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Model-based Assessment of the Integration of Zero-Emission Vehicles into Dynamic Environmental Traffic Management for Air Pollution Control in Urban Areas

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Abstract

Air pollution has been and still is an important issue that causes numerous negative impacts on health, the environment, and the economy. It is particularly problematic in urban areas due to the accumulation of regional, urban, and local air pollutant concentrations as well as high population, building, and traffic density. Road transport-related air pollution or, in other words, traffic-related air pollution (TRAP) is one of the important contributors to outdoor air pollution in urban areas. There are several policy instruments to cope with traffic-related air pollution. Promoting cleaner vehicles, in particular zero-emission vehicles (ZEVs), is one of the measures to reduce emissions from road vehicles. Dynamic environmental traffic management (DETM) is another measure that primarily aims to hinder short-term high air pollution levels caused by road traffic in critical areas by activating temporary traffic restrictions. Both measures have potentials and limitations in coping with air pollution in cities.

This thesis aims to evaluate a joint consideration of these two measures and to assess if they can promote each other to reduce TRAP. Although the number of electric vehicles is increasing and ZEVs are making ground, there is little information on the possible impacts of ZEVs on local air pollution in urban areas. Likewise, there is hardly any DETM measure that takes these vehicles with zero tail-pipe emissions into account, so far. Consequently, this thesis essentially asks if these zero-tailpipe-emission vehicles should be considered explicitly in air pollution-related dynamic traffic management measures, for example by being excluded from such temporary restrictions. In this context, the thesis focuses on nitrogen dioxide (NO_2) which is one of the critical air pollutants in urban areas caused mostly by road transport and specifically on NO_2 concentrations in urban street canyons.

Existing literature shows that there are numerous methods to analyze TRAP and the selected methodology plays an important role in the application and evaluation of environmental traffic management measures. As a result, during the methodology development procedure, experiments are conducted to evaluate the relative merits of macroscopic or microscopic approaches. The analysis indicates that microscopic air quality monitoring methods (meaning detection and modelling) are beneficial (with some computational and calibration-related limitations) for the precise monitoring of air pollution hotspots as well as for the evaluation of dynamic traffic management measures, in addition to comprehensive macroscopic screening procedures.

In line with these outcomes, a microscopic DETM approach is designed to analyze the integration of ZEVs in DETM in this thesis. This approach is composed of two main steps: monitoring of the air quality and implementation of the traffic management strategy. In the developed microscopic approach, air quality monitoring is conducted by integrating existing modelling tools (i.e. VISSIM, PHEM, OSPM). Similarly, common action steps suggested by literature are adopted for traffic management strategy implementation (i.e. situation assessment, problem detection, the decision on traffic management measure(s), implementation, and tracking of impacts).

Before analyzing the DETM-ZEV integration in detail, potentials of ZEVs in air quality improvement are investigated by using the developed microscopic air quality modelling approach on a simple artificial network (without traffic management strategy implementation, i.e. without implementing any DETM measure). Results show that increasing the share of ZEVs in vehicle fleet can improve air quality particularly at critical air pollution hotspots (originating from high traffic volumes, congestion, and/or street canyon structure) and during critical times (originating from traffic peak and/or environmental conditions). These results support the idea that ZEVs can contribute to DETM whose primary goal is to reduce short-term peak traffic-related air pollution concentrations at hotspots.

