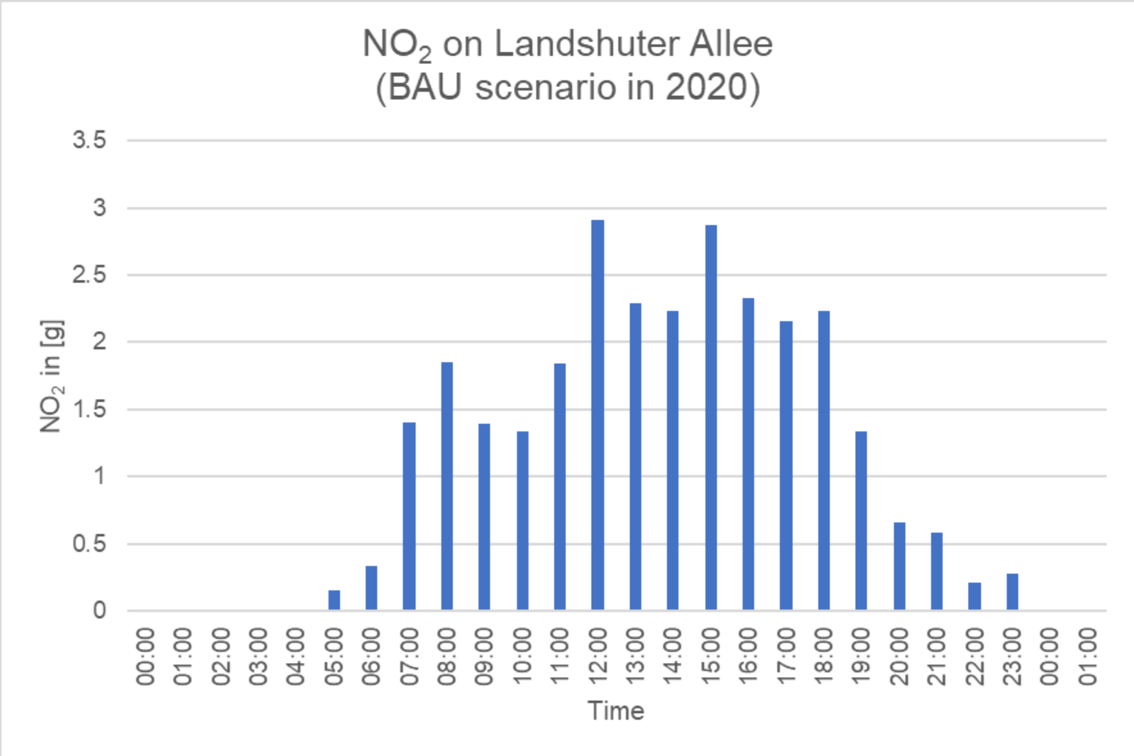

Figure 41: One day course of NO_2 on Landshuter Allee (BAU scenario in 2020)

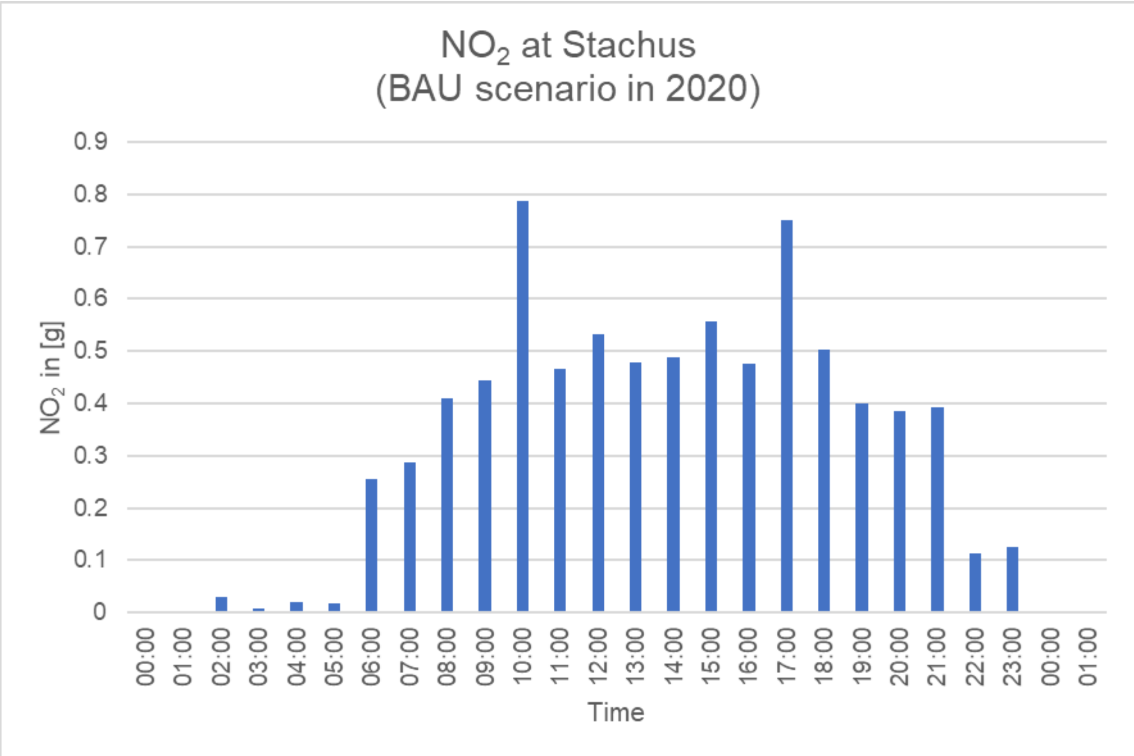

Figure 42: One day course of NO_2 at Stachus (BAU scenario in 2020)

BAU scenario for 2030

The BAU scenario for 2030 estimates the emissions produced by an unchanged vehicle composition with the increased trip numbers at 189,391. These trips result in an increase of 6 % compared to those of the year 2020, a total of 211,595 g NO_2. In this scenario, the number of the links in the categorization 10.0, 30.0 and 50.0 have increased up to 7 % compared to those of the year 2020. This is especially noticeable in the north-east and south-east side of Munich.

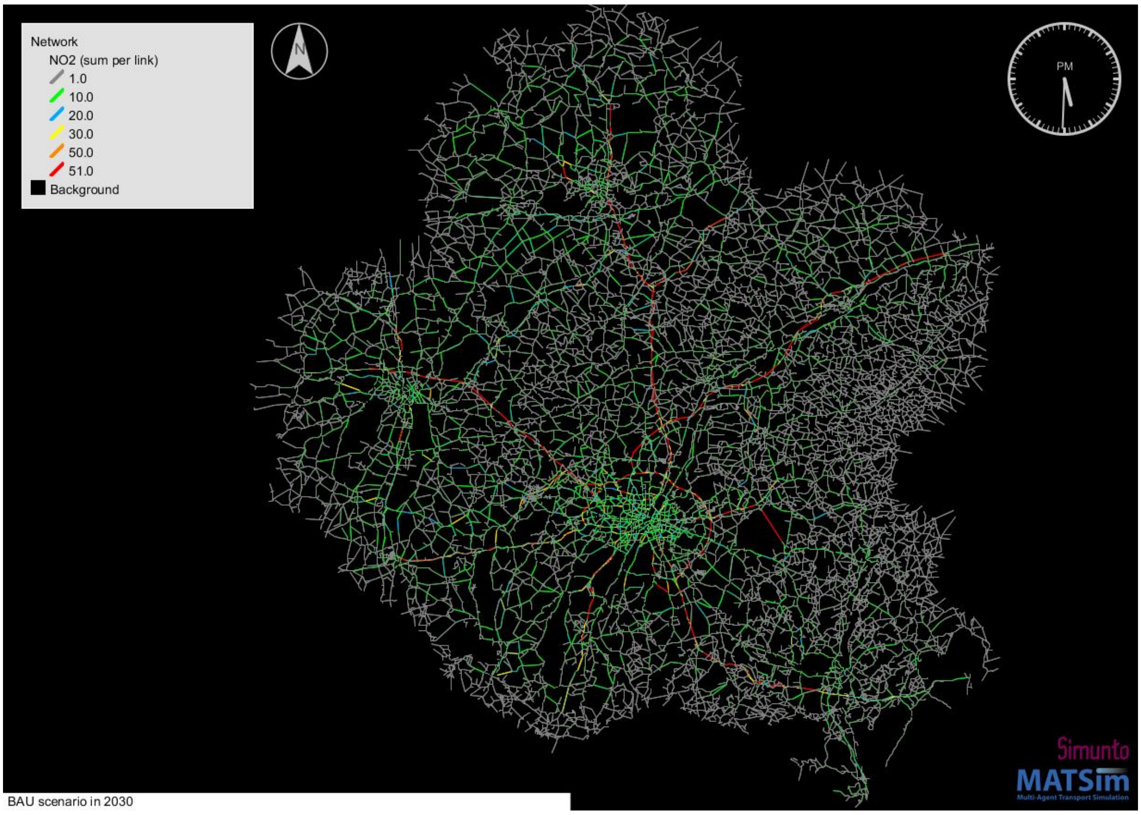

Figure 43: One-day model of NO_2 (BAU scenario in 2030)

Not much difference in the emission level can be detected in the inner city compared to the emission trends in the BAU scenario for 2020.

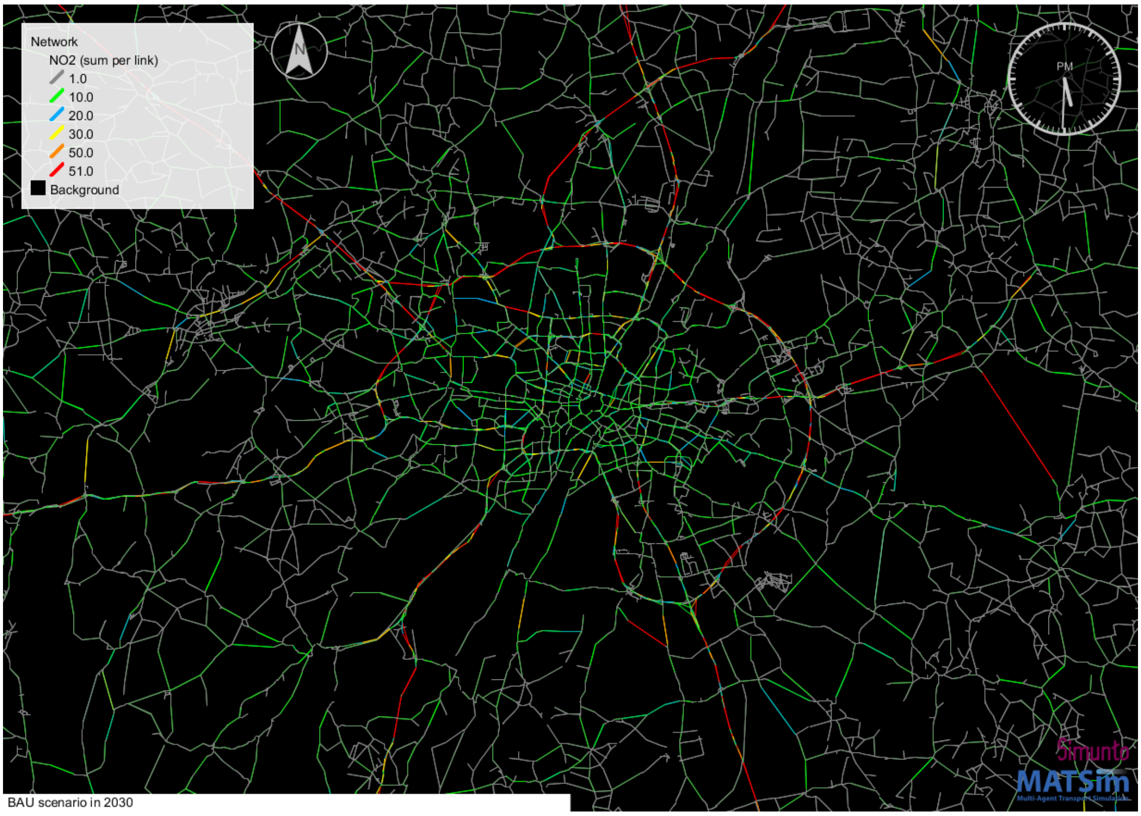

Figure 44: One-day model of NO_2 in Munich (BAU scenario in 2030)

Similar to the one-day model, higher emission levels of NO_2 are seen in the North-east and the South-east for both peak hours.

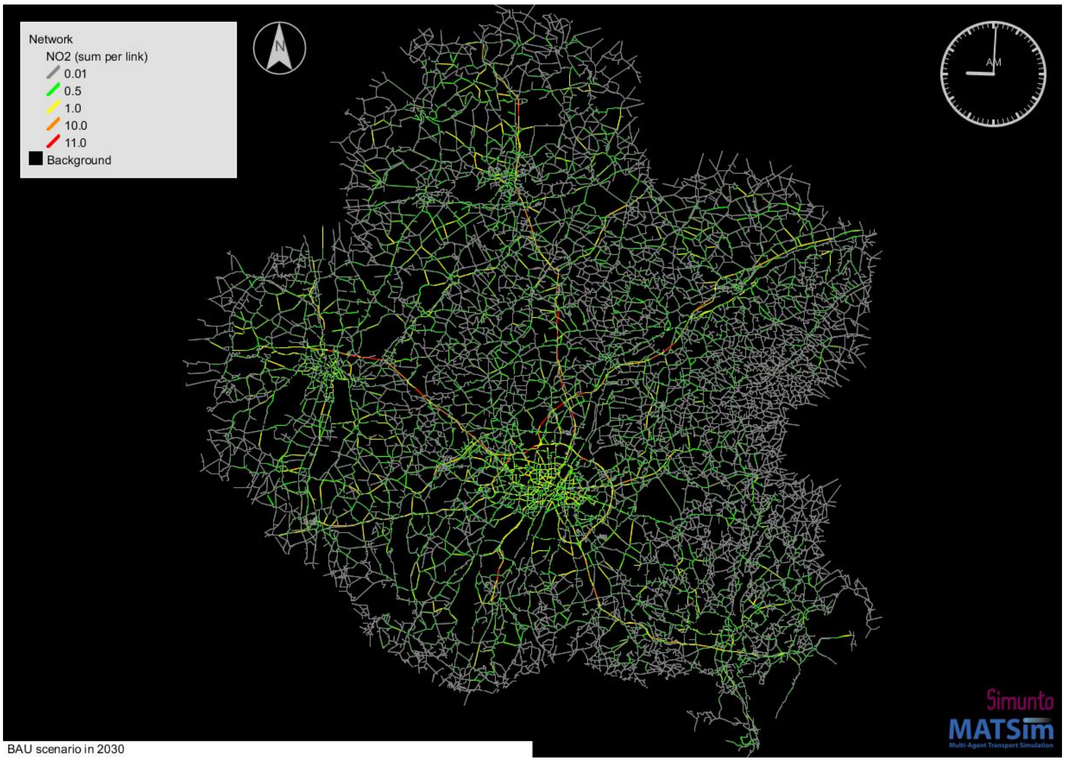

Figure 45: One-hour model of NO_2 during the morning peak (BAU scenario in 2030)

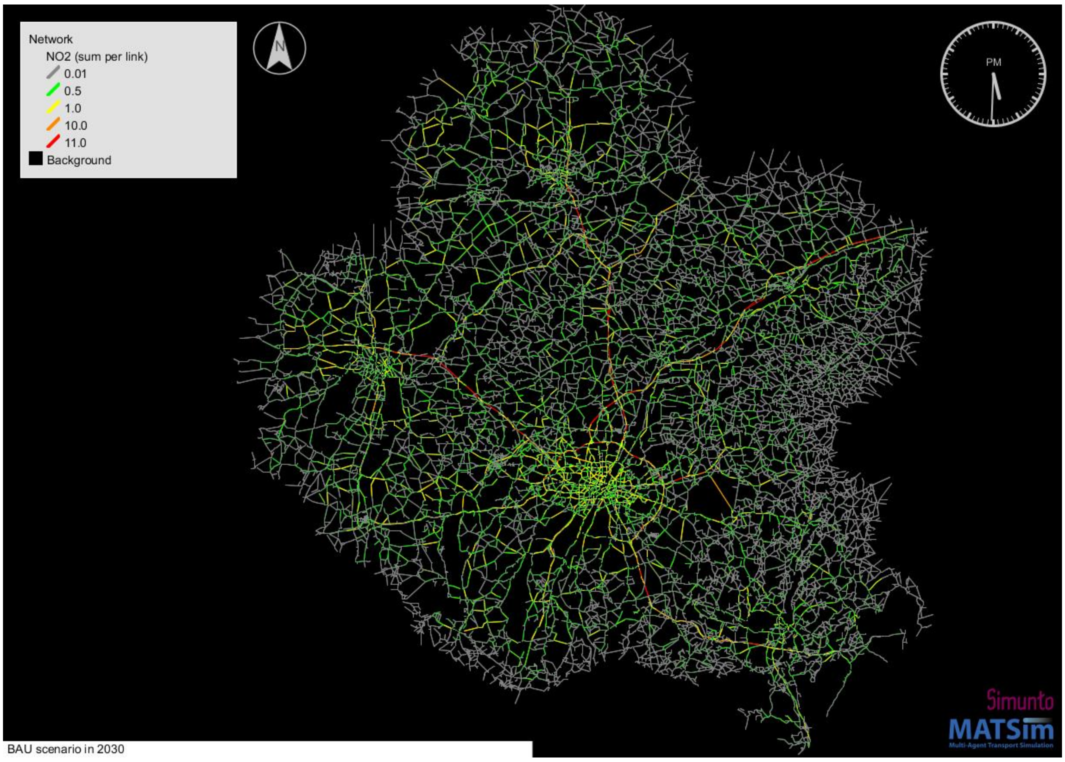

Figure 46: One-hour model of NO_2 during the evening peak (BAU scenario in 2030)

The Munich city area in the peak hours do not have big difference compared to those in the previous observation year.

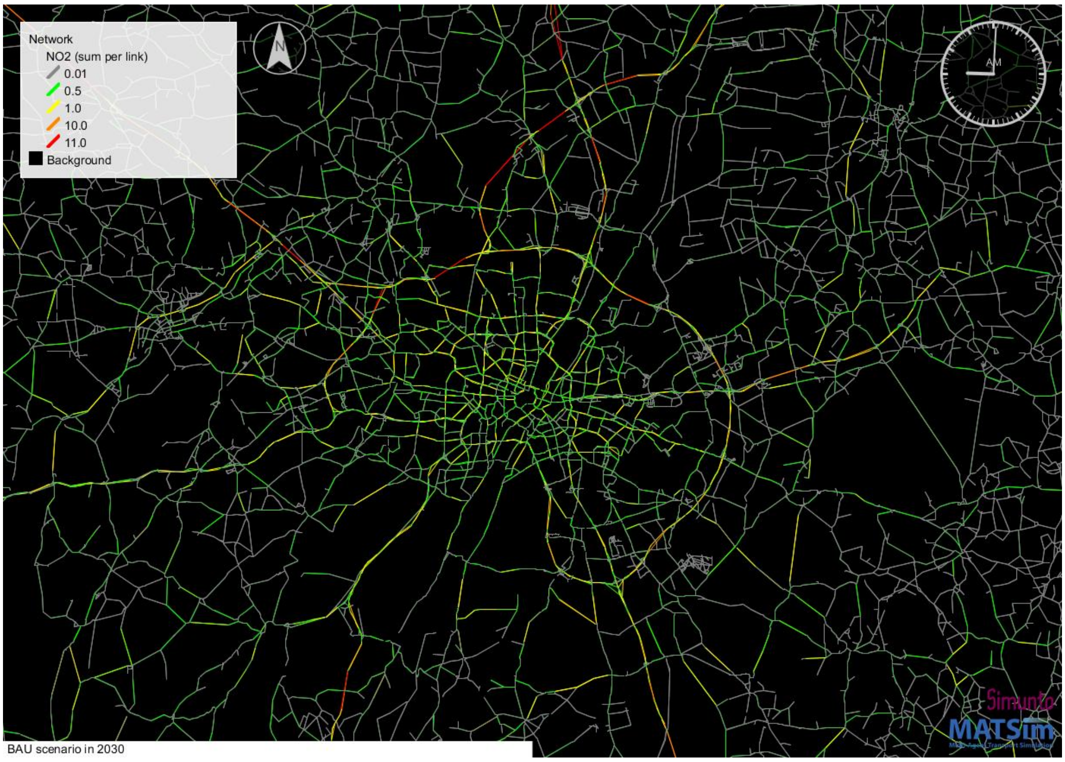

Figure 47: One-hour model of NO_2 in Munich during the morning peak (BAU scenario in 2030)

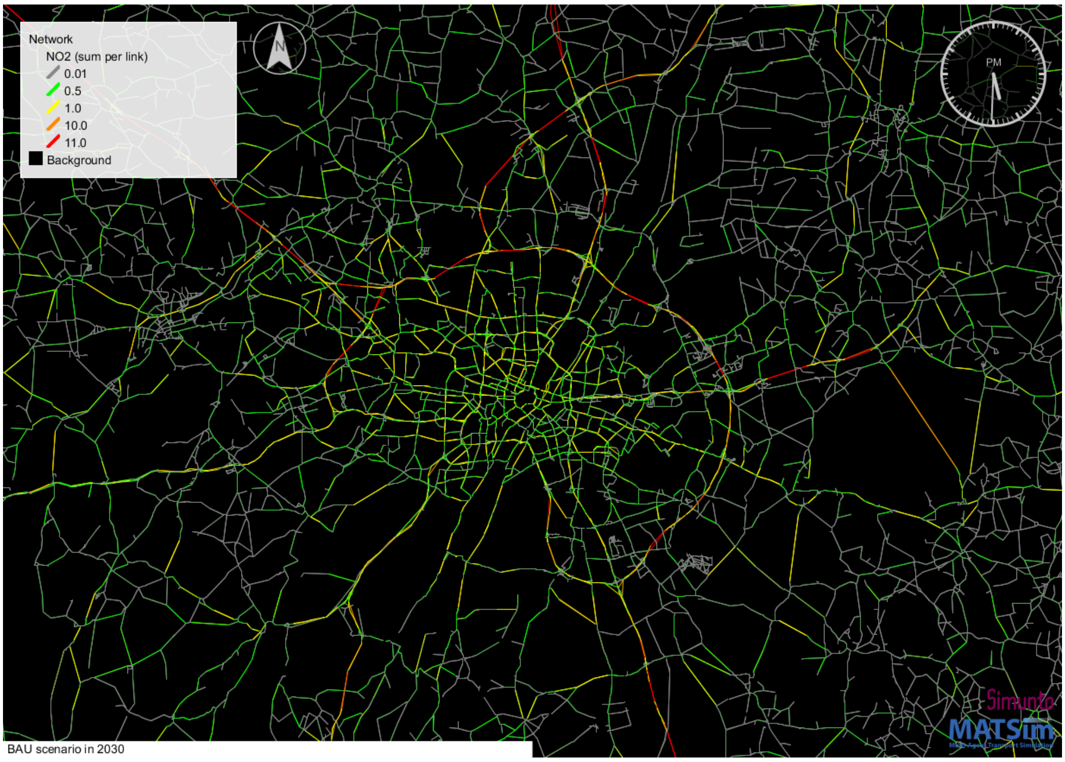

Figure 48: One-hour model of NO_2 in Munich during the evening peak (BAU scenario in 2030)

The general growth in the emissions is reflected by the hotspots. The accumulated daily NO_2 results in 172 g for Landshuter Allee and in 41 g for Stachus. These are increased by 10 % and 4 % respectively compared to the amounts in the BAU scenario for 2020. On Landshuter Allee, the maximum NO_2 reaches 3.15 g, and the average value is 1.1 g. At Stachus, the maximum NO_2 is 0.8 g, and the average NO_2 is 0.3 g.