Finally, the complete DETM approach is used to assess the integration of ZEVs into DETM and to evaluate the impacts of this integration on the effectiveness and efficiency of the DETM measures as well as on the attractiveness of ZEVs. This analysis is conducted through the modelling of two example DETM measures, temporary re-routing and temporary traffic flow metering, on an artificial urban network. ZEVs are considered in DETM by being exempted from related restrictions during the activation period of the temporary traffic management measures. Outcomes of the analysis indicate that giving such privileges to ZEVs from air quality-related temporary measures can result in several benefits, starting from low ZEV shares. ZEV privileges can increase the effectiveness of DETM measures by diminishing hotspot-relocation-effect as well as by increasing the overall network performance. Such DETM measures that consider exempting ZEVs can also improve the network recovery time and increase the efficiency of DETM measures. ZEV privileges would not only bring significant advantages to ZEVs in traffic and promote their attractiveness but can also bring advantages to conventional vehicles due to the overall improvement in traffic. These benefits can be hindered at some locations when a certain ZEV share is reached, and traffic control is not adaptive. However, model results also show that at higher ZEV shares hotspots are solved to a large extent. Consequently, this thesis concludes that consideration of ZEVs in DETM applications is meaningful starting from a low fleet share of ZEVs until a certain share is reached, where the air pollution situation is not critical anymore and/or there is no need to consider ZEVs as special vehicles in traffic management measures.

Kurzfassung

Luftverschmutzung war und ist ein wichtiges Thema, welches zahlreiche negative Auswirkungen auf Gesundheit, Umwelt und Wirtschaft hat. Aufgrund der Überlagerung von regionalen, städtischen und lokalen Luftschadstoffkonzentrationen sowie hoher Verkehrs-, Bebauungs- und Bevölkerungsdichte sind urbane Räume besonders von diesem Problem betroffen. Der Anteil der straßenverkehrsbedingten Luftschadstoffe stellt hierbei einen der wichtigsten Einflussfaktoren auf die Luftverschmutzung in städtischen Räumen dar. Zur Reduzierung der verkehrsbedingten Luftschadstoffe stehen verschiedene Maßnahmen zur Verfügung. Die Förderung sauberer Fahrzeuge, insbesondere abgasfreier Fahrzeuge (eng.: Zero-Emission Vehicle - ZEV), ist eine der Maßnahmen zur Verringerung der Emissionen von Straßenfahrzeugen. Das dynamische Umweltsensitive Verkehrsmanagement (DUVM) ist eine weitere Maßnahme, die in erster Linie darauf abzielt, kurzfristige hohe straßenverkehrsbedingte Luftschadstoffbelastungen in kritischen Bereichen durch die Aktivierung temporärer Verkehrsbeschränkungen zu verhindern. Beide Maßnahmen haben Potenziale und Grenzen bei der Luftreinhaltung in Städten.

Ziel dieser Arbeit ist es, eine gemeinsame Betrachtung dieser beiden Maßnahmen durchzuführen und zu beurteilen, ob sie sich gegenseitig bei der Reduzierung von verkehrsbedingten Luftschadstoffen unterstützen können. Obwohl die Zahl der Elektrofahrzeuge zunimmt, gibt es nur wenige Informationen über die möglichen Auswirkungen von diesen Fahrzeugen auf die lokale Luftschadstoffbelastung in urbanen Räumen. Ebenso gibt es bisher kaum eine UVM-Maßnahme, die die Fahrzeuge ohne Abgasemissionen berücksichtigt. Daher geht diese Arbeit im Wesentlichen der Frage nach, ob ZEV explizit in immissionsbedingten dynamischen Verkehrsmanagementmaßnahmen berücksichtigt werden sollten, beispielsweise durch die Befreiung von derartigen Maßnahmen. In diesem Zusammenhang fokussiert sich die Arbeit auf Stickstoffdioxid (NO_2), als einer der kritischen Luftschadstoffe in städtischen Räumen, die hauptsächlich durch den Straßenverkehr verursacht werden, und insbesondere auf NO_2-Konzentrationen in städtischen Straßenschluchten.

Die vorhandene Literatur zeigt, dass es zahlreiche Methoden zur Analyse von straßenverkehrsbedingten Luftschadstoffbelastungen gibt und die gewählte Methodik eine wichtige Rolle bei der Anwendung und Bewertung von UVM-Maßnahmen spielt. Infolgedessen werden bei der Entwicklung der Methode dieser Arbeit verschiedene Studien durchgeführt, um die Vorteile makroskopischer oder mikroskopischer Ansätze zu bewerten. Die Analyse zeigt, dass mikroskopische Methoden zum präzisen Luftqualität-Monitoring von Luftverschmutzungs-Hotspots (d.h. Detektion und Modellierung) sowie für die Bewertung dynamischer Verkehrsmaßnahmen von Vorteil sind - zusätzlich zu umfassenden makroskopischen Screening-Verfahren. Sie bringen aber einige rechnerische und kalibrierungsbedingte Einschränkungen mit sich.

Im Einklang mit diesen Ergebnissen wurde in dieser Arbeit ein mikroskopischer Ansatz für das DUVM entwickelt, um die Integration von abgasfreien Fahrzeugen in das DUVM zu analysieren. Der Ansatz

besteht aus zwei Hauptschritten: das Monitoring der Luftqualität und die Umsetzung der Verkehrsmanagementstrategie. Im entwickelten mikroskopischen Ansatz wird das Monitoring durch die Integration bestehender Modellierungswerkzeuge (d.h. VISSIM, PHEM, OSPM) durchgeführt. In ähnlicher Weise werden in der Literatur vorgeschlagene Verfahrensschritte für die Umsetzung von Verkehrsmanagementstrategien angewendet (d. h. Situationsbewertung, Problemerkennung, Auswahl und Entscheidung über die Maßnahmen, Umsetzung und Überwachung der Wirkungen).

Vor der detaillierten Analyse der ZEV-Integration in das DUVM werden Potenziale von abgasfreien Fahrzeugen zur Verbesserung der Luftqualität unter Verwendung des entwickelten mikroskopischen Modellierungsansatzes in einem einfachen beispielhaften Straßennetz (ohne Umsetzung einer Verkehrsmanagementstrategie, d. h. ohne Implementierung einer DUVM-Maßnahme) untersucht. Die Ergebnisse zeigen, dass die Erhöhung des Anteils von ZEV in der Fahrzeugflotte die Luftqualität insbesondere an kritischen Luftverschmutzungs-Hotspots (hervorgerufen durch hohes Verkehrsaufkommen, Staus und/oder die Bebauungscharakteristik) und in kritischen Zeiten (hervorgerufen durch Verkehrsspitzen und/oder Umweltbedingungen) verbessern kann. Diese Ergebnisse unterstützen die Idee, dass ZEV zum DUVM beitragen können, dessen primäres Ziel es ist, kurzfristige verkehrsbedingte Luftschadstoffkonzentrationen an Hotspots zu reduzieren.

Schließlich wird der vollständige DUVM-Ansatz genutzt, um die ZEV-Integration in das DUVM zu bewerten und die Auswirkungen dieser Integration auf die Wirksamkeit und Effizienz der Maßnahmen sowie auf die Attraktivität von ZEV zu bewerten. Diese Analyse wird durch die Modellierung von zwei Beispielen von DUVM-Maßnahmen, temporäres alternatives Routing und temporäre Zuflussdosierung, in einem fiktiven innerstädtischen Straßennetz durchgeführt. ZEV werden in DUVM berücksichtigt, indem sie während des Aktivierungszeitraums der temporären Verkehrsmanagementmaßnahmen von den entsprechenden Einschränkungen befreit werden. Die Ergebnisse der Analyse deuten darauf hin, dass die Gewährung solcher Privilegien für ZEV als temporäre luftreinhaltungsrelevante Maßnahme bereits bei niedrigen Anteilen in der Fahrzeugflotte zu mehreren Vorteilen führen kann. Befreiungen für ZEV können die Effektivität von DUVM-Maßnahmen erhöhen, indem sie den Hotspot-Verlagerungs-Effekt verringern und die Gesamtleistung des Straßennetzes erhöhen. Solche Maßnahmen, können auch die Netzwerk-Erholungszeit verbessern und die Effizienz von DUVM-Maßnahmen erhöhen.