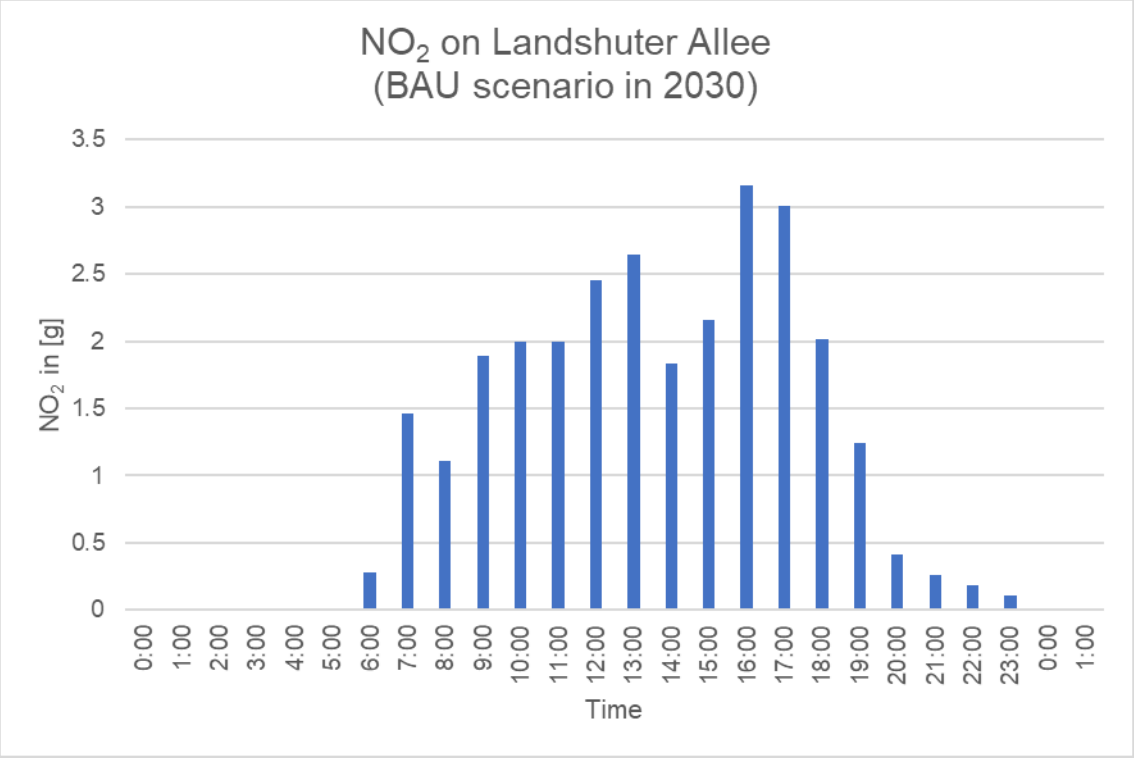

Figure 49: One-day course of NO_2 on Landshuter Allee (BAU scenario in 2030)

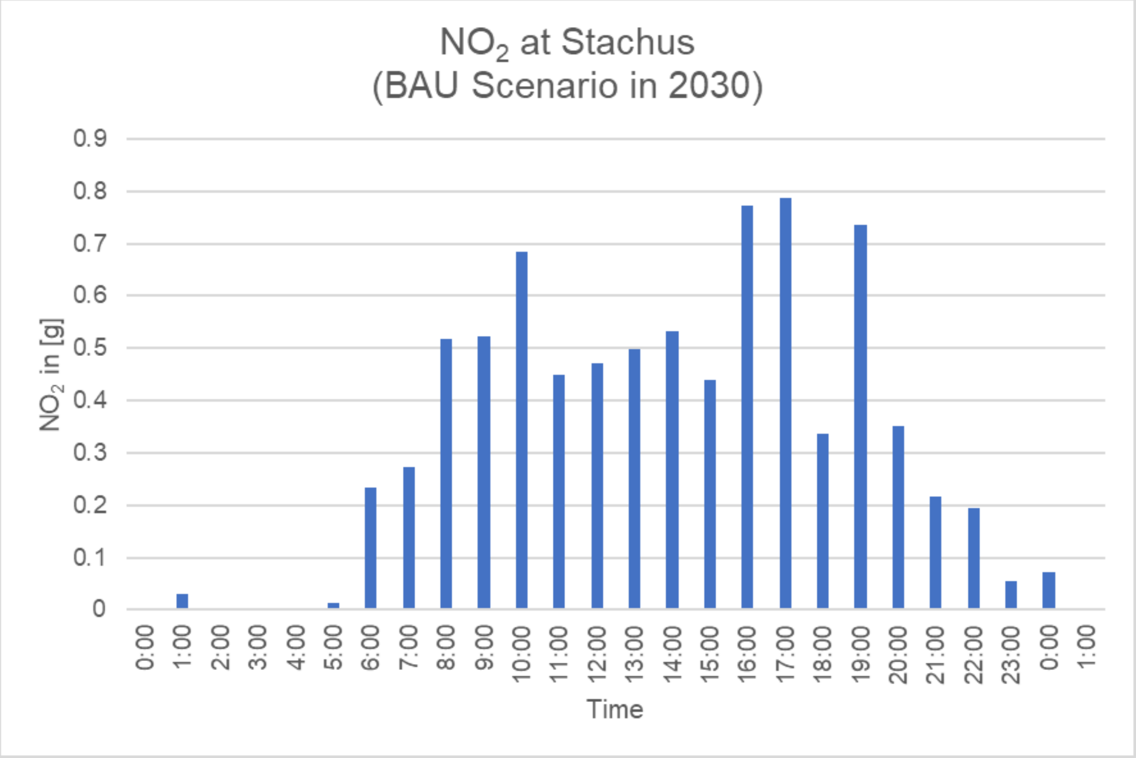

Figure 50: One-day course of NO_2 at Stachus (BAU scenario in 2030)

The subsequent section presents the emission estimation based on the intervention scenarios.

9.2 Intervention Scenarios

The introduction of electric vehicles leads to a reduction of emissions. The emissions are estimated for the three scenarios that differ based on the achievement of the target. From 2011 to 2030, the Contra EV estimates an increase of 4 % in the emissions, whereas the Middle EV and the Pro EV scenarios forecasts a decrease of 14 % and 34 % respectively.

Table 11: Total NO_2 in the intervention scenarios

Total emission in $[g\ NO_2]$	**2011**	**2020**	**2030**
Contra EV	185,988.20	194,837.41	194,089.78
Middle EV	185,988.20	191,038.83	160,486.22
Pro EV	185,988.20	182,561.90	122,278.14

This section is divided into three subsections according to the three scenarios which present the results for the scenario years 2020 and 2030.

9.2.1 Contra EV scenario

Contra EV scenario in 2020

From 2011 to 2020, 0.3 % growth of electric vehicles leads to an increase in emissions of 5 %, 194,827 g NO_2. Together with the overall increase in the emissions, the number of the links in the highest emission level will have increased by 2 %. Figure 51 and Figure 52 present the one-day model of NO_2. These does not show much difference from those of the base year.

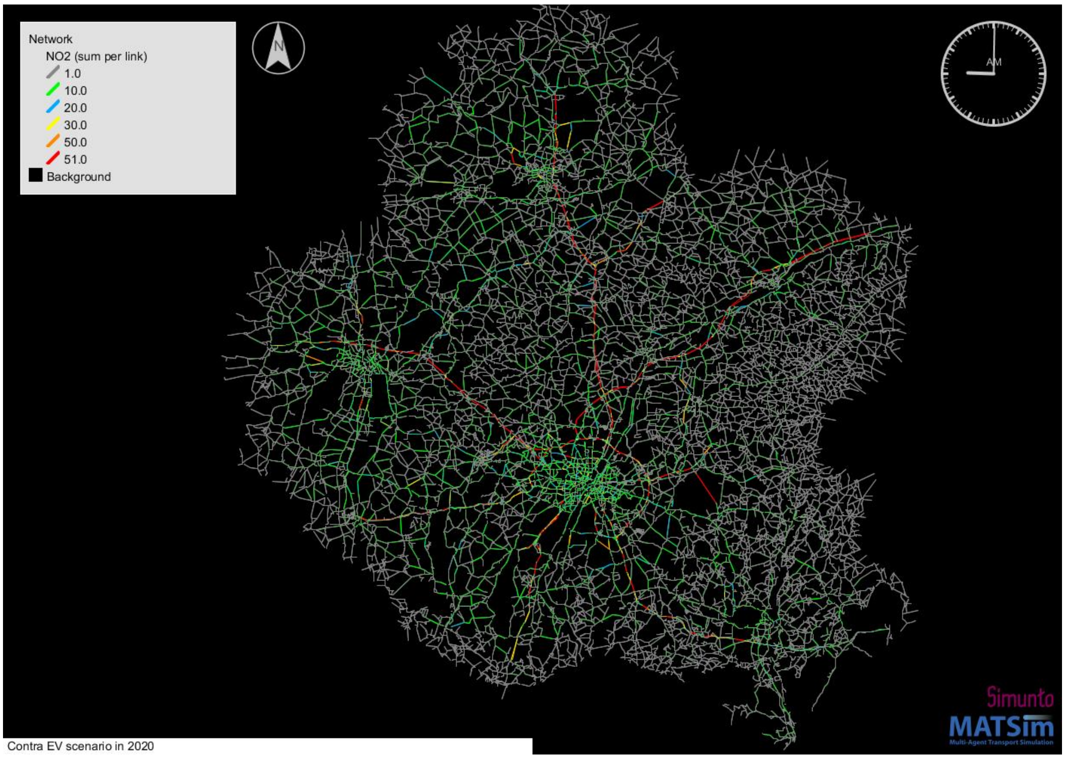

Figure 51: One-day model of NO_2 (Contra EV scenario in 2020)

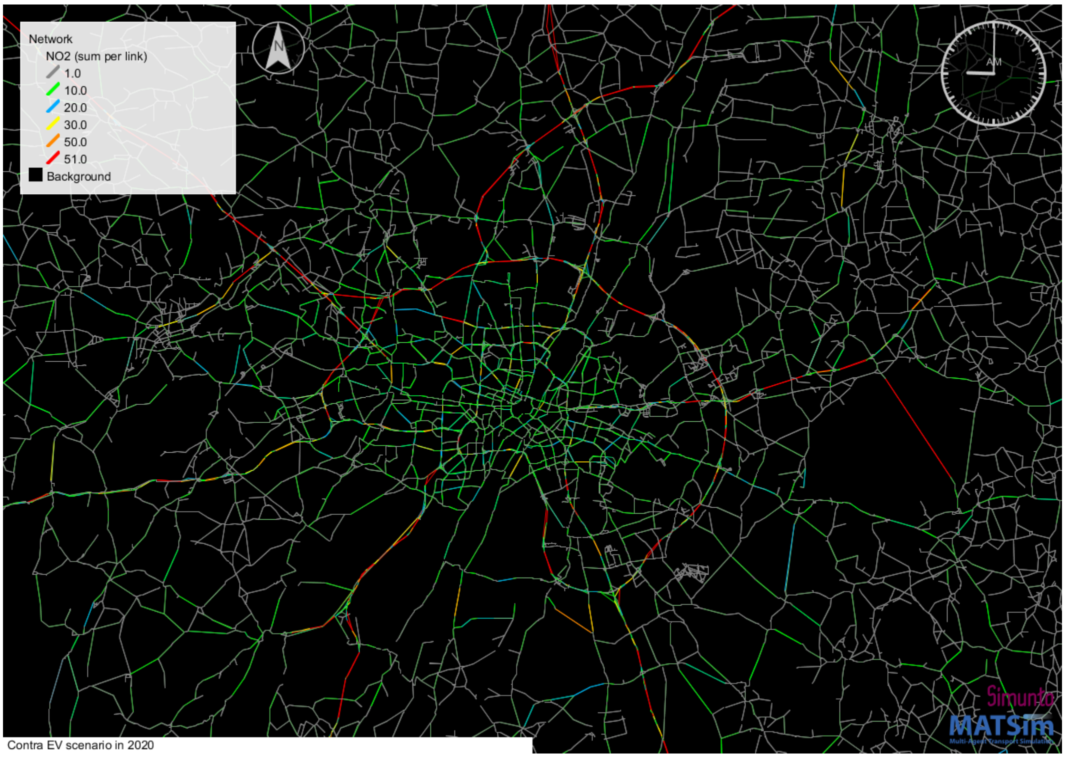

Figure 52: One-day model of NO_2 in Munich (Contra EV scenario in 2020)

Much like the accumulated one-day NO_2, the emissions in the peak hours hardly differ from the trends in the base year.

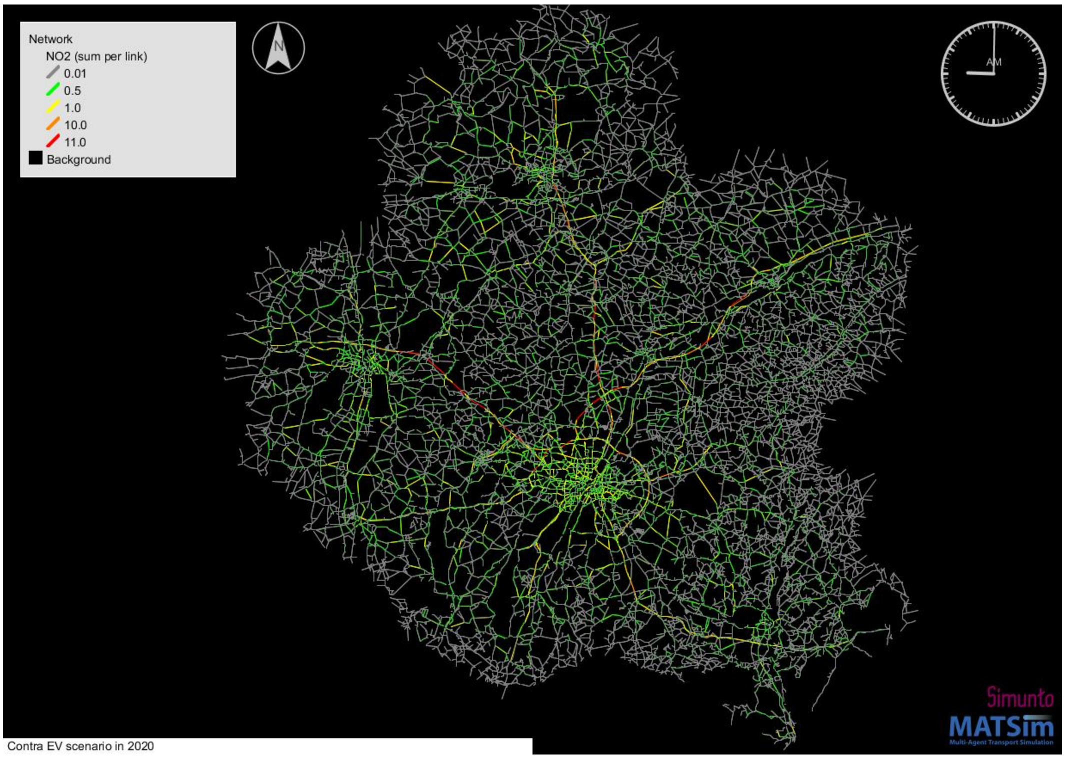

Figure 53: One-hour model of NO_2 during the morning peak (Contra EV scenario in 2020)

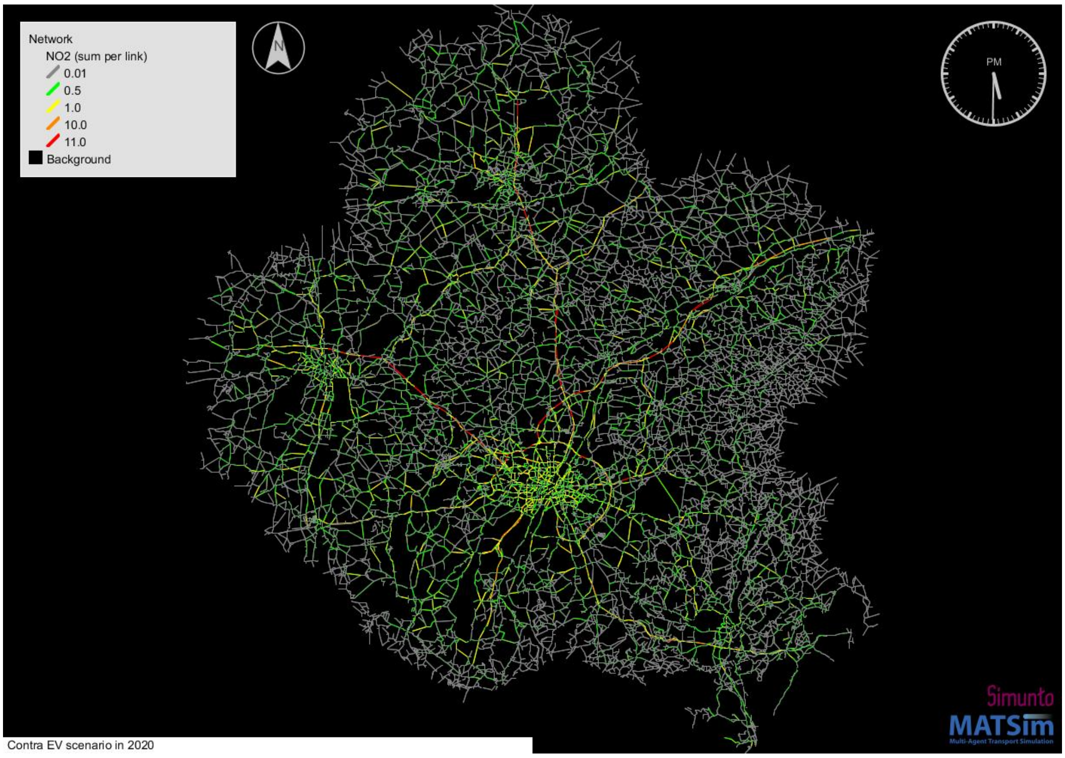

Figure 54: One-hour model of NO_2 during the evening peak (Contra EV scenario in 2020)

The Munich area in the peak hours shows emission trends similar to those of the base year.

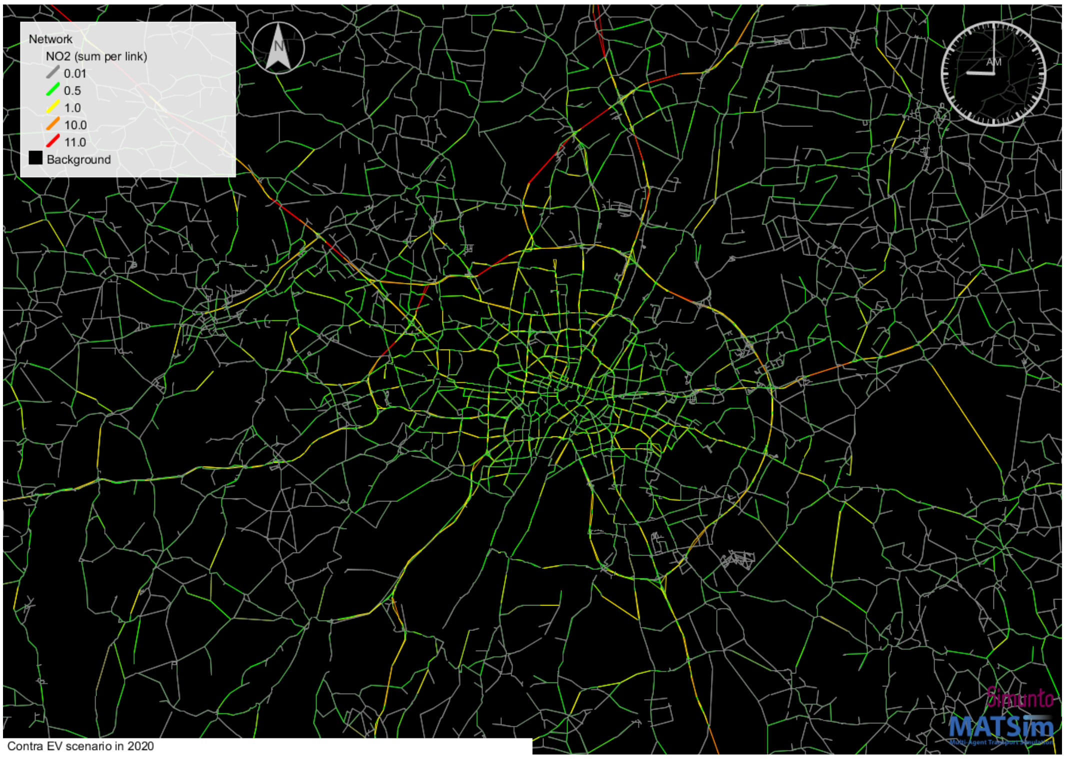

Figure 55: One-hour model of NO_2 in Munich during the morning peak (Contra EV scenario in 2020)

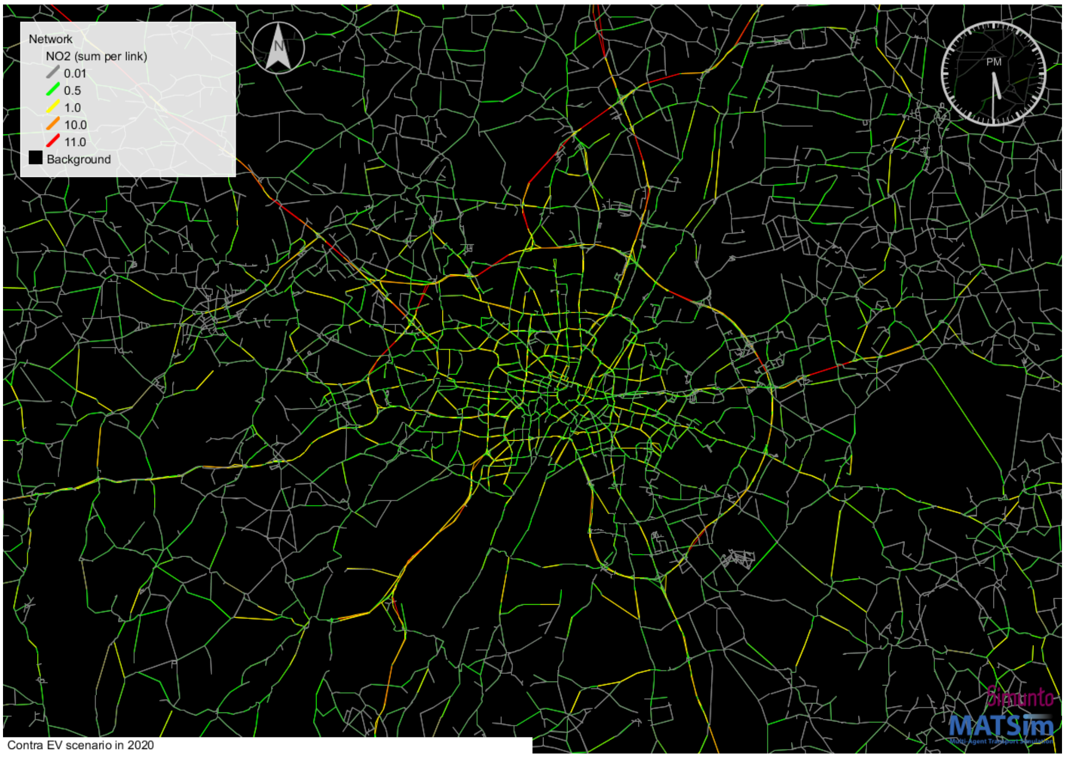

Figure 56: One-hour model of NO_2 in Munich during the evening peak (Contra EV scenario in 2020)

While the emissions on Landshuter Alle show only a slight increase of 0.5 % (150.7 g), those at Stachus increase by 15 % (42.3 g) compared to those of the base year. In contrast to the increase of the total emissions on Landshuter Allee, their maximum and the average values decrease by up to 3 %, and amount to 3.0 g and 1.0 g respectively. At Stachus, both values increase strongly, by up to 28 %, and the emissions reach 0.85 g at the maximum and 0.3 g at average.