Aufgrund der allgemeinen Verbesserung des Verkehrsablaufes würden solche ZEV-Privilegien nicht nur erhebliche Vorteile für diese Fahrzeuge im Verkehr bringen und ihre Attraktivität fördern, sondern auch Vorteile für konventionelle Fahrzeuge erzielen. Diese Vorteile werden in einigen Bereichen im Netz eingeschränkt, wenn ein bestimmter Flottenanteil erreicht ist und keine adaptive Verkehrssteuerung angewendet wird. Die Ergebnisse zeigen aber auch, dass bei höheren ZEV-Anteilen Luftschadstoff-Hotspots weitgehend gelöst werden. Aus diesem Grund kommt diese Arbeit zu dem Schluss, dass die Berücksichtigung von ZEV in DUVM-Anwendungen sinnvoll ist. Der Einsatzbereich erstreckt sich ausgehend von geringen Flottenanteil bis zum Erreichen eines bestimmten Anteils, bei dem die Luftschadstoffsituation nicht mehr kritisch ist und / oder es nicht mehr notwendig ist, ZEV als Spezialfahrzeuge in Verkehrsmanagementmaßnahmen zu berücksichtigen.

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1. Introduction

In this chapter, firstly, the overall context and the motivation of the thesis are described. In line with the motivation, the main thesis statement, related hypotheses, and research questions are listed. Finally, the scope, methodology and structure of the thesis are illustrated.

1.1 Context and Motivation

Road transport-related emissions have several negative impacts. While carbon dioxide emissions are one of the most important problems at the global scale; at the local scale, air pollutants cause fair concerns due to their direct effects on health. Especially in urban central areas with high urban density where high traffic volumes and congestion are seen, air pollutant concentrations often exceed the threshold values that are set by European Commission [EC, 2008] or suggested by World Health Organization [WHO, 2006]. There are several policy instruments to reduce the share of road transport-related air pollution, or i.e. traffic-related air pollution (TRAP), which cover different policy areas from urban and infrastructure planning to vehicle and fuel technology as well as traffic management.

Traffic management as one of the policy tools has essentially four goals: improving traffic efficiency, increasing traffic safety, minimizing costs, and reducing the environmental effects of traffic. These goals are achieved by influencing traffic demand and supply through the application of several measures [FGSV, 2011, 2003]. These measures can be divided into two categories as static and dynamic, depending on their validity period. While static traffic management measures are unified and valid independent of the situation; dynamic measures (i.e. active traffic management) are activated under certain conditions for a specific time and location [FGSV, 2011].

Currently, various traffic control measures are increasingly being taken to improve air pollution, especially in urban areas. Traffic management applications that deploy measures dynamically based on the environmental situation such as temporary speed limits, temporary re-routing, or access restrictions for air quality improvement are called dynamic environmental traffic management (DETM). Together with other air pollution reduction strategies, DETM measures are used to relieve areas with high air pollution levels (i.e. air pollution hotspots). Unlike static measures such as emission zones, these measures are activated under critical air pollution situations and for a specific time and location. As expected, in the long term, static regulations have higher impacts on overall emission reduction compared to dynamic measures. However, additional dynamic traffic management measures are useful to avoid short-term air pollution peaks which occur as a result of air pollution being highly dynamic; meaning being dependent on regional pollution levels and weather conditions which can vary greatly in short time intervals [DIEGMANN, V., 2014; BOLTZE, M. AND KOHOUTEK, S., 2010].

The advantages of dynamic traffic management measures in air pollution control compared to static measures can be summarized as being fast in avoiding short-term emission peaks, reducing the frequency of exceedances of the threshold values, not creating permanent alternative routes and thus not relocating hotspots in the long term (as some static measures may cause) and reducing the period of access-restrictions to the areas where TRAP is critical only under certain conditions (e.g. seasons, wind conditions, peak hours, etc.) [BOLTZE, M. AND KOHOUTEK, S., 2010; DIEGMANN, V., 2014; LUDES, G. ET AL., 2010]. Therefore, air quality plans (AQPs) include both static and dynamic measures to cope with air pollution in the long and short term.