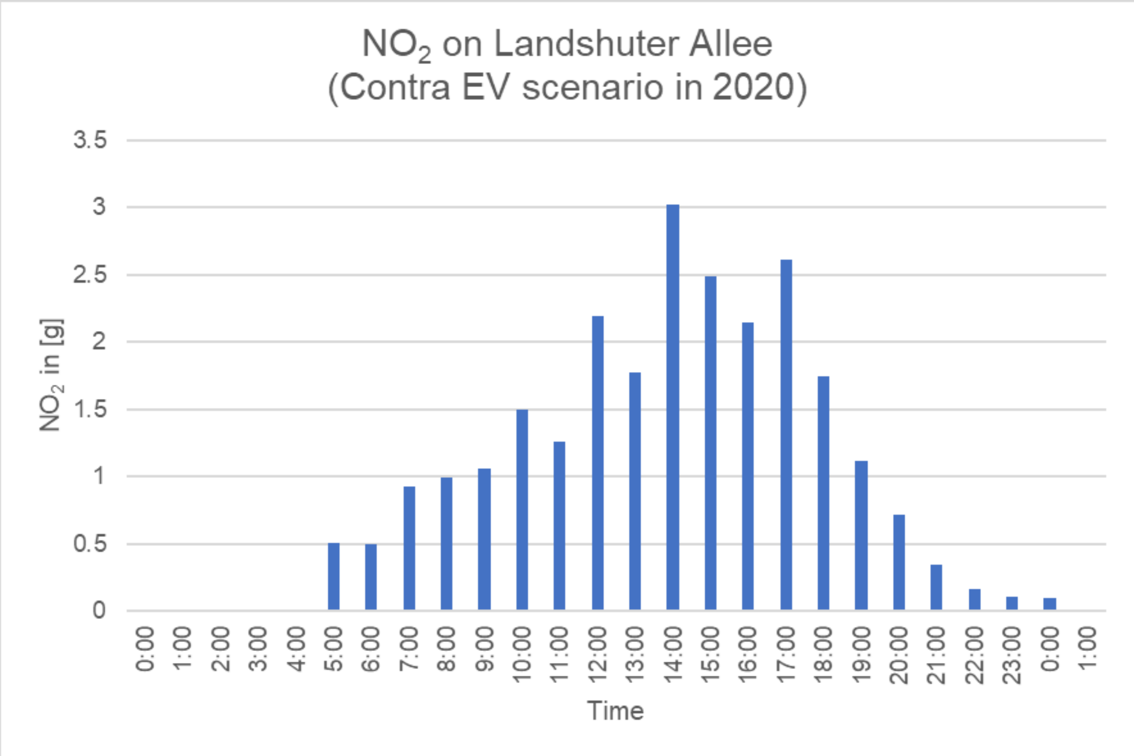

Figure 57: One-day course of NO_2 on Landshuter Allee (Contra EV scenario in 2020)

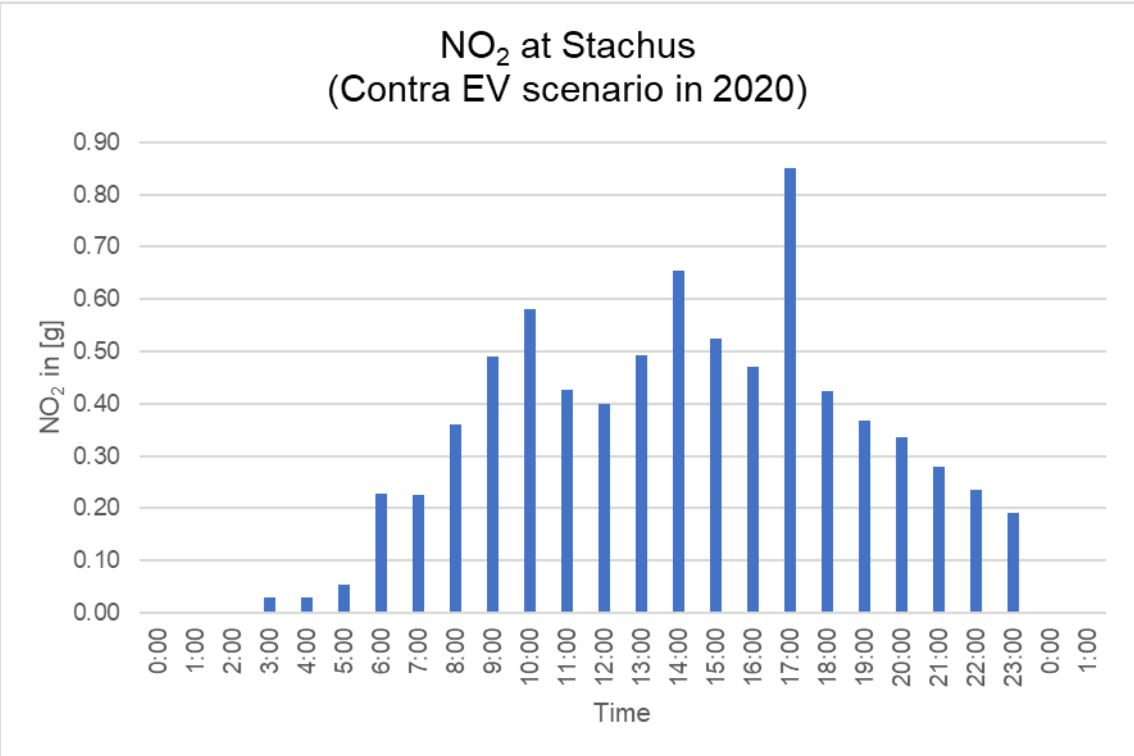

Figure 58 One-day course of NO_2 at Stachus (Contra EV scenario in 2020)

Contra EV scenario in 2030

For 2030, the Contra EV scenario estimates 1.6 % growth of electric cars. This results in 194,089 g NO_2, which means a slight reduction of 0.4 % compared to the total NO_2 in the Contra EV scenario for 2020. This reduction is hardly recognizable in Figure 59 and Figure 60. The number of the links at the highest level remains unchanged, whereas the number of the links indicated by green increases in the north and the west side of Munich and as well as in the inner city.

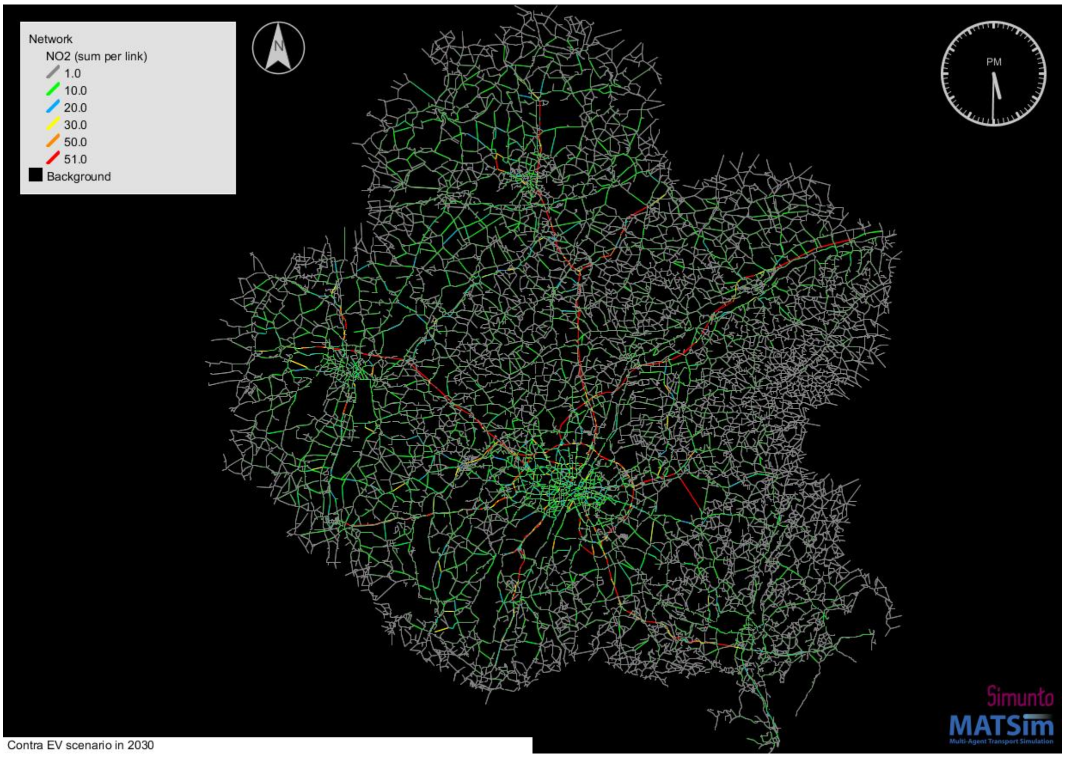

Figure 59: One-day model of NO_2 (Contra EV scenario in 2030)

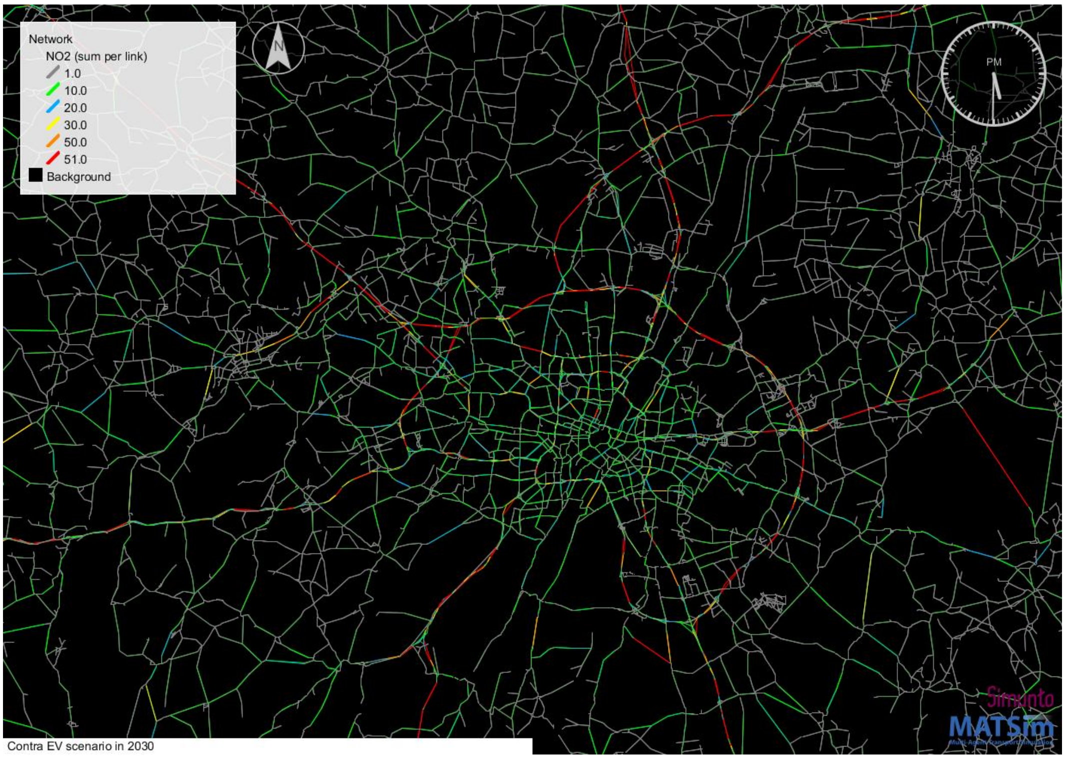

Figure 60: One-day model of NO_2 in Munich (Contra EV scenario in 2030)

These increases of the emission levels are also reflected by the one-hour model of NO_2. Moreover, the southern side of the area shows a growth of emissions.

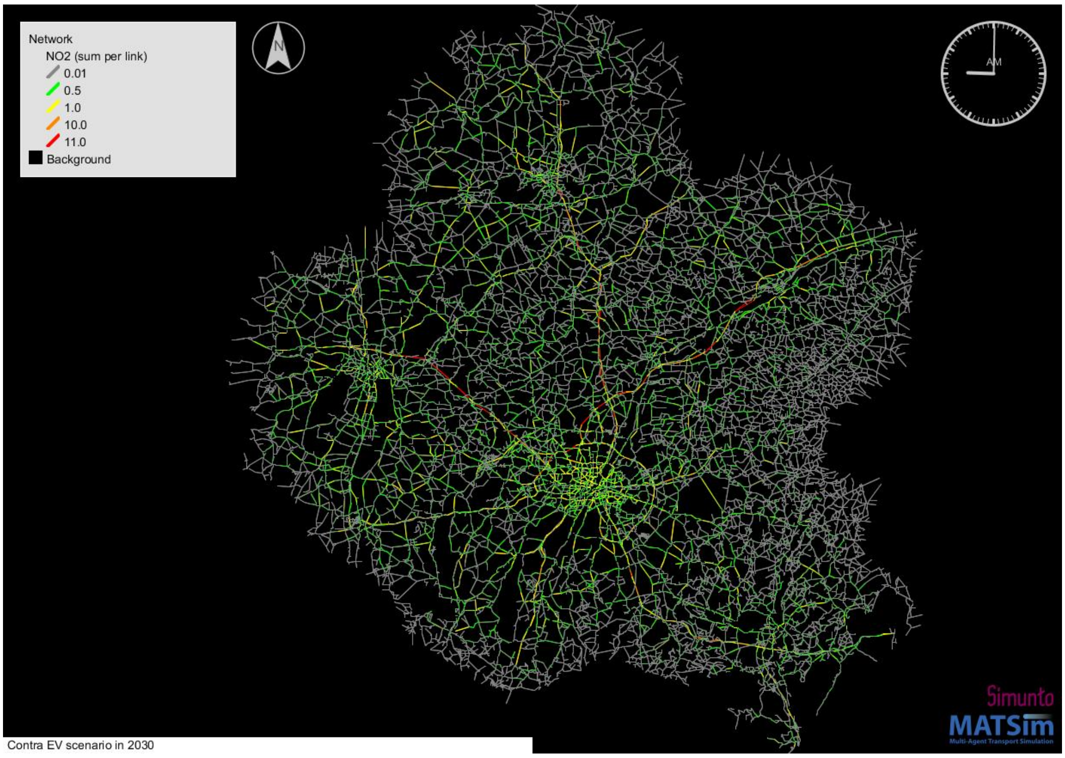

Figure 61: One-hour model of NO_2 during the morning peak (Contra EV scenario in 2030)

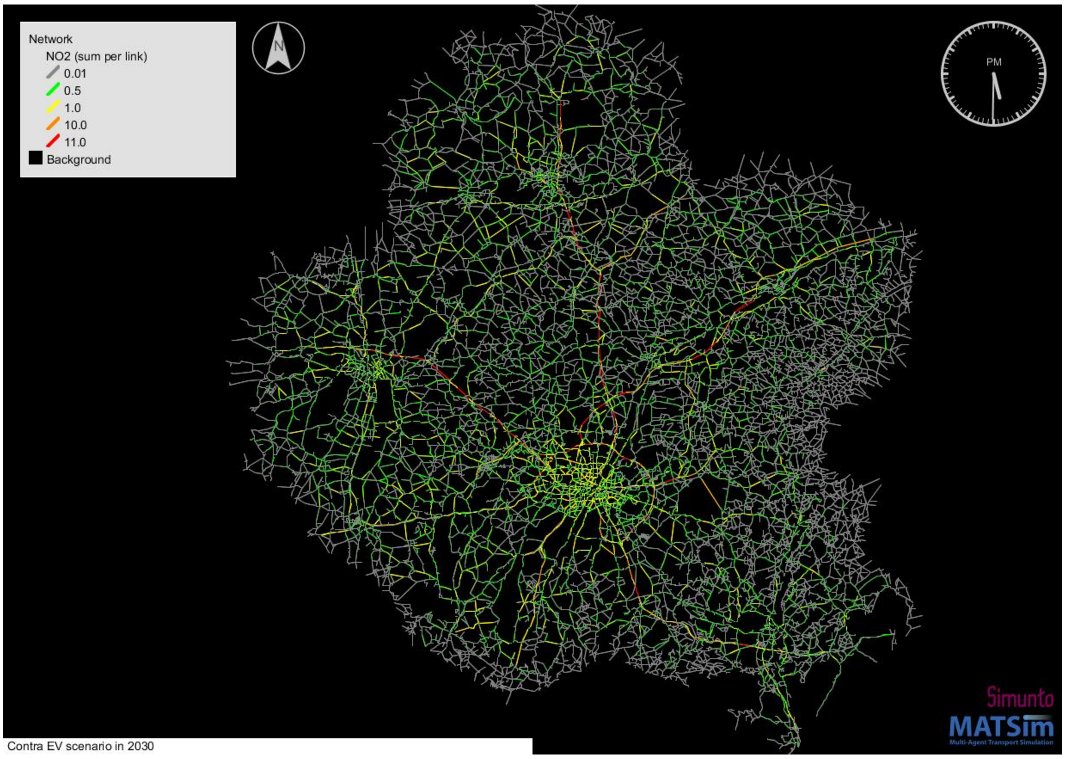

Figure 62: One-hour model of NO_2 during the evening peak (Contra EV scenario in 2030)

The hourly NO_2 trends in Munich hardly differ from those of the Contra EV for 2020.

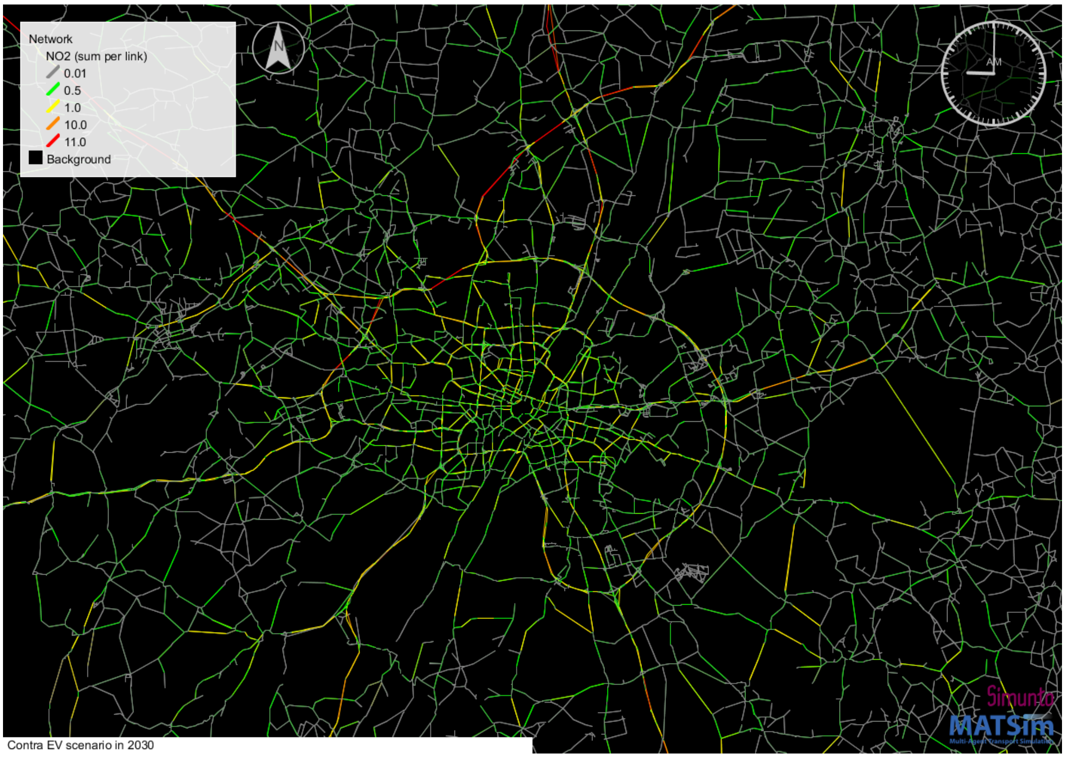

Figure 63: One-hour model of NO_2 in Munich during the morning peak (Contra EV scenario in 2030)

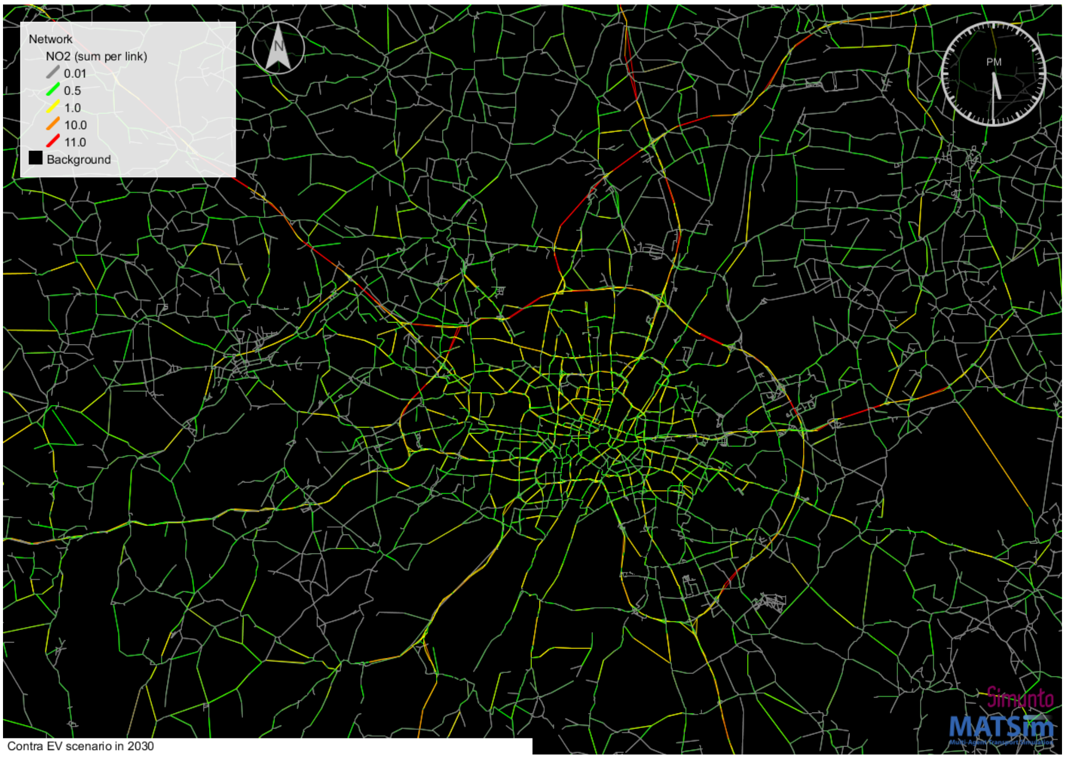

Figure 64: One-hour model of NO_2 in Munich during the evening peak (Contra EV scenario in 2030)

The reduction in the total NO_2 is reflected in the hotspots. The one-day accumulation of NO_2 on Landshuter Allee amounts to 149.9 g, which is 1 % less than the previous observation year, and at Stachus amounts to 40.7 g, which is a 4 % reduction. However, the maximum (3.6 g) as well as the average (1.1 g) values modeled on Landshuter Allee increase by 19 %. At Stachus, the average NO_2 (0.3 g) increases by 14 %, whereas the maximum (0.8 g) decreases by 4 %.

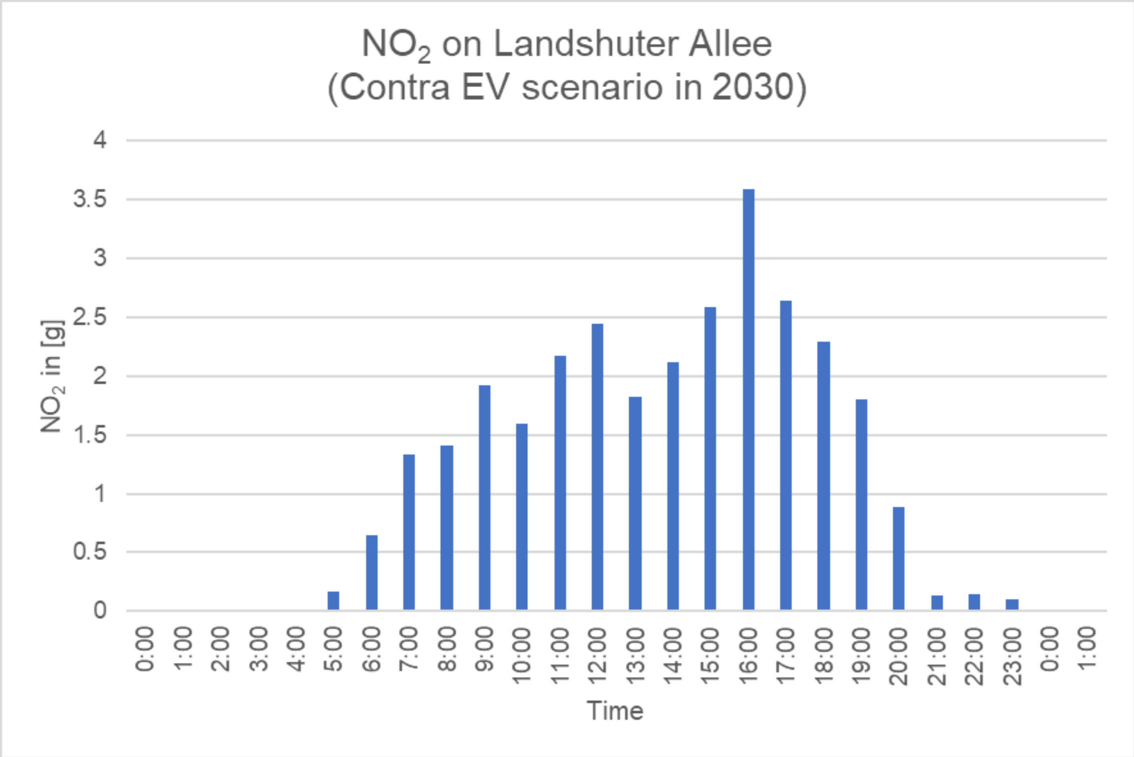

Figure 65: One-day course of NO_2 on Landshuter Allee (Contra EV scenario in 2030)

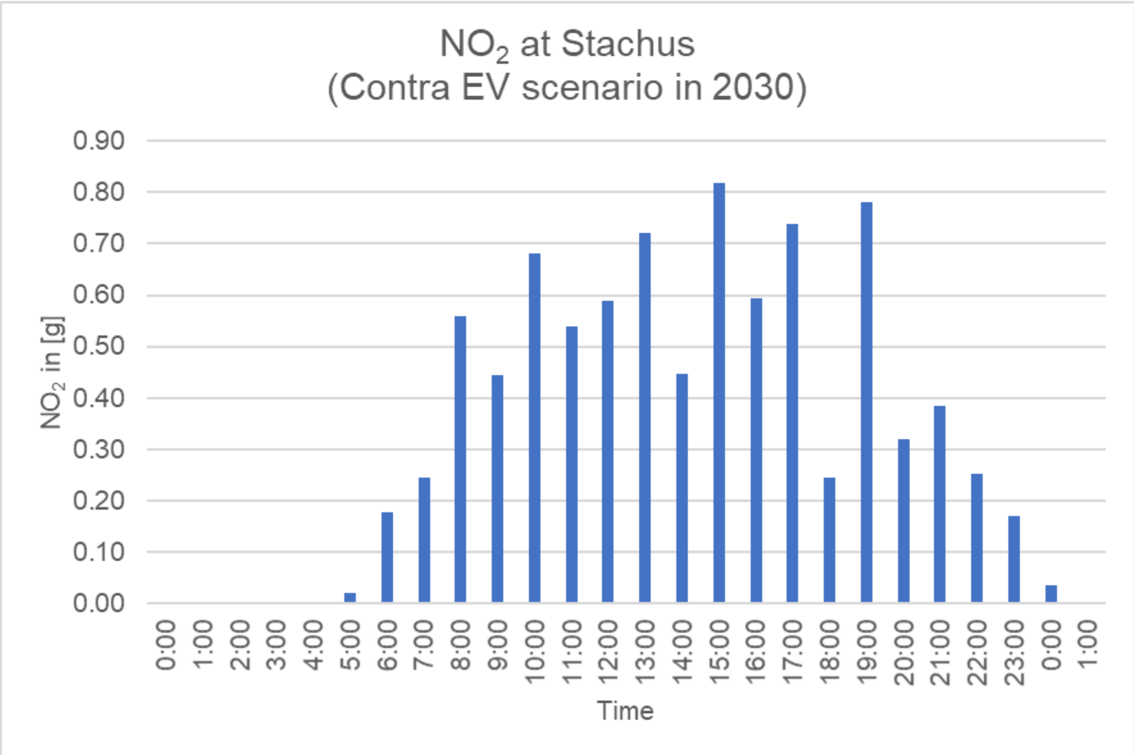

Figure 66: One-day course of NO_2 at Stachus (Contra EV scenario in 2030)

The following subsection presents the second of the intervention scenarios.

9.2.2 Middle EV scenario

Middle EV scenario for 2020

The Middle EV scenario for 2020 bases on the proportion of electric vehicles at 2.3 %. This forecasts the daily accumulated NO_2 of 191,038 g, which means 3 % increase of emissions compared to those of the base year. These does not show much difference from those of the base year.

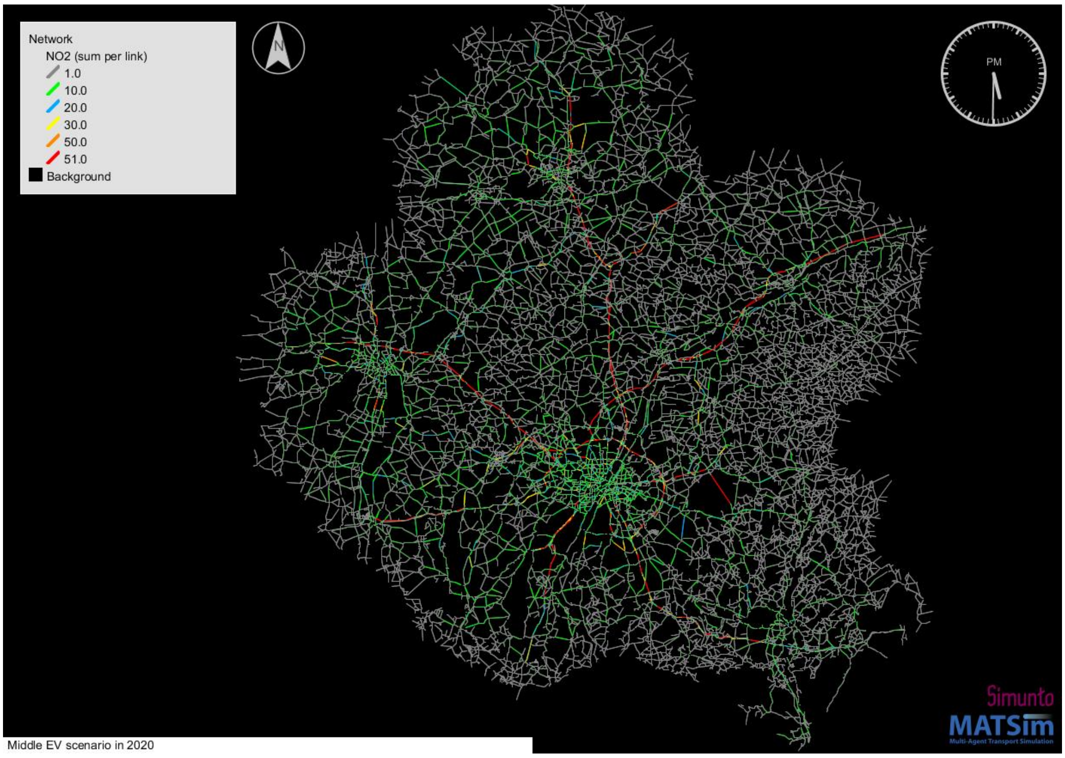

Figure 67: One-day model of NO_2 (Middle EV scenario in 2020)

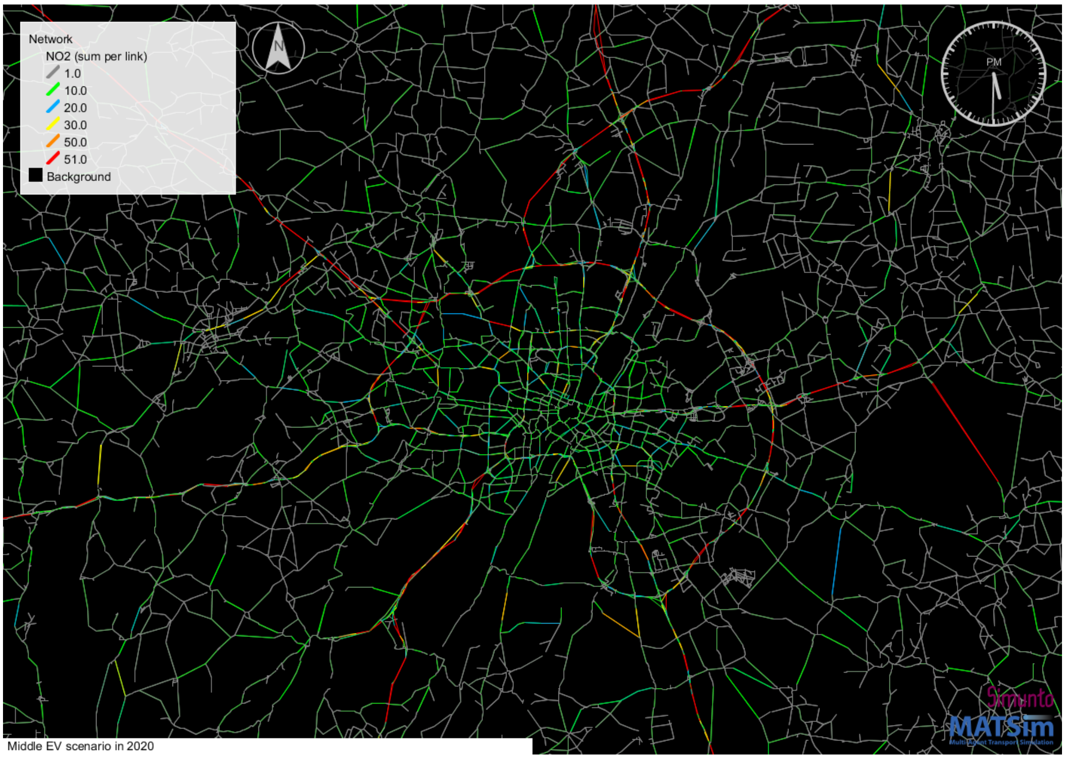

Figure 68: One-day model of NO_2 in Munich (Middle EV scenario in 2020)

The one-hour model in the following figures present a slight increase of emission levels along the major transport axes. Moreover, the links located in the rural areas, which showed grey previously, are now indicated by green.

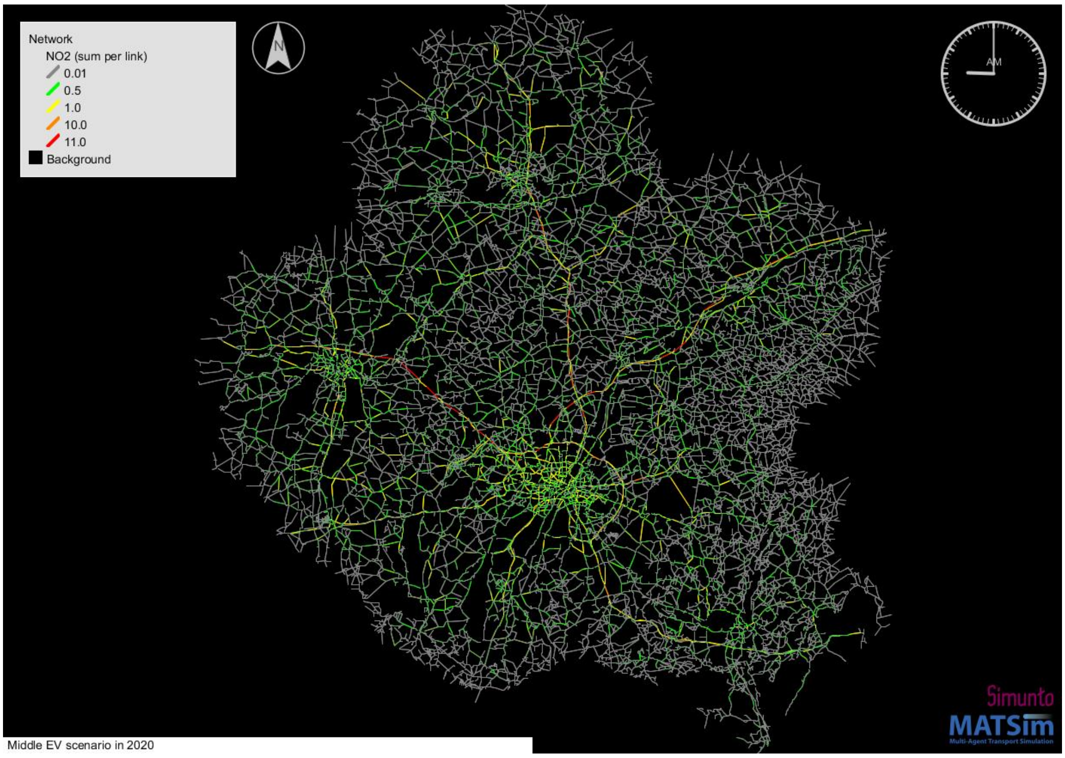

Figure 69: One-hour model of NO_2 during the morning peak (Middle EV scenario in 2020)

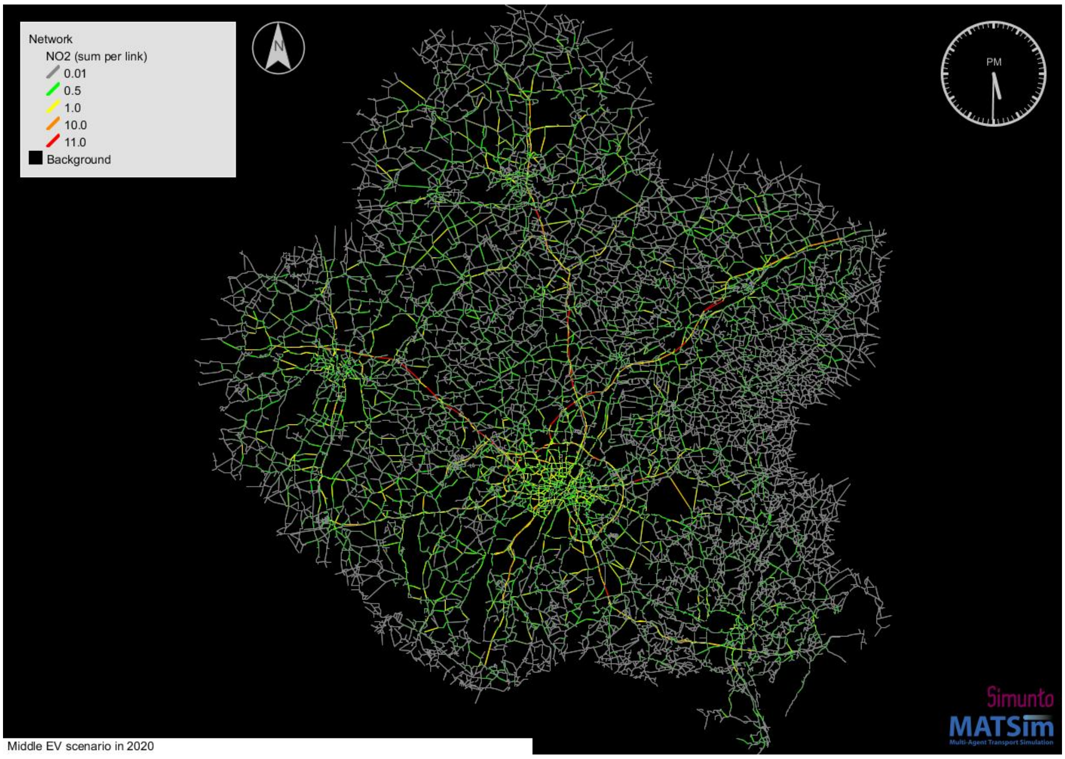

Figure 70: One-hour model of NO_2 during the morning peak (Middle EV scenario in 2020)

The city area emissions at peak hours do not greatly differ from those of the year 2011.