DETM measures for air pollution reduction have three main principles: improvement of the overall traffic flow (e.g. temporary speed reduction, dynamic traffic signal coordination), management of the traffic composition (e.g. temporary heavy-duty vehicle restrictions), and reduction of traffic volumes in the concerned area (e.g. temporary access restrictions, traffic re-routing). Briefly, DETM measures aim to reduce and manage TRAP by using existing means such as optimizing the traffic flow as well as shifting part of the traffic to less polluted and well-ventilated road sections. Examples of implemented DETM measures in Germany [DIEGMANN, V. ET AL., 2020] show that stricter measures that reduce overall traffic or change the traffic composition in a hotspot have higher effects than lighter measures focusing on optimizing traffic flow. However, in many cases, the applicability and effectiveness of these strict DETM measures are limited by local conditions such as the availability of an alternative route or a suitable metering area with non-critical air pollution levels, where traffic can be relocated without creating another hotspot.

When it comes to the management of traffic composition, most of the existing dynamic traffic management measures do not make a distinction between different vehicle types, except for some cases where heavy-duty vehicles (HDVs) are considered separately (e.g. temporary restriction or re-routing of HDVs). Yet, vehicle types, engine types, and emission classes have a high influence on road transport emissions and air quality. Consequently, traffic management measures should, in addition to managing traffic flow, also focus more on the management of the traffic composition for emission reduction and air quality improvement on certain road sections [PLANK-WIEDENBECK, U. ET AL., 2017].

Today electric road vehicles (EVs) are on the rise and promise emission reduction in transport. There are two types of electric cars: pure electric vehicles (i.e. all-electric vehicles, only-electric vehicles, fully-electric vehicles) that solely use electric motor(s) and hybrid electric vehicles that combine electric motor with an internal combustion engine for propulsion. EVs bring new vehicle types that can be considered in road traffic-related air pollution assessment and setting of dynamic reduction measures in urban areas. Especially pure electric vehicles which have no tailpipe emissions (i.e. zero direct emissions or zero local emissions) offer particular potential for the reduction of local emissions. These vehicles are also called zero-emission vehicles (ZEVs) due to having zero tailpipe emissions. The European sustainable and smart mobility strategy gives particular importance to zero-emission mobility and sets the goal of having nearly all road vehicles zero-emission by 2050 for road transport [EC, 2020].

Although EVs are ambitiously supported internationally as well as by governments and local authorities, fleet turnover does take time and reaching ambitious and urgent emission reduction goals through fleet change is not always possible, as quickly as desired. On one hand, static measures that give permanent privileges to EVs in traffic (e.g. free parking spaces, use of bus lanes) are rightfully questioned in terms of private vehicle use promotion. On the other hand, drastic measures that forbid comparably more polluting conventional vehicles (e.g. diesel ban) are facing acceptance problems. For this reason, until a certain share of EVs is reached, DETM measures which are activated only under critical situations can offer a chance to use the potential of EVs in the reduction of local road transport-related air pollution. Moreover, especially ZEVs can help to solve the above-mentioned problem with limited positive impacts and applicability of DETM measures. Since these vehicles do not emit exhaust emissions, they can make it easier to redistribute traffic in the network, in the case of critical air pollution levels in a specific area, without creating new air pollution hotspots.

The fact that vehicles are becoming connected and EVs starting to have dedicated number plates in several countries also allows the differentiation of these vehicles in traffic and apply specific dynamic traffic control measures. This is meaningful, particularly for the consideration of zero-emission vehicles in local air quality-related traffic management measures. Such strategies may include giving privileges to ZEVs during an activated access restriction or, in other words, exempting ZEVs from air pollution-related restrictions (e.g., re-routing, traffic metering). By doing this, the use of ZEVs can be encouraged, which may contribute to an increase in the share of ZEVs and to improved air quality in the long run.