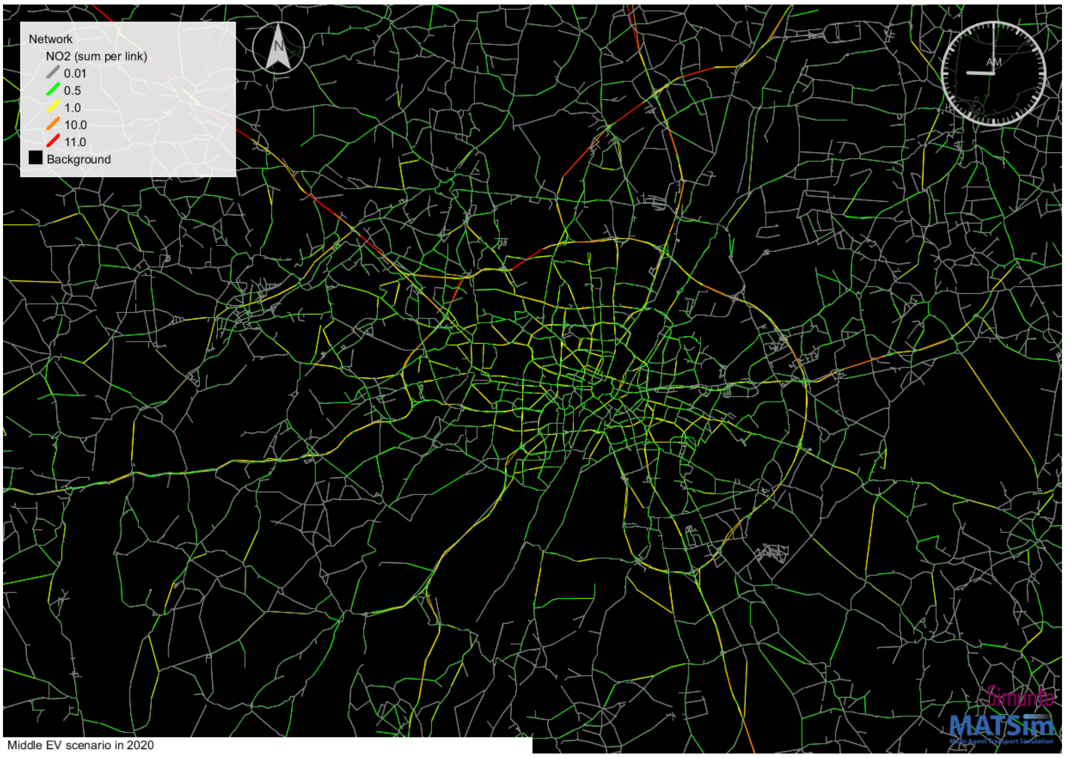

Figure 71: One-hour model of NO_2 in Munich during the morning peak (Middle EV scenario in 2020)

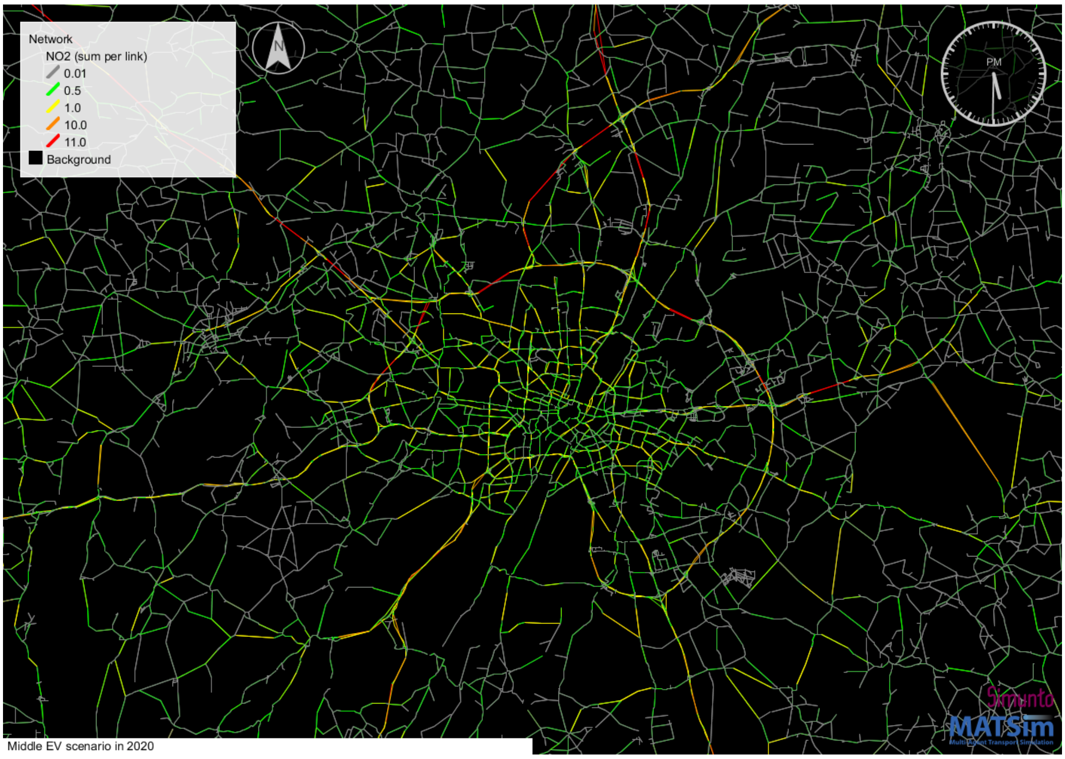

Figure 72: One-hour model of NO_2 in Munich during the evening peak (Middle EV scenario in 2020)

The emissions on the hotspots increases proportionally to the one-day accumulation of NO_2. The emissions are estimated 154.4 g for Landshuter Allee and 38.1 g for Stachus. Their characteristic values such as the maximum and the average are increased respectively. On Landshuter Allee, the average NO_2 is 1.1 g, and the emissions reach 3.1 g at the maximum. At Stachus, the average emissions are 0.3 g, and the maximum is 0.7 g.

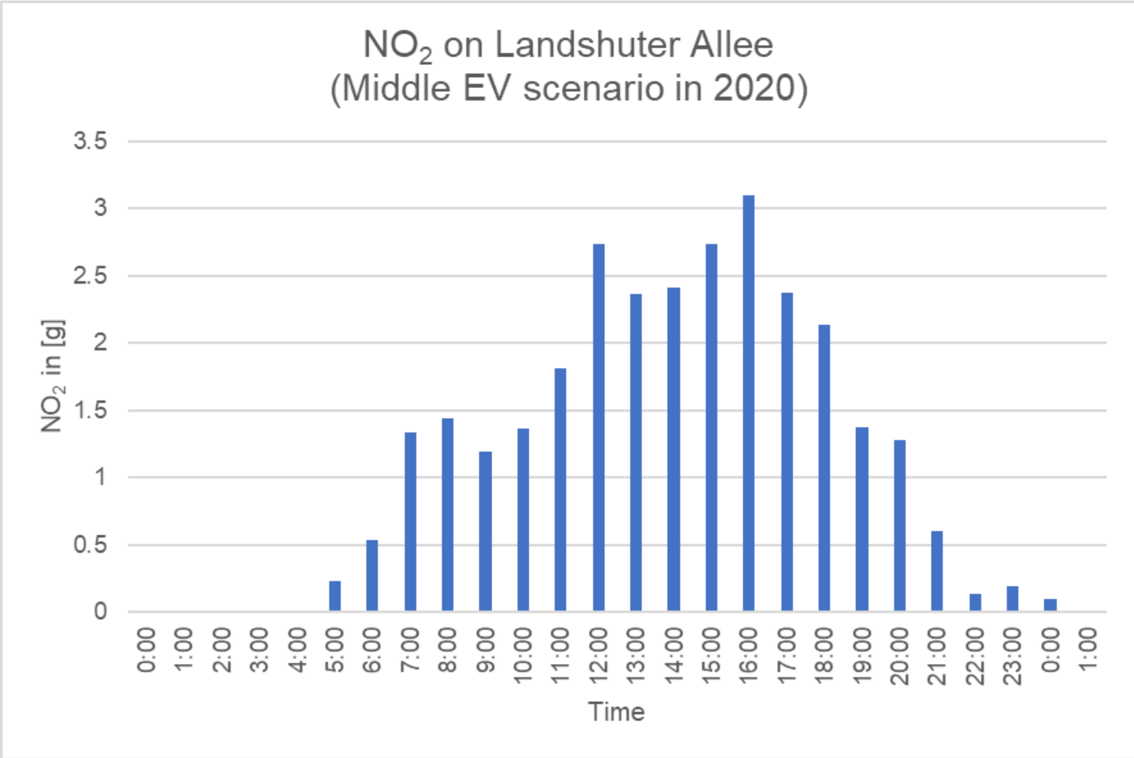

Figure 73: One-day course of NO_2 on Landshuter Allee (Middle EV scenario in 2020)

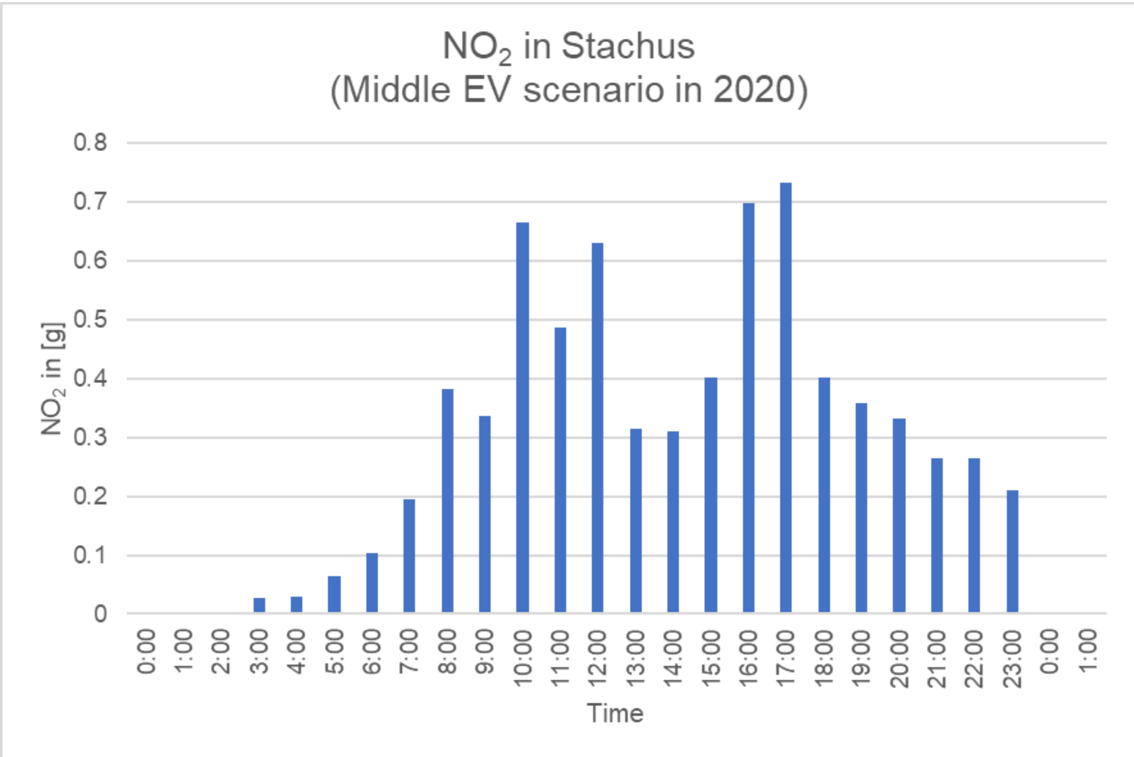

Figure 74: One-day course of NO_2 at Stachus (Middle EV scenario in 2020)

Middle EV scenario for 2030

From 2020 to 2030, the Middle EV scenario assumes a further increase of electric vehicles up to 7.4 %. This results in 160,486 g NO_2, which means a reduction of 16 % compared to the previous observation. This decline only achieves to maintain the overall emission trend in the year 2020, as presented in Figure 75 and Figure 76. The number of the links at the highest level reduces by 26 %.

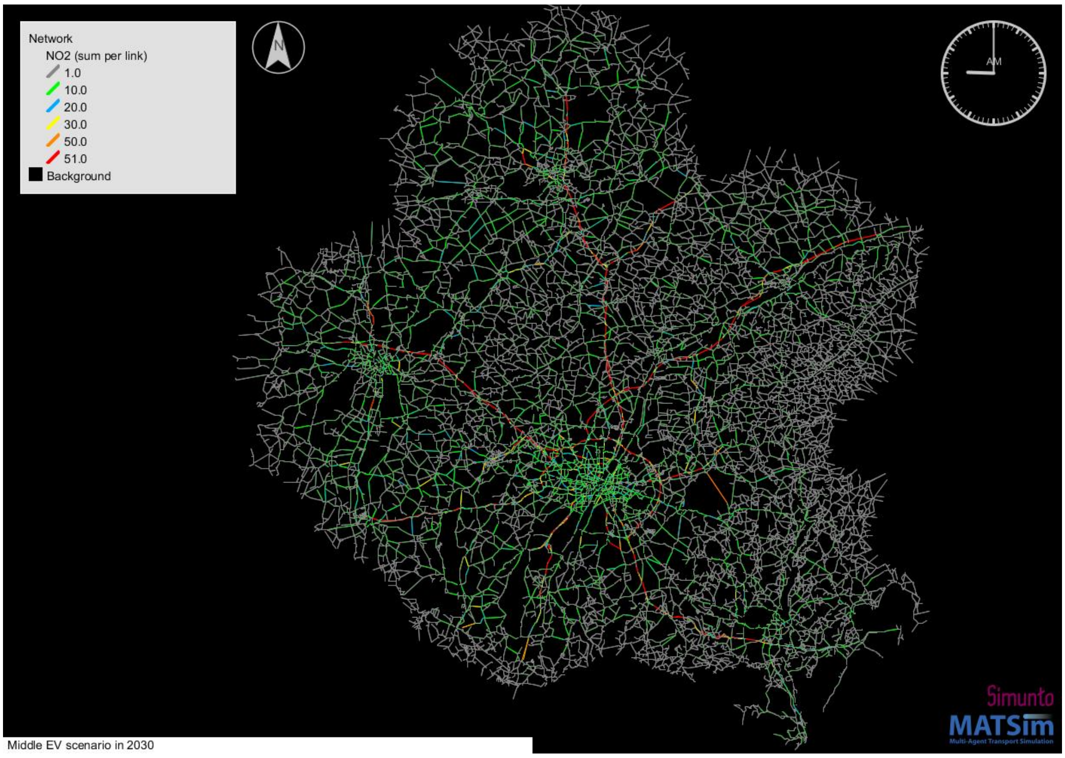

Figure 75: One-day model of NO_2 (Middle EV scenario in 2030)

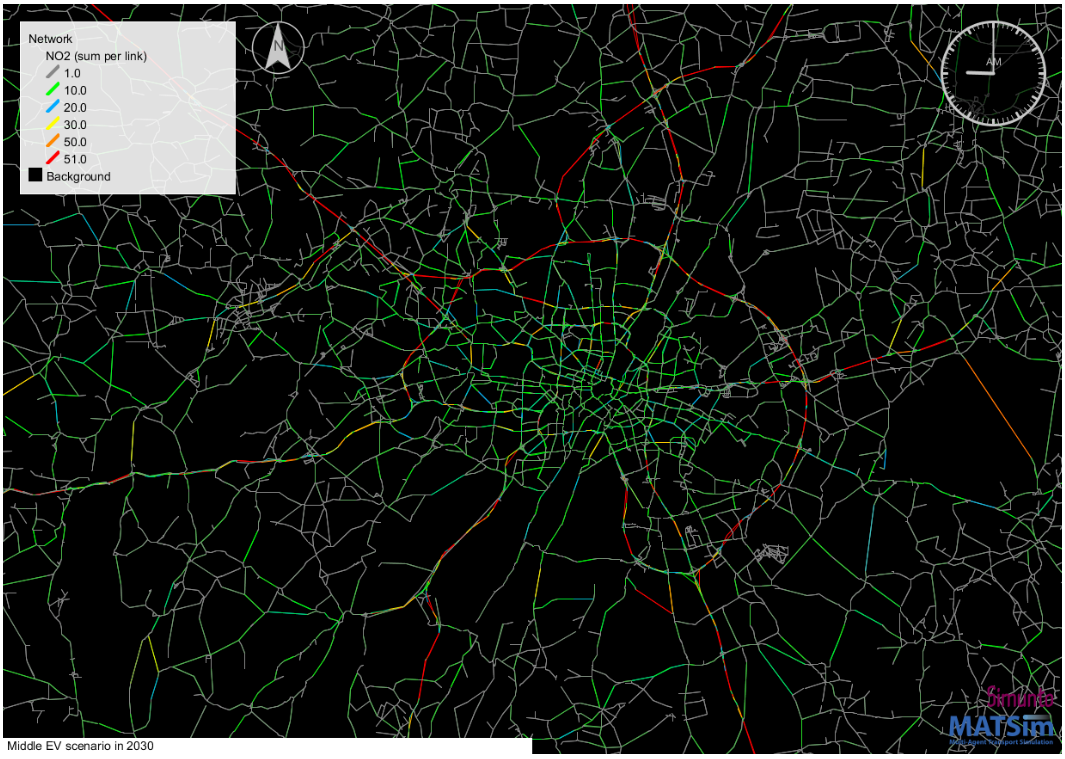

Figure 76: One-day model of NO_2 in Munich (Middle EV scenario in 2030)

In the one-hour model during the peak hours, more links become the level 0.5 generally in the rural areas. However, many of the links that showed yellow in the previous observation are now downgraded particularly during the morning peak hour.

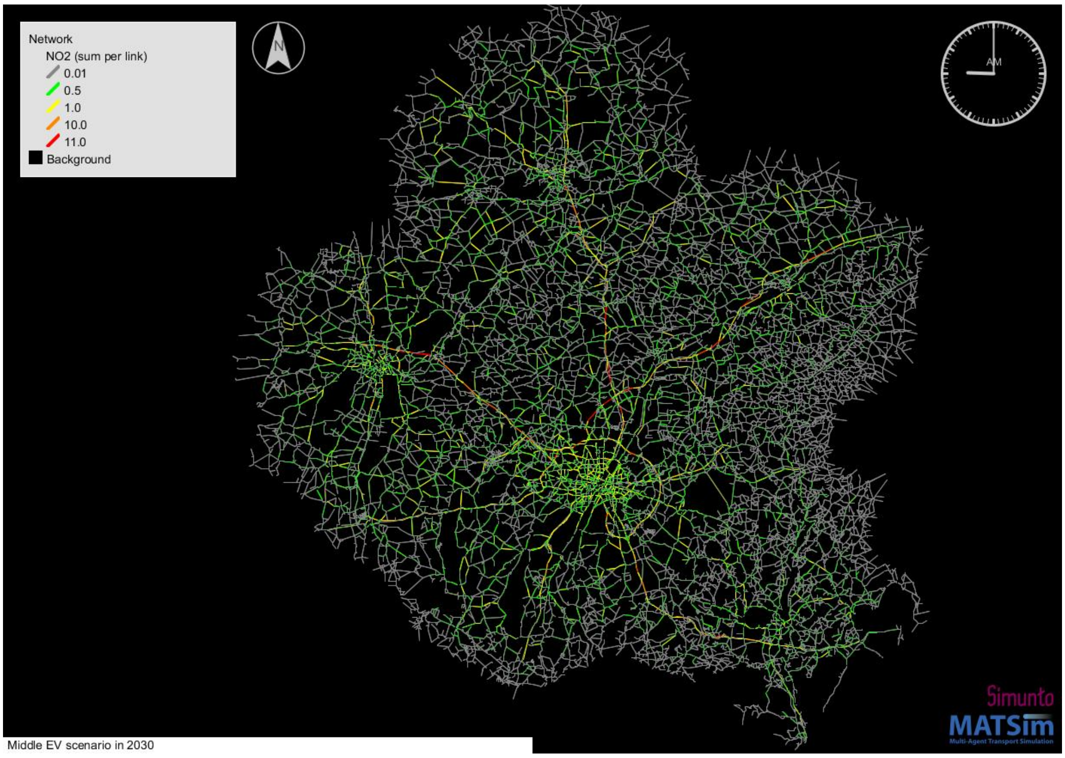

Figure 77: One-hour model of NO_2 during the morning peak (Middle EV scenario in 2030)

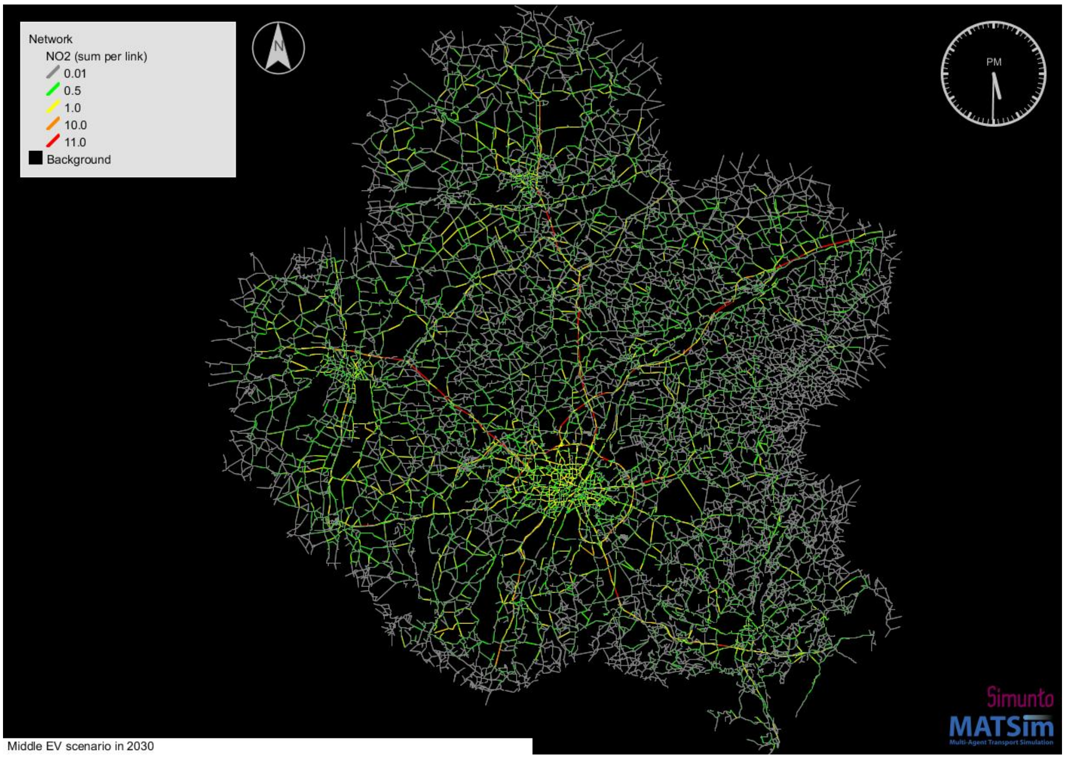

Figure 78: One-hour model of NO_2 during the evening peak (Middle EV scenario in 2030)

The Munich area in the peak hours shows emission trends similar to those of the year 2020.

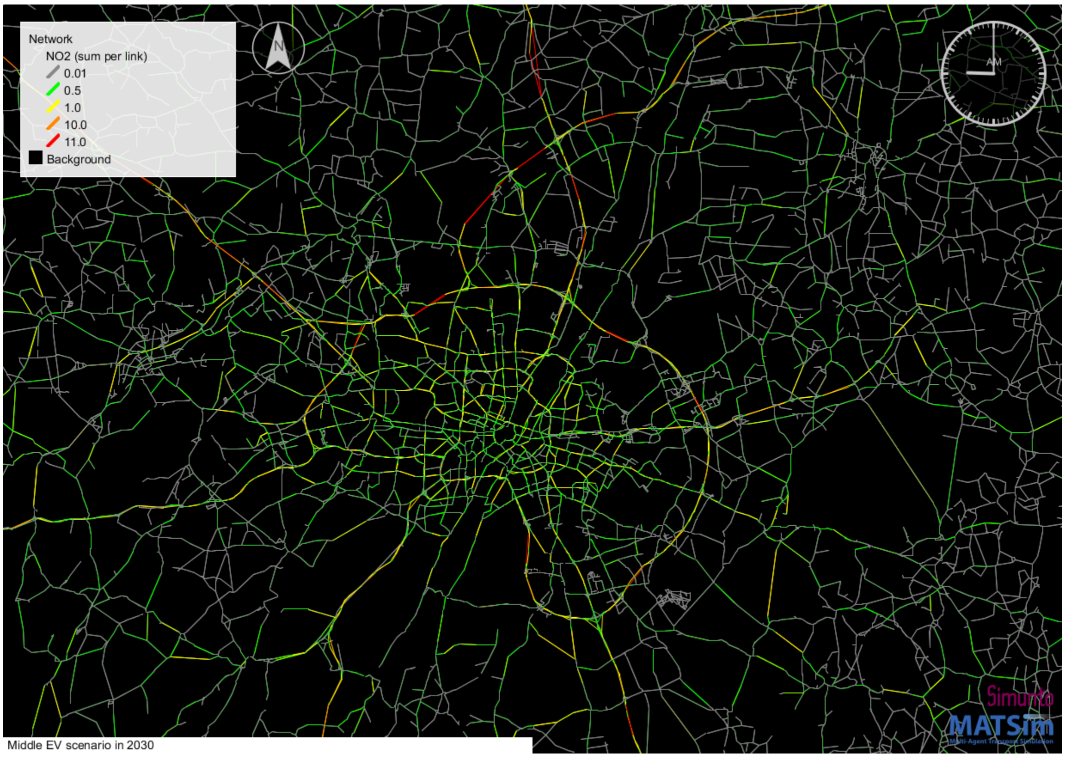

Figure 79: One-hour model of NO_2 in Munich during the morning peak (Middle EV scenario in 2030)

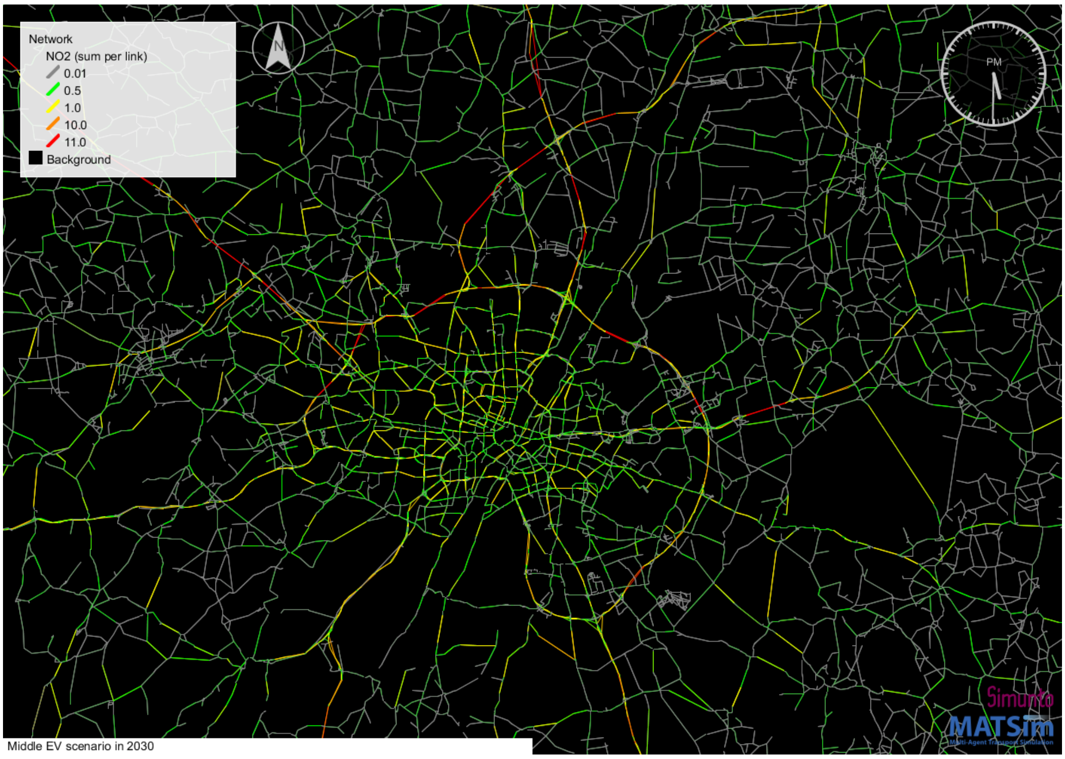

Figure 80: One-hour model of NO_2 in Munich during the evening peak (Middle EV scenario in 2030)

The reduction in the overall emissions leads to a decline in the hotspots. The one-day accumulation of NO_2 results in 116 g for Landshuter Allee and in 35 g for Stachus. There are declined by 25 % and 8 % respectively compared to the amounts in the Middle EV scenario for 2020. In contrast to this reduction, the maximum and the average values at Stachus increased by up to 23 %, and amount to 0.9 g and 0.3 g respectively. On Landshuter Allee, the maximum (3.3 g) increases by 6 % and the average (1.0 g) decreases by 8 % compared to those of the previous observation year.

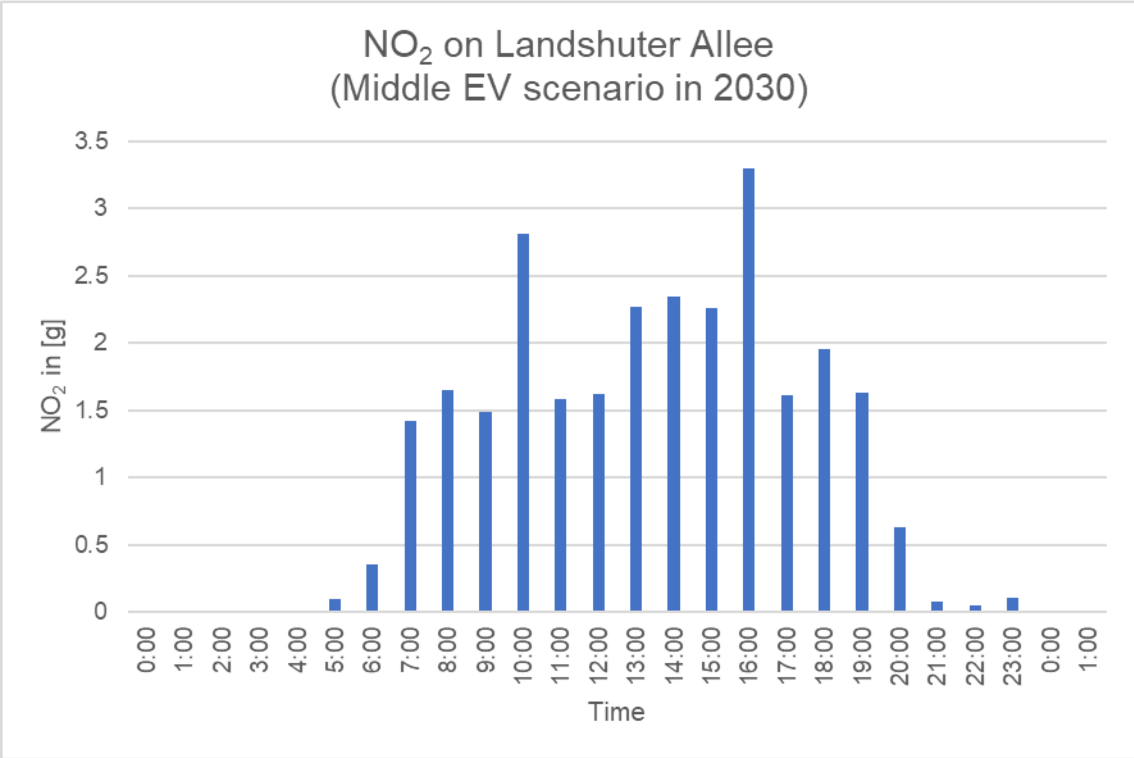

Figure 81: One-day course of NO_2 on Landshuter Allee (Middle EV scenario in 2030)

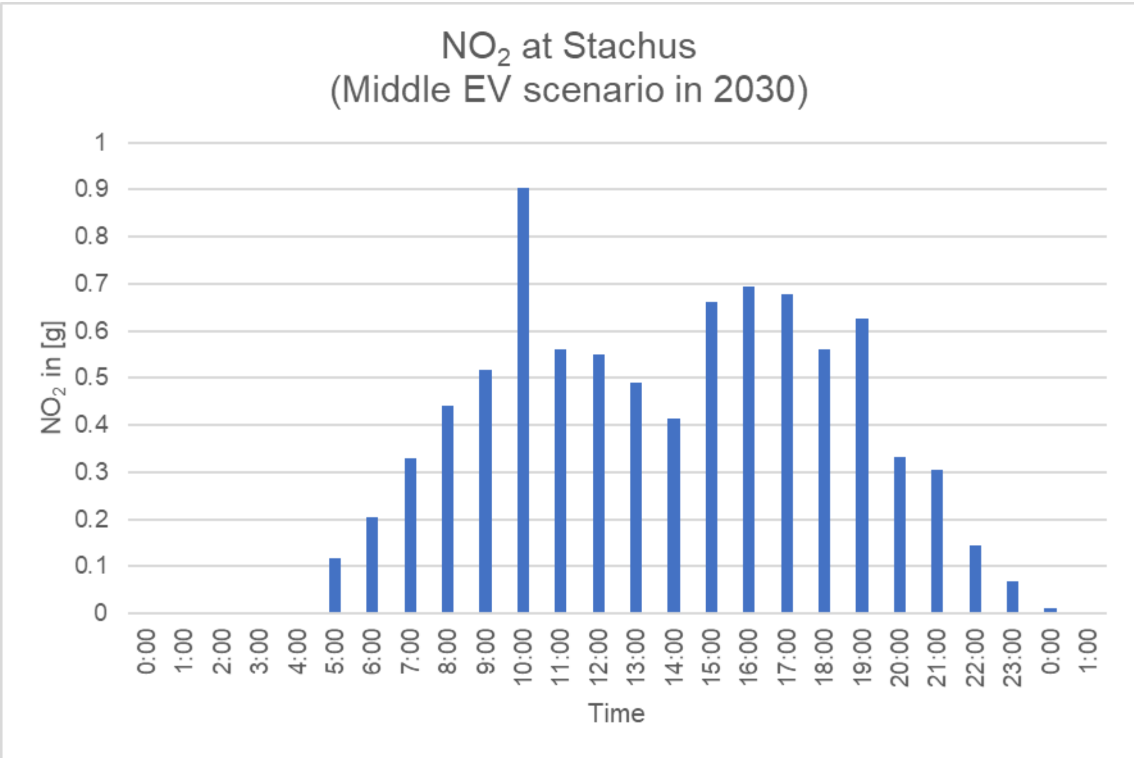

Figure 82: One-day course of NO_2 at Stachus (Middle EV scenario in 2030)

The subsequent subsection indicates the estimation with the highest share of electric cars for the years 2020 and 2030.

9.2.3 Pro EV scenario

Pro EV scenario for 2020

The Pro EV scenario bases on the optimistic scenario of the intervention. With the share of 3.7 % electric cars, the emissions will have decreased by 2 % compared to the base year and amount to 194,827 g NO_2. The number of the links at the highest-level decreases by 3 %. However, these changes are not noticeable in the overall emission trends presented in Figure 83 and Figure 84.

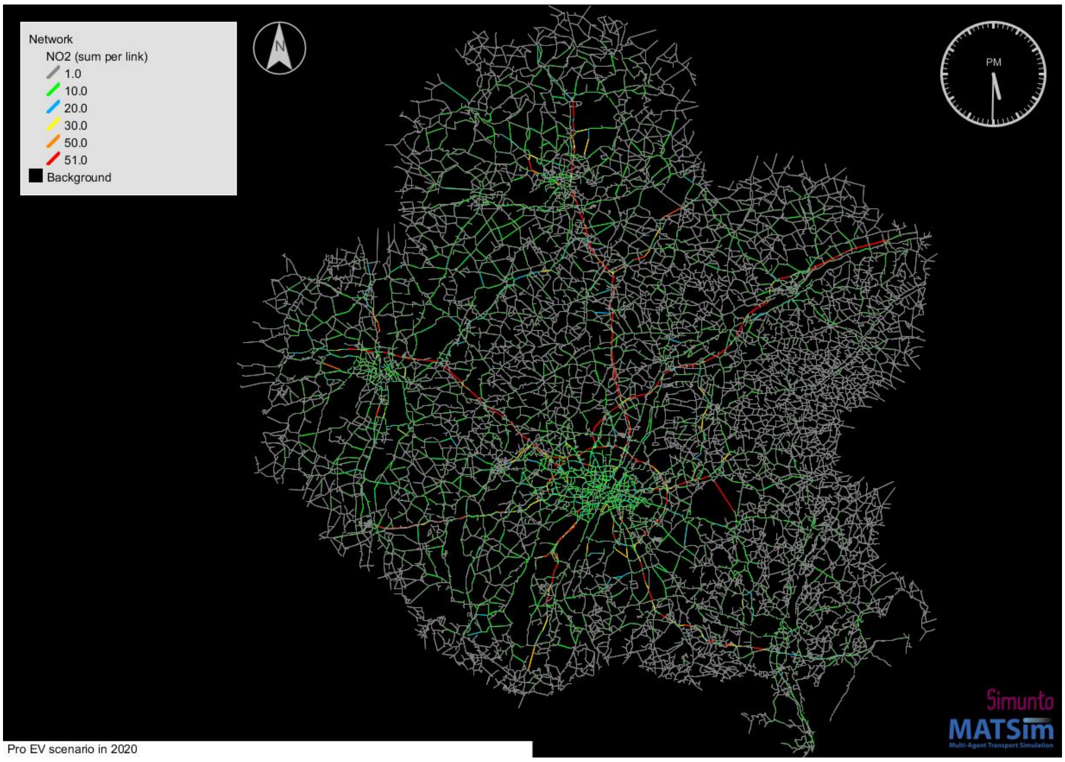

Figure 83: One-day model of NO_2 (Pro EV scenario in 2020)

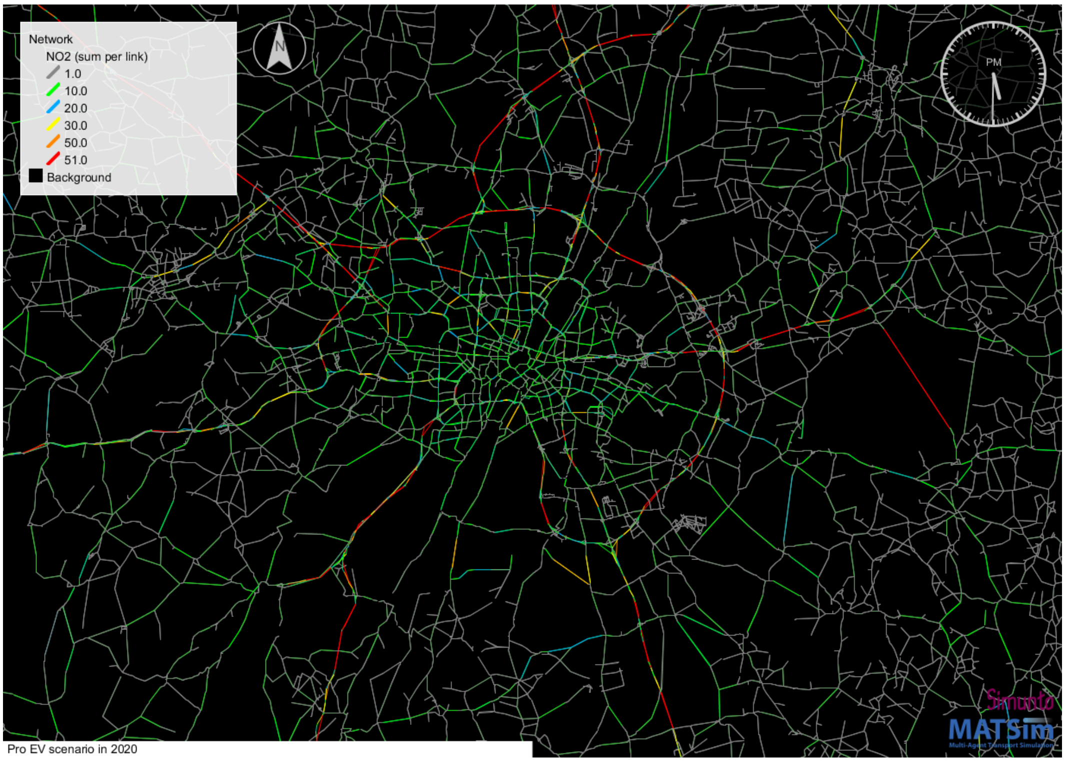

Figure 84: One-day model of NO_2 in Munich (Pro EV scenario in 2020)

The one-hour model of NO_2 during the peak hours presents minor differences compared to those of the base year. These are reductions in emission levels in the rural area.

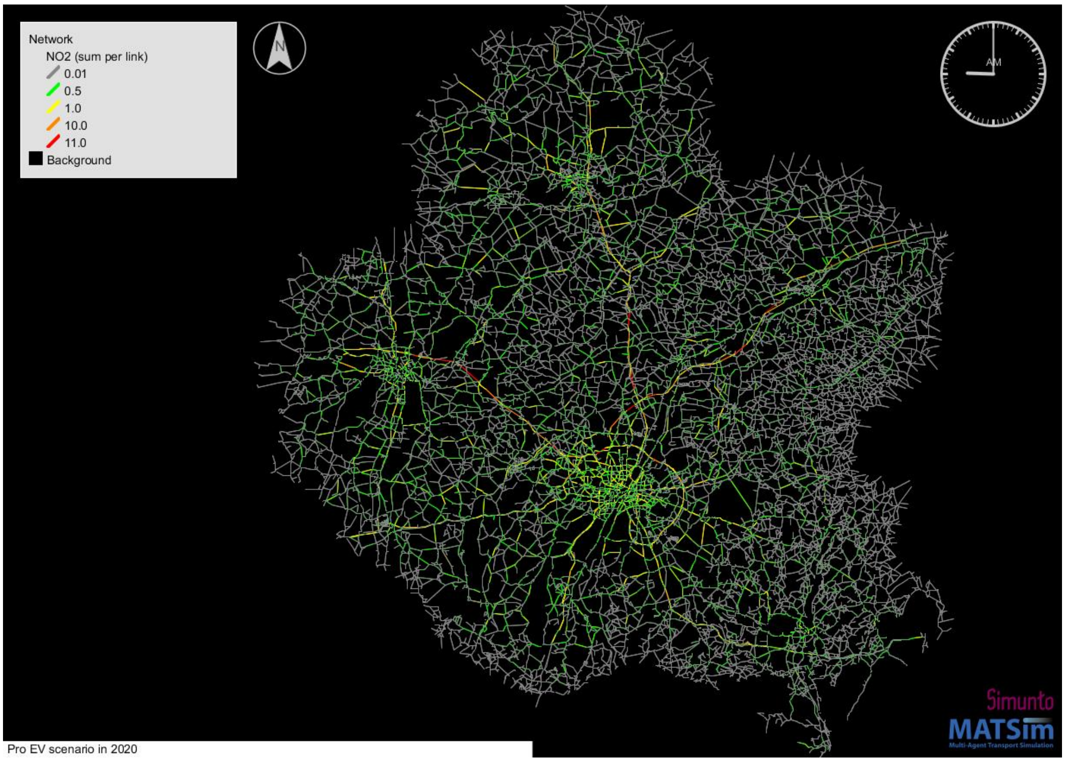

Figure 85: One-hour model of NO_2 during the morning peak (Pro EV scenario in 2020)

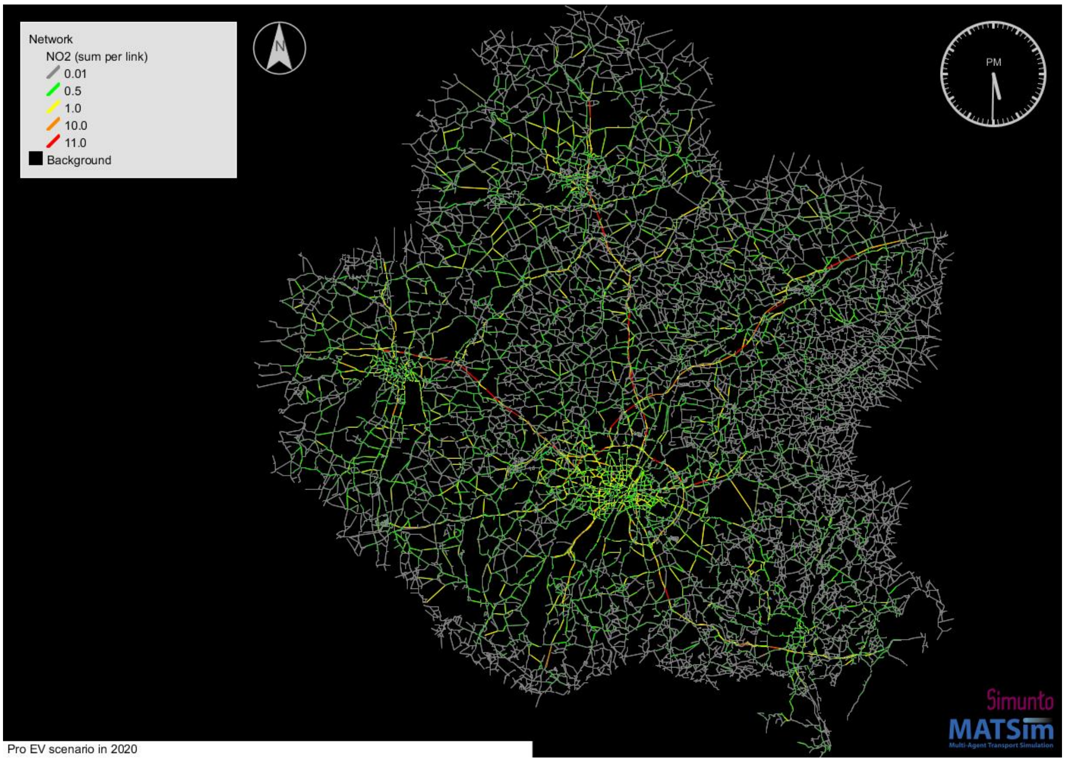

Figure 86: One-hour model of NO_2 during the evening peak (Pro EV scenario in 2020)

The Munich city area shows a slight decrease as well. In particular, the emissions during the morning peak reduce in the southwest part of the city. However, those during the evening peak seems unchanged compared to the results in 2011.