There are numerous studies on the overall environmental impacts of e-mobility that analyze its effects by considering different electric vehicle types and stages from vehicle, battery and energy production to recycling. However, currently, there is little knowledge of the potentials of ZEVs for the reduction of local air pollution in urban street canyons and their consideration under dynamic air pollution-related traffic management. For all the reasons detailed above, the main motivation of this research is to investigate the integration of ZEVs in existing dynamic environmental traffic management measures and assessment of their potential impacts on air quality in urban street canyons.

1.2 Thesis Statement, Hypotheses, and Research Questions

The main thesis statement of this work can be summarized as follows:

> ***Consideration and integration of zero-emission vehicles in dynamic environmental traffic management measures is important due to the increasing shares of electric vehicles and can increase the short-term and long-term positive effects of these measures.***

Under this main statement, there are three hypotheses:

Hypothesis 1: Consideration of ZEVs in DETM measures can increase the **effectiveness** of these measures by reducing the spatial relocation of traffic and traffic-related air pollution to other areas (**Short-Term Effect: less relocation**).

Hypothesis 2: Consideration of ZEVs in DETM measures can increase the **efficiency** of these measures by scaling down the temporal relocation of traffic and traffic-related air pollution (**Short-Term Effect: shorter peaks**).

Hypothesis 3: Consideration of ZEVs in DETM measures can increase the **attractiveness** of these vehicles by bringing considerable advantages in traffic during the activation time (**Long-Term Effect: promotion of ZEVs**).

In order to research the integration of ZEVs in DETM and their impacts, the following seven research questions are to be answered in this dissertation:

The first two research questions are related to defining the scope and the methodology of this dissertation in terms of road vehicles, emissions, air pollutants, and traffic-related air pollution.

Research Question 1: Particularly for which traffic-related air pollutants can electric vehicles offer a reduction? Which electric vehicle types offer a higher potential?

Research Question 2: What type of air quality monitoring approach is advantageous for the evaluation of DETM measures; specifically measures related to ZEVs?

Research question 3 deals with the potential of zero-emission vehicles in air quality improvement in urban areas in general, focusing on DETM applications.

Research Question 3: How much can ZEVs contribute to local air pollution reduction in urban areas? How does their reduction potential change spatially and temporally (i.e. when and where do they bring higher reduction)?

Research questions 4, 5, and 6 are related respectively to Hypothesis 1, 2, and 3 and deal with effectiveness, efficiency, and attractiveness aspects. The last one, research question 7, covers all three aspects by investigating them in relation to the increasing share of ZEVs.

Research Question 4: Can ZEV-inclusive dynamic measures bring a significant increase in the effectiveness of DETM, compared to the conventional DETM measures?

Research Question 5: Can ZEV-inclusive dynamic measures bring a significant increase in the efficiency of DETM, compared to the conventional DETM measures?

Research Question 6: Can such ZEV-inclusive measures, additionally, provide significant benefits to these vehicles in traffic?

Research Question 7: How do the traffic and air quality impacts of privileging ZEVs change with increasing ZEV shares in traffic? Can such measures have drawbacks at certain ZEV shares?

1.3 Scope

This thesis deals with the ambient air pollution problem caused by road transport vehicles and focuses on air pollution in urban areas, specifically in urban street canyons. Geographically it concentrates on road transport-related air pollutants that are problematic in Europe (explained in **Chapter 2.2.2**).

Under the term electric vehicles, the study deals only with private electric road vehicles (i.e. does not review electric public transport vehicles) and focuses on zero-emission vehicles. Considering the emissions from private road vehicles, the thesis analyses the emissions caused by vehicle use (i.e. local emissions) and does not include other aspects such as production of vehicles, fuels, energy, and batteries as well as disposal or recycling of materials.

In terms of emission reduction measures, the focus is on short-term dynamic traffic management strategies and not on long-term policy or planning aspects. Examples of DETM applications are from Germany. From the methodological point of view, the study does focus on strategical consideration and application of such measures and not the operational aspects on the field. However, since monitoring and modelling approaches behind such systems have a decisive impact on strategical decision-making, these aspects are also covered.