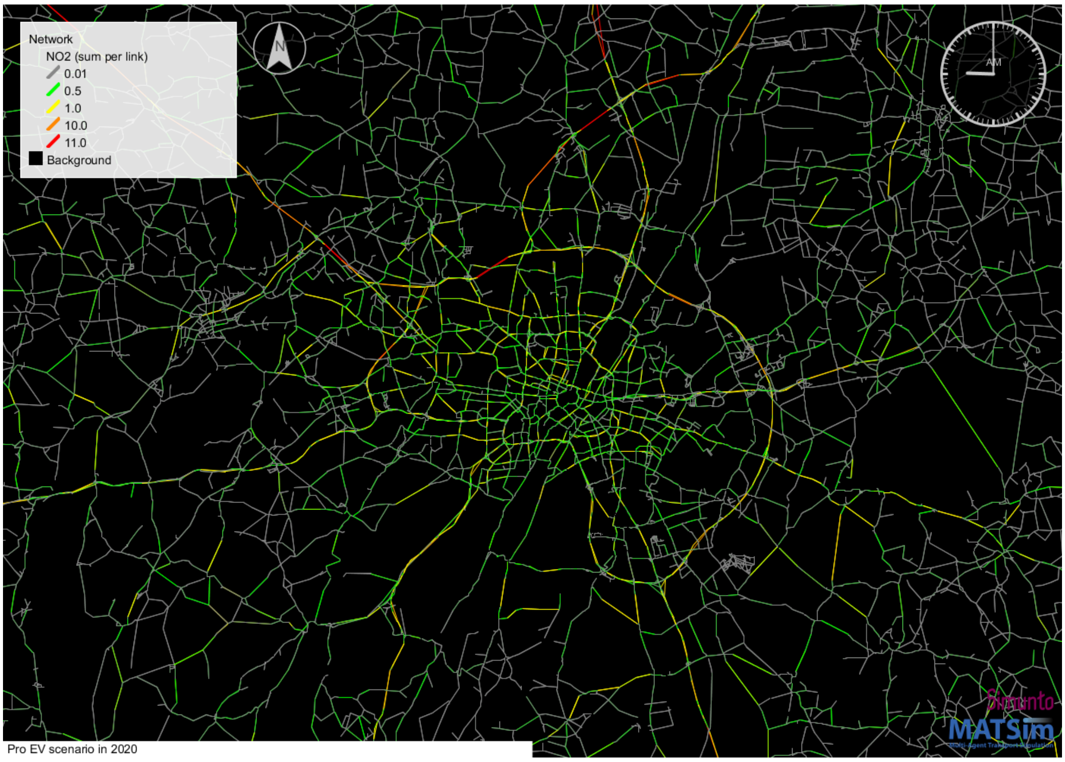

Figure 87: One-hour model of NO_2 in Munich during the morning peak (Pro EV scenario in 2020)

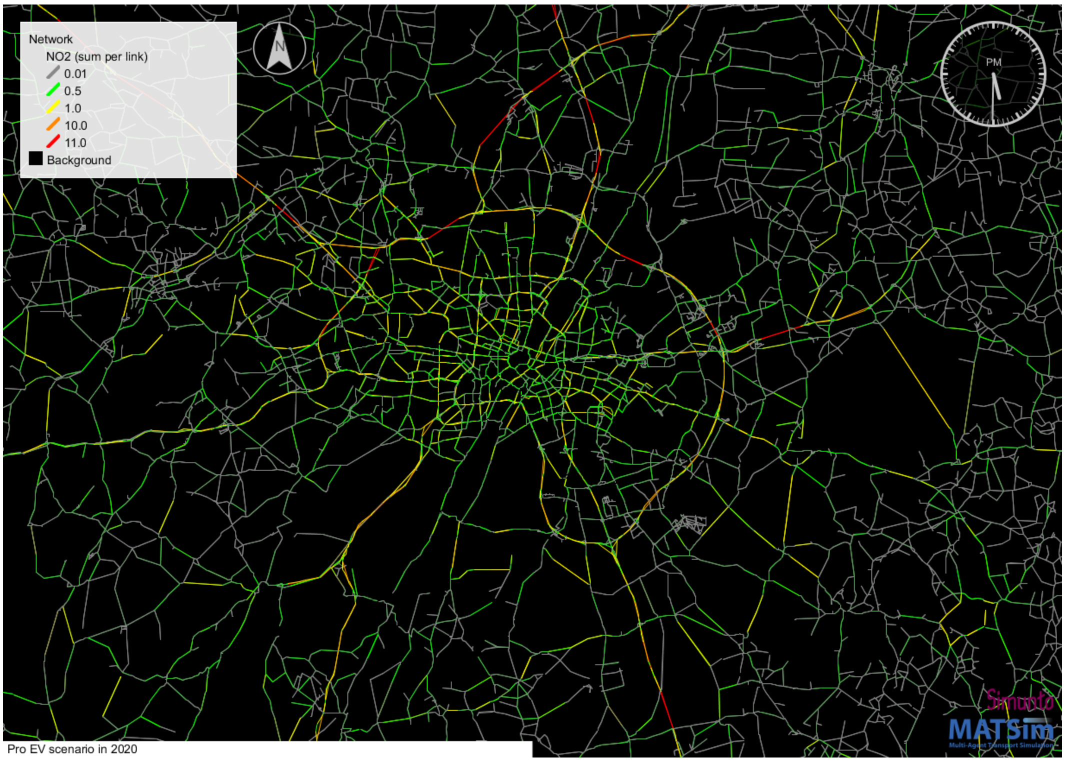

Figure 88: One-hour model of NO_2 in Munich during the evening peak (Pro EV scenario in 2020)

Landshuter Allee indicates a decline of the emissions. The emissions result in 141 g NO_2, which are a 6 % reduction compared to those of the base year. However, the one-day emissions at Stachus increase by 4 % and results in 38.4 g. The characteristic values on Landshuter Allee decrease respectively. The maximum reaches 2.2 g and the average amounts to 0.9 g. At Stachus, the maximum (0.8 g) decreases by 8 %, whereas the average (0.3 g) increases slightly.

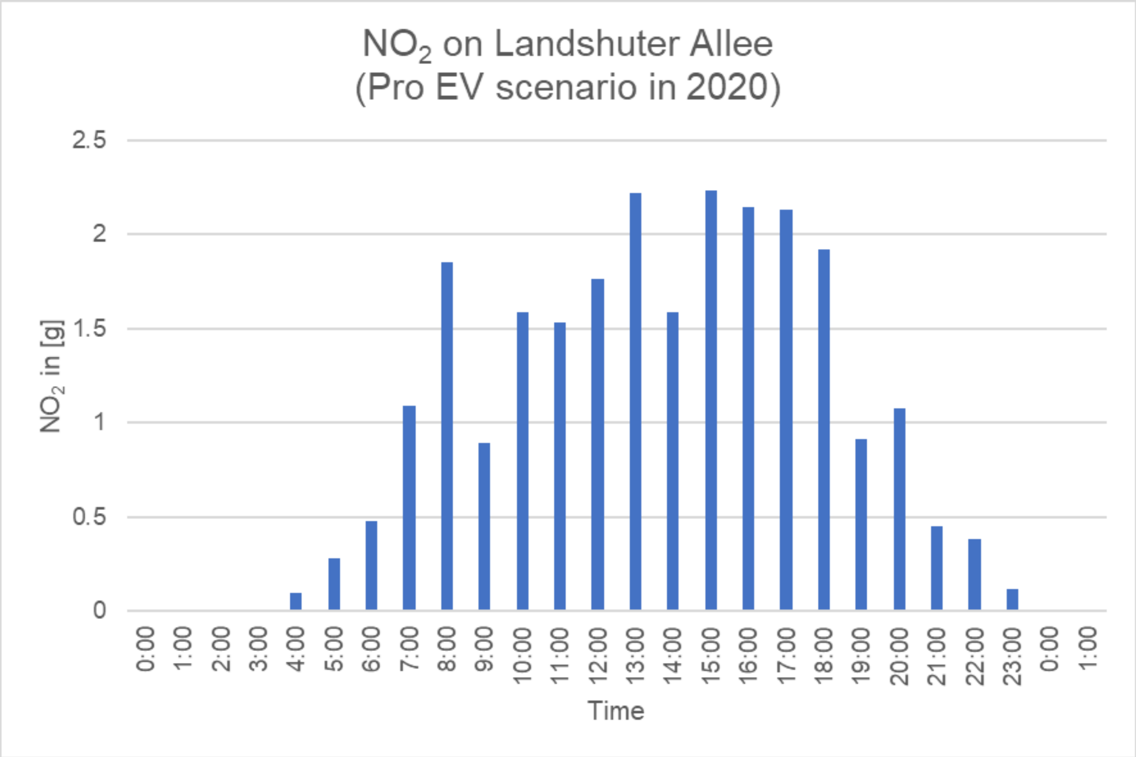

Figure 89: One-day course of NO_2 on Landshuter Allee (Pro EV scenario in 2020)

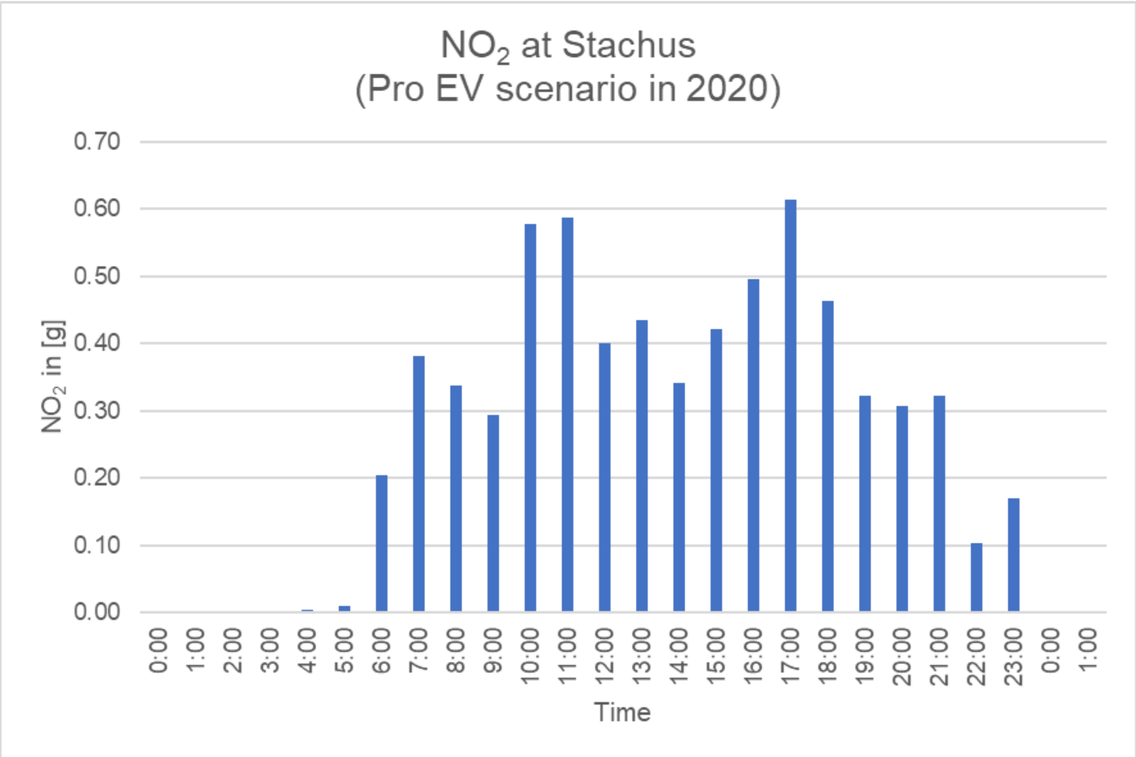

Figure 90: One-day course of NO_2 at Stachus (Pro EV scenario in 2020)

Pro EV scenario for 2030

For 2030, the Pro EV scenario assumes 14.7 % of electric vehicles. A strong growth leads to a sharp decline in the total emissions and results in 122,278 g NO_2. These amounts are 34 % less than the previous observation. Furthermore, the number of the links at the highest emission level is decreased by 43 %. This is recognizable decrease in the overall emissions presented in the figures below. In general, the majority of the links that was indicated by green is now downgraded to grey. The emissions are still concentrated in the cities, but the surrounding areas are lightened of the emissions.

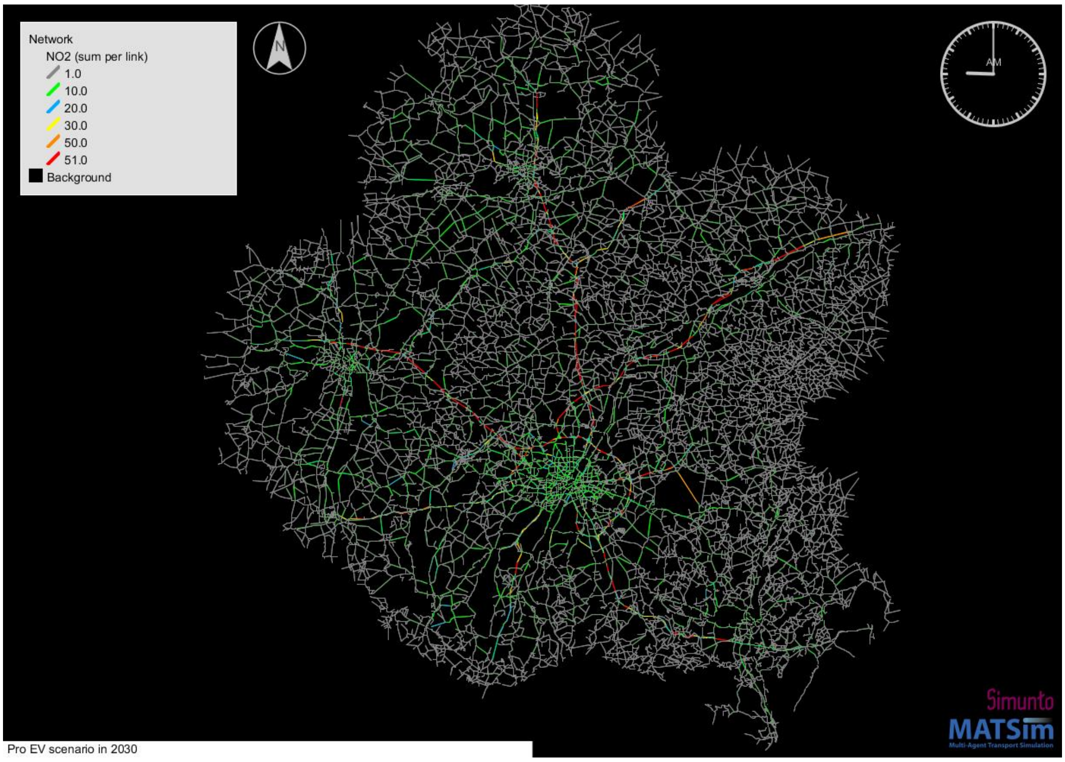

Figure 91: One-day model of NO_2 (Pro EV scenario in 2030)

A closer look at the city of Munich, a high share of the links presents lower emission levels. Moreover, the model predicts no longer a significant high level of the emissions.

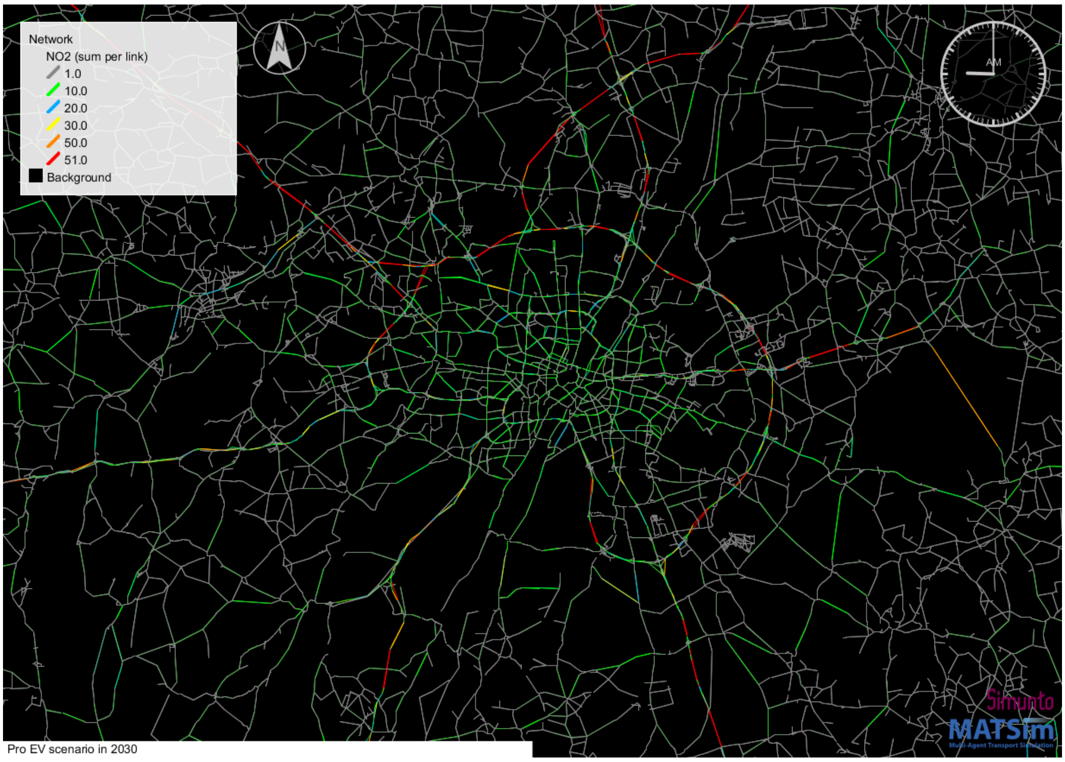

Figure 92: One-day model of NO_2 in Munich (Pro EV scenario in 2030)

Similar to the one-day model, the overall decline in the emissions are seen in the one-hour models, particularly during the morning peak hour. A high share of the major transport axes as well as in the rural areas, emission levels are decreased compared to those of the Pro EV scenario for 2020.

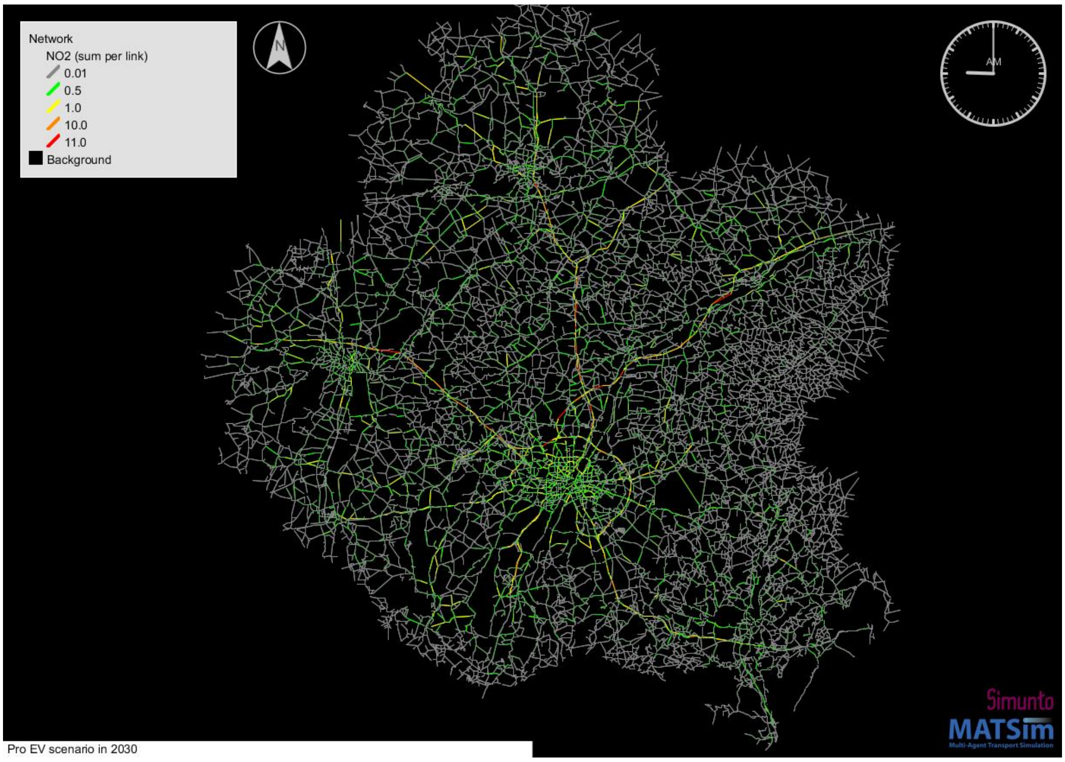

Figure 93: One-hour model of NO_2 during the morning peak (Pro EV scenario in 2030)

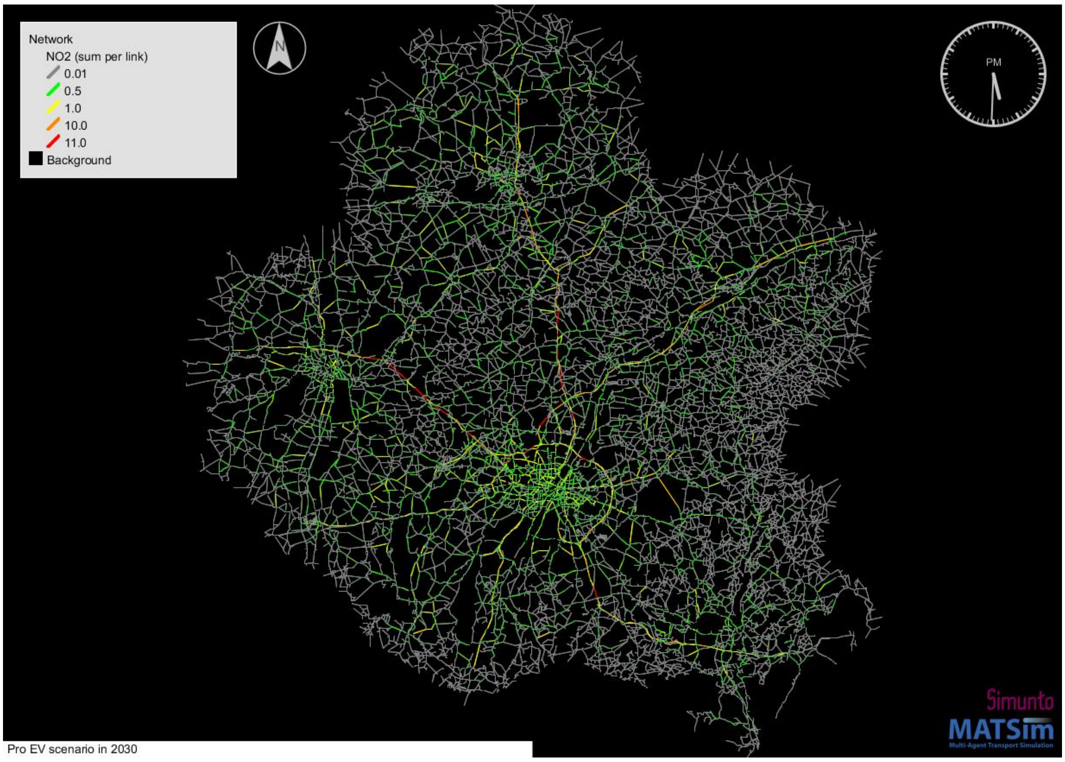

Figure 94: One-hour model of NO_2 during the evening peak (Pro EV scenario in 2030)

The reduction can be seen in the city area as well. The major share of the links presents the emission level 0.5. Furthermore, there is no links at the highest level of the emissions.

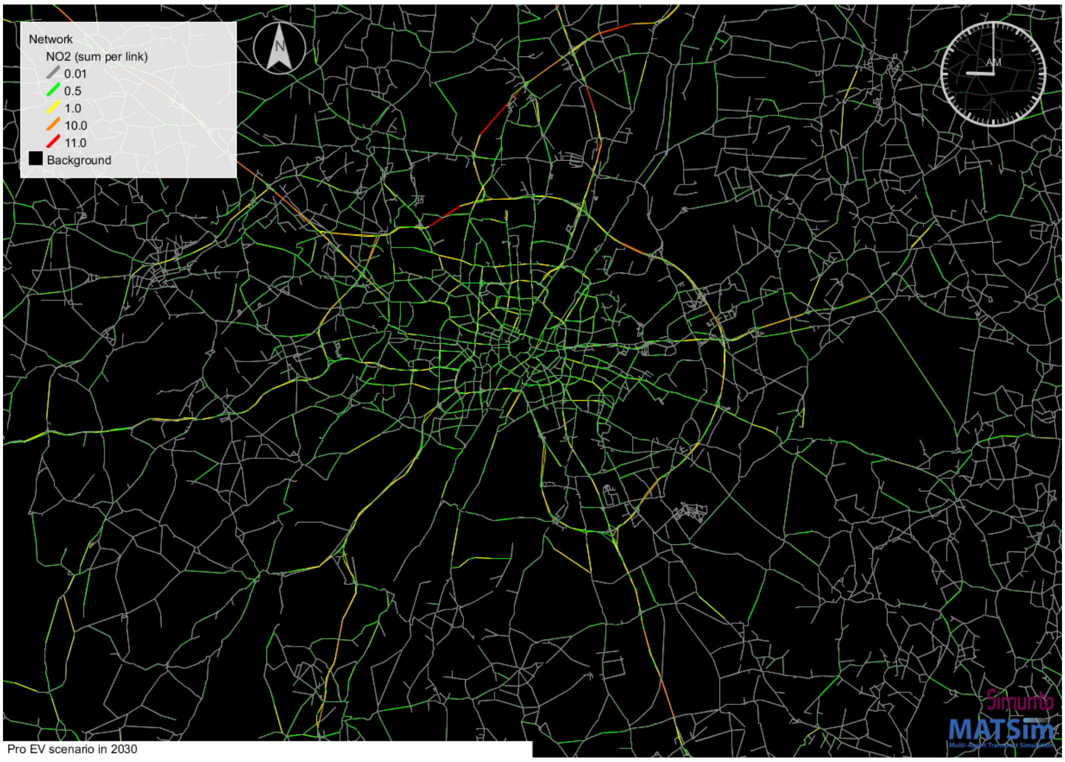

Figure 95: One-hour model of NO_2 in Munich during the morning peak (Pro EV scenario in 2030)

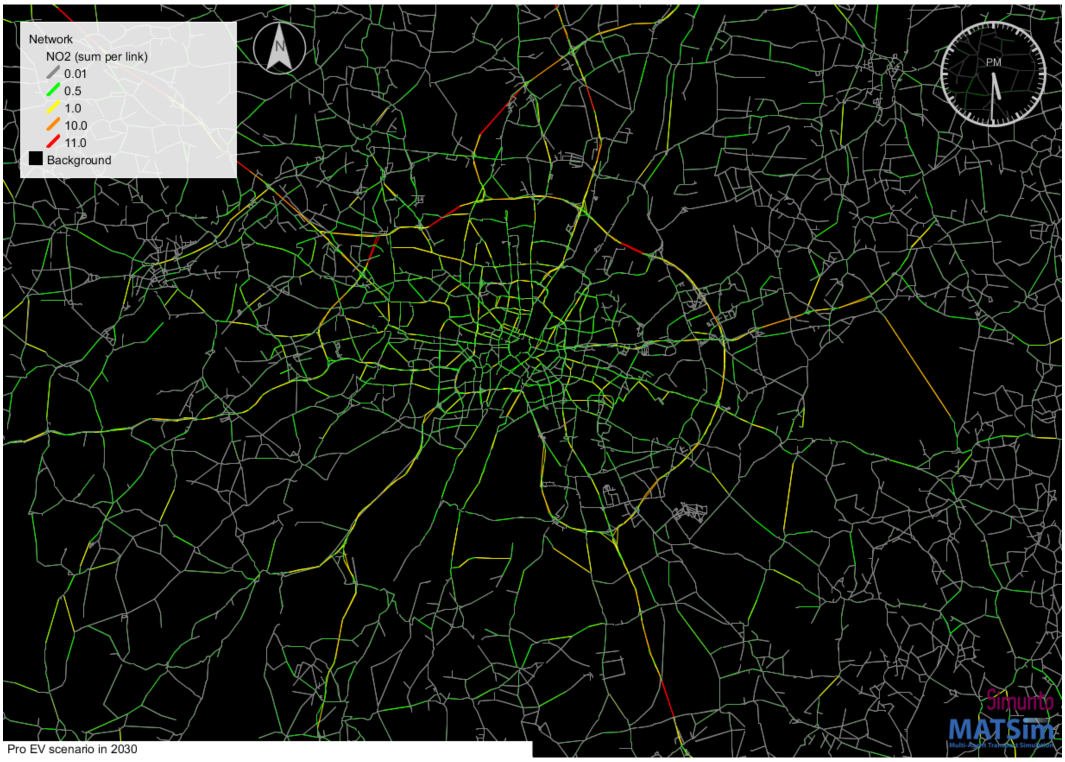

Figure 96: One-hour model of NO_2 in Munich during the evening peak (Pro EV scenario in 2030)

The significant decline of NO_2 is reflected by the hotspots. The one-day accumulation of NO_2 results in 89.7 g for Landshuter Allee and in 36.4 g for Stachus. These are decreased by 36 % and 5 % respectively compared to the previous observation. On Landshuter Allee, the maximum NO_2 reaches 1.7 g and the average value is 0.6 g. These indicate a reduction of 22 % and 39 % respectively. At Stachus, the emissions decline by up to 31 %. These reach 0.5 g at maximum and amount to 0.2 g on average.

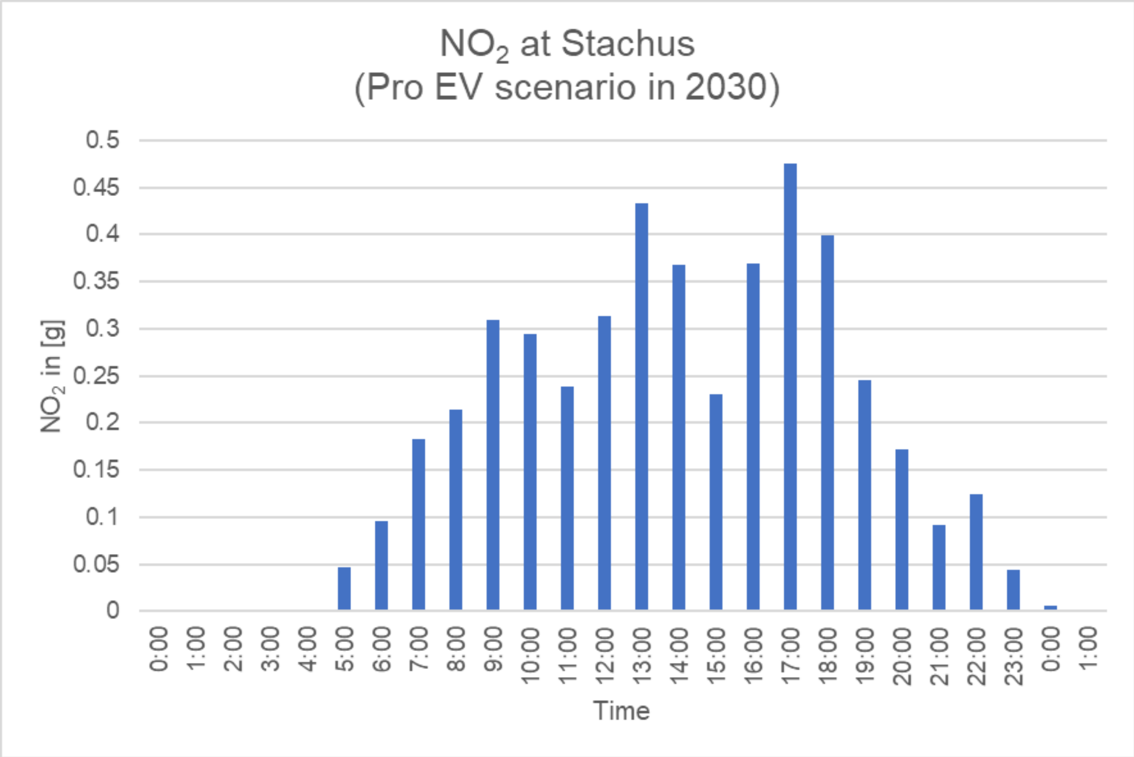

Figure 97: One-day course of NO_2 on Landshuter Allee (Pro EV scenario in 2030)

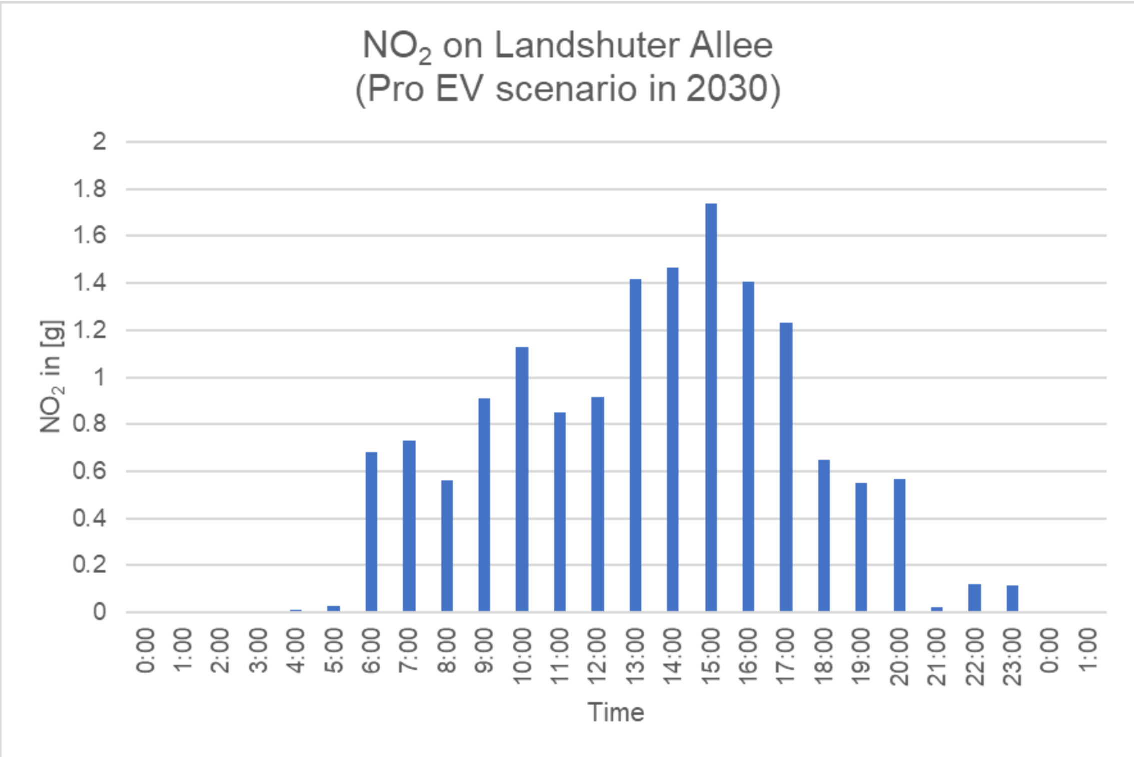

Figure 98: One-day course of NO_2 at Stachus (Pro EV scenario in 2030)

The following section provides an overview of the scenarios.

9.3 Comparing the Emissions between the Scenarios

Reaching the goal of one million electric vehicles by 2020 will help to reduce the emissions by improving the vehicle efficiency of motorized trips. According to the estimation made in this thesis, this improvement would reduce the NO_2 emissions by up to 9 % compared to the BAU scenario for the year 2020. Moreover, if the intervention scenarios for the year 2030 are implemented as described, a further significant reduction could be expected. More precisely, the Pro EV and the Middle EV scenarios would pull down the emissions below the 2011 level with reductions of 42 % and 24 % respectively. The Contra EV scenario would decrease NO_2 by 8 %. These comparisons are shown in Figure 99.

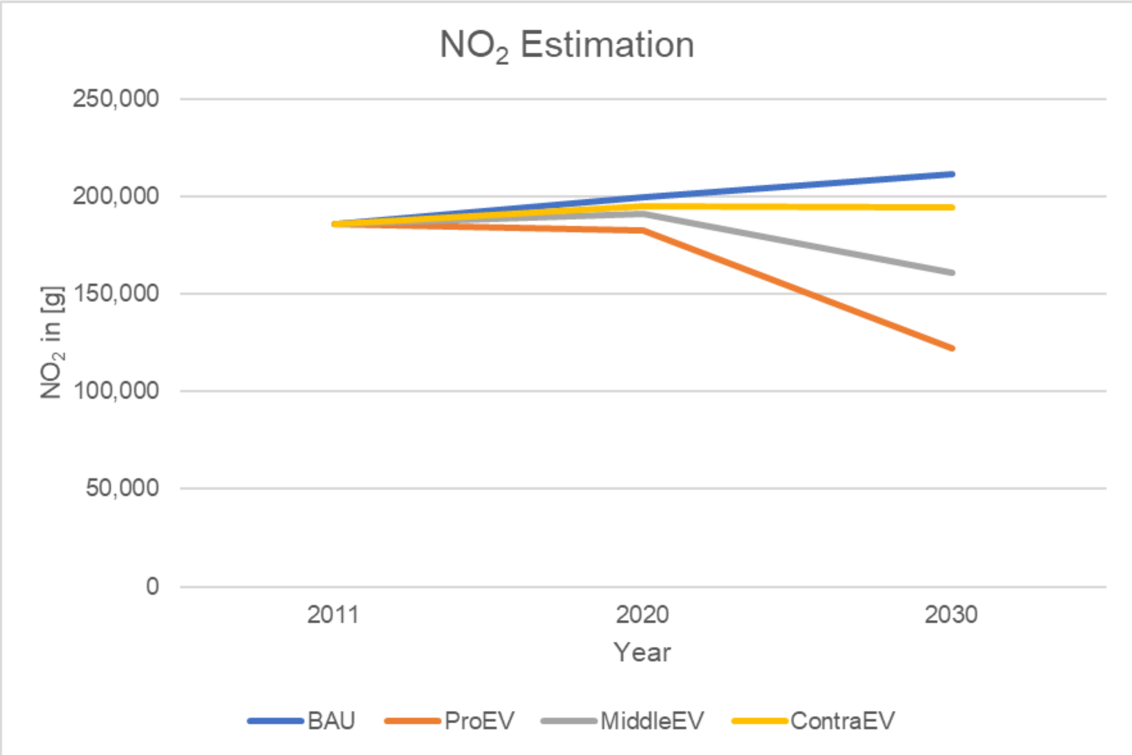

Figure 99: Overview of the emissions resulting from the scenarios

In general, the differences in the NO_2 totals are particularly recognizable in the emission levels along the major transport axes as well as in rural areas. Changes in the city areas only occur when the differences in the one-day accumulation of NO_2 are very high.

Although all intervention scenarios would reduce the emissions, only the Pro EV scenario visualizes clear differences from the BAU scenario in the one-day accumulation of NO_2 in the network. The other scenarios certainly lead to a decrease, but the reductions are not obvious in the results.

In the hotspots, we can see an emission decrease only if the total NO_2 is highly reduced. A slight reduction or an increase of the emissions leads to a growth in these areas. Moreover, a general reduction in the hotspots does not mean a reduction of their characteristic values. The overall decline in these values occurs only if the one-day accumulation of NO_2 strongly decreases, as seen in the Pro EV results.

10. Conclusion

While Munich has implemented various emission reduction measures to improve air quality, a decrease of NO_2 significant enough to meet the EU limit has not been successful until today. Along with the surrounding regions, Munich aims at to reduce NO_2 by promoting electric vehicles.

The methodology to estimate the potential reductions due to the number of electric vehicles used a case comparison technique in which the emissions are compared to four scenarios in each of the years 2011, 2020 and 2030: A business-as-usual scenario without any measures; the optimistic, and the pessimistic scenarios, and a scenario averaging optimistic and pessimistic. The last three are differentiated by the achievement of the objective.

The results of the emission estimations of this thesis determined that, compared to the business-as-usual scenario, the implementation of the measure will see reductions in a range from 8 % to 42 % by 2030.

There are some limitations to this thesis that may impact the quality of the results. First, the proportion of petrol cars is assumed to be constant during the observation period, due to the difficulties of quantifying the share shifting to electric cars. The vehicle type shift can be estimated more accurately. Second, the projection of vehicle numbers in Germany and the reflection of the vehicle proportion onto the study area are quite rough. Finally, heavy-duty vehicles are not considered in the model, because there was no data available on freight transport in the provided data, even though these would make up a significant share of the emissions.

Nevertheless, these results provide an important overview of the NO_2 emissions for the Munich metropolitan area. Given the significant reduction of emissions due to the introduction of electric cars as predicted in this thesis, the Munich metropolitan region can improve its NO_2 emissions while the number of trips still increases.

Furthermore, as seen in the results, a reduction in one-day accumulation of NO_2 leads to a decrease of emission levels in the network particularly along the major transport axes or in the rural areas. A decline of emission levels in the city areas only occurs when the one-day emissions accumulation reduces greatly. Therefore, the investigation of this thesis highly suggests fulfilling or even surpassing the planned increase of electric vehicles, to maximize the impacts on the emissions.

While this study is primarily focused on the benefits in air quality to be achieved by increasing the number of electric vehicles, there will undoubtedly be many other co-benefits.

Electric vehicles not only generate no local emission, but also no global and noise emissions. Furthermore, the introduction of the alternative power unit guarantees liberation from the fossil fuels, which are progressively depleting and becoming more expensive. Such benefits will certainly play a role in the holistic cost-benefit analysis for promoting electric vehicles.

The aspects of promoting electric vehicles examined in this thesis apply to the concept of ‘improve’ to implement emission reductions in the transportation sector of the Munich metropolitan area. To forecast further mitigation effects of the emissions, additional ‘avoid’ and ‘shift’ strategies could be examined. Moreover, as described in Chapter 7, the provided data only covers the trips that are traveled by passenger cars. Complementation of other transportation modes such as heavy-duty vehicles and the public transportation would enable a more precise estimation of the emissions.

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Statement of independent work

I hereby confirm that this thesis was written independently by myself without the use of any sources beyond those cited, and all passages and ideas taken from other sources are cited accordingly.

Munich, 15.01.2019

Place, Date	Signature

Appendix 1: Numbers of passenger cars

		2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Total	Germany total	41,321,171	41,737,627	42,301,563	42,927,647	43,431,124	43,851,230	44,403,124	45,071,209	45,803,560	46,474,594
	Bavaria total	6,772,212	6,862,802	6,958,119	7,110,701	7,214,493	7,311,093	7,427,661	7,550,273	7,695,182	7,845,761
	Munich Metropolitan Region	3,049,426	3,086,784	3,123,491	3,210,118	3,264,967	3,319,322	3,377,225	3,434,612	3,505,889	3,580,981
City	Munich	612,380	616,318	618,787	663,127	674,394	684,713	691,050	705,476	722,384	727,179
	Augsburg	113,640	114,546	117,442	119,803	122,527	125,162	127,262	129,486	132,123	134,698
	Ingolstadt	79,385	79,287	81,816	84,943	87,215	89,990	91,937	94,398	96,240	95,562
	Kaufbeuren	20,355	20,518	21,013	21,238	21,605	21,814	22,175	22,746	23,257	23,926
	Landshut	31,089	31,083	31,412	31,980	32,684	33,381	33,788	34,525	35,401	36,208
	Rosenheim	29,819	30,236	30,581	31,309	31,630	32,042	32,686	33,143	33,770	34,167
District	Aichach-Friedberg	70,794	72,176	73,315	74,848	76,044	77,463	78,755	80,270	81,976	83,541
	Altötting	58,582	59,733	60,794	61,884	62,740	63,340	64,372	65,487	66,849	68,261
	Augsburg	134,159	136,596	138,929	141,968	144,573	146,857	149,635	152,972	155,777	158,888
	Bad Tölz-Wolfratshausen	66,680	68,086	69,196	70,742	72,020	73,011	73,924	75,060	76,524	77,669
	Dachau	71,368	73,347	74,920	76,899	78,584	80,373	82,324	84,353	86,641	88,893
	Dillingen an der Donau	53,610	54,569	55,664	56,635	57,489	58,185	59,217	60,048	61,017	62,259
	Dingolfing-Landau	53,610	54,489	55,386	56,645	56,727	58,305	59,780	61,498	61,372	65,248
	Donau-Ries	75,319	76,596	77,904	79,448	80,914	82,385	83,758	85,186	86,821	88,220
	Ebersberg	66,811	67,937	69,314	71,195	72,907	74,202	75,640	77,697	79,764	81,580
	Eichstätt	66,457	67,844	69,389	70,677	72,269	73,556	75,312	77,254	79,196	81,041
	Erding	69,617	71,118	72,813	74,667	76,352	77,571	79,504	81,549	83,693	85,506
	Freising	88,458	90,386	91,794	93,483	95,361	96,911	98,661	100,863	103,471	105,034
	Fürstenfeldbruck	102,415	104,565	106,564	108,635	110,741	111,844	113,802	115,988	118,323	119,956
	Garmisch-Partenkirchen	44,411	45,151	45,851	46,598	47,292	47,851	48,361	49,306	50,053	50,803
	Kelheim	64,075	65,213	66,639	68,037	69,284	70,388	71,948	73,556	75,362	77,038
	Landsberg am Lech	63,970	65,473	67,024	68,390	69,828	71,107	72,903	74,593	76,497	78,040
	Landshut	86,116	87,872	89,713	91,667	93,325	94,774	96,775	98,986	101,308	103,375
	Miesbach	54,782	55,792	56,487	57,411	58,301	59,229	60,440	61,688	62,853	63,730
	Mühldorf am Inn	59,340	60,541	61,768	62,879	63,934	65,006	66,437	68,040	69,682	71,036
	München	242,990	236,644	225,294	221,552	221,388	224,805	228,596	219,472	220,578	241,015
	Neuburg-Schrobenhausen	51,694	52,816	53,834	54,767	55,857	57,087	58,399	59,801	61,228	62,724
	Ostallgäu	72,914	74,537	78,087	77,810	79,175	80,642	82,472	84,433	86,026	87,786
	Pfaffenhofen an der Ilm	65,769	67,064	68,363	69,757	71,380	72,741	74,690	76,385	78,489	80,357
	Rosenheim	136,183	139,165	142,314	145,445	148,598	151,348	154,629	157,979	161,781	164,843
	Starnberg	75,747	76,725	77,565	78,795	79,926	80,673	81,773	82,887	84,093	85,340
	Traunstein	95,087	96,867	98,740	100,788	102,431	103,933	106,052	107,899	110,147	112,194
	Weilheim-Schongau	71,800	73,494	74,779	76,096	77,472	78,633	80,168	81,588	83,193	84,864

Adapted from Kraftfahrt-Bundesamt 2009, 2010b, 2011b, 2012b, 2013b, 2014b, 2015b, 2016b, 2017b, 2018b