1.4 Methodology and Structure

The methodology and structure of this thesis are illustrated in **Figure 1.1**. In **Chapter 2** readers can find the relevant background information on the general air pollution problem and the contribution of road transport to this problem. Furthermore, basic principles of electric vehicles and traffic management that are relevant for emission and air quality reduction are summarized. Information given in this chapter explain how the scope of this research is concretized; why certain air pollutants and electric vehicle types are not included (see *Research Question 1*).

Chapter 3 gives detailed information about dynamic environmental traffic management (DETM). This is done by explaining the overall DETM system with its components and application steps. In this chapter, the literature review is presented which describes the principles and different methods of necessary traffic and air quality monitoring approaches for DETM, state of the art in air quality monitoring for transport-related studies as well as application examples from Germany. Finally, identified research needs are summarized in the conclusions section.

Two research needs are determined. The first one is the strategical research need which is the consideration of ZEVs in DETM and it is the focus and aim of this thesis. The second research need arises from methodological questions encountered during the state-of-the-art analysis. The analysis showed that there are numerous different ways to evaluate air quality impacts of road traffic, that evaluation of measures is therefore highly related to the methodology used, and that there are potentials for improvement in these methodological approaches (Details can be found in **Chapter 3.5**).

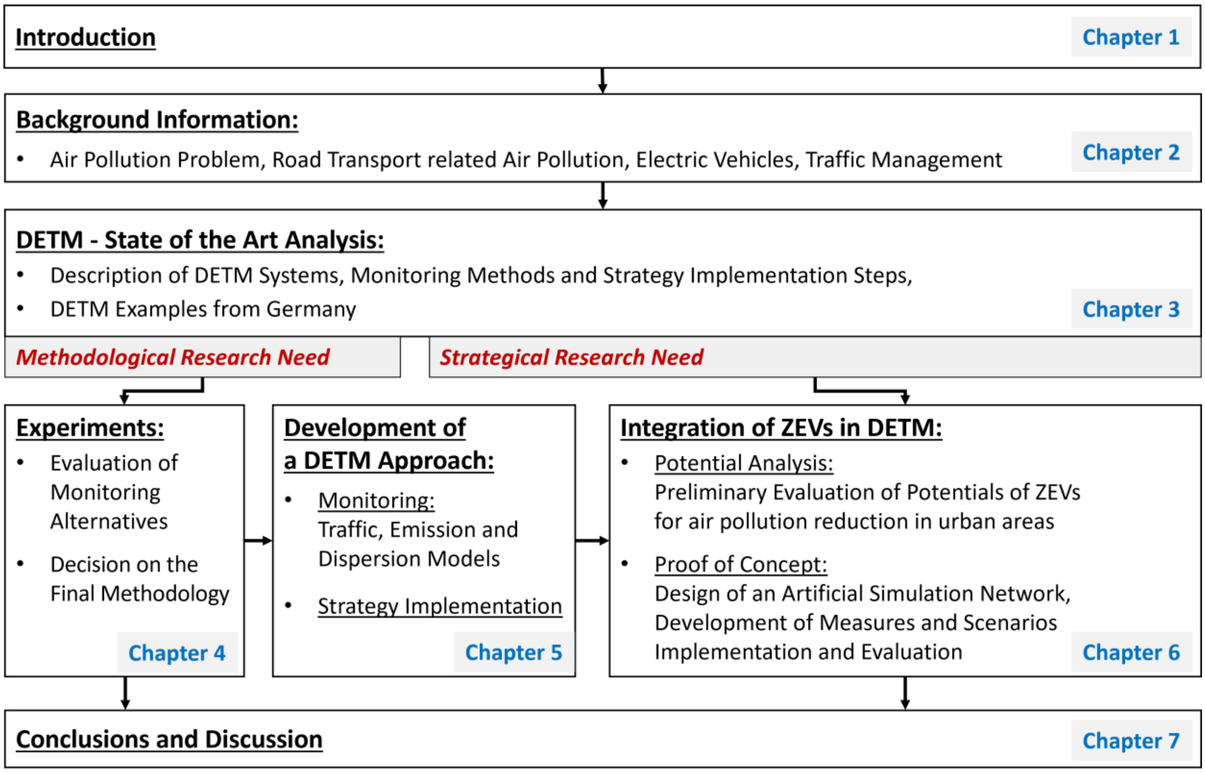

Figure 1.1 Methodology and structure

Chapter 4 focuses on this additional methodological research need (see *Research Question 2*) and investigates how air quality and traffic monitoring approaches in DETM can be improved and which methodology should be implemented for the analysis of the integration of ZEVs in DETM. This is done by presenting results from two experiments conducted in a test-case area in Munich.

The next two chapters deal with the main research need and present a proof of concept for the integration of ZEVs in DETM. Firstly, in **Chapter 5**, the developed DETM approach for the proof of concept is introduced. In this context, the utilized model-chain, used data, as well as applied settings are illustrated in detail. In **Chapter 6**, the integration of ZEVs in DETM and their effects are analyzed by using the described model-chain. Initially, a preliminary potential analysis is conducted in order to gain insights into the potential of ZEVs in local emission reduction in urban areas (see *Research Question 3*). Later, the proof of concept is conducted which consists of the design of an artificial simulation network and example ZEV-inclusive DETM measures as well as simulation of scenarios through the model-chain. The chapter ends with an evaluation of the results in terms of the short- and long-term impacts of the integration of ZEVs into DETM (see *Research Questions 4, 5, 6, and 7*).

Chapter 7 sums up the final conclusions of the thesis and final discussions.

2. Background Information

In this chapter, essential background information on the air pollution problem is given covering its history, its relevance to road transport, and its criticality in urban areas. In line with the scope of the thesis, air quality situation, vehicle emissions, and air pollution regulations and control policies in Europe are demonstrated.

2.1 Air Pollution

Air pollution occurs due to the existence of substances with harmful effects on human health and/or the environment in the air which are called air pollutants [EEA, 2016b; EC, 2008]. There are numerous hazardous air pollutants with different negative effects. To illustrate, the first air quality guidelines from World Health Organization (WHO), published in 1987, cover health risk assessments of “the 28 most common air pollutants” [WHO, 1987, 2000, 2006]. The major problematic air pollutants (i.e. common, critical, or key air pollutants) can vary by location and therefore are defined and updated by countries or organizations. The four “classical air pollutants” listed by the WHO are sulfur dioxide, nitrogen dioxide, particulate matter, and ozone [WHO, 2000, 2006].

Pollutant	Physical State	Formation	Major Sources	Example Effects
Sulfur dioxide (SO_2)	Gas	Primary	• Combustion of sulfur-containing fossil fuels for heating, power generation, transport • Volcanoes	• Eye/nose/throat irritations, • Respiratory problems, • Cardiovascular diseases, • Acidification of soil and water
Nitrogen dioxide (NO_2)	Gas	Primary and Secondary	• Combustion processes from heating, power generation, and in motor vehicles	• Eye/nose/throat irritations, • Respiratory problems, • Smog and acid rain, • Formation of secondary pollutants such as PM, O_3
Particulate Matter (PM)	Solid or liquid Particles	Primary and Secondary	• Combustion processes (fossil fuel, wood, or biomass) in agriculture, industry, households, transport • Desert dust, volcanoes, wildfires, and sea spray	• Eye/nose/throat irritations, • Respiratory diseases; from inflammation to lung cancer, • Cardiovascular diseases, • Increased risk of premature mortality
Ozone (O_3)	Gas	Secondary	• Precursor air pollutants NO_X and VOC in polluted atmospheres	• Eye/nose/throat irritations, • Respiratory problems, • Cardiovascular diseases

Table 2.1 Basic information about the four classical air pollutants [WHO, 2006; EEA, 2019a; NAGL, C. ET AL., 2019; MANISALIDIS, I. ET AL., 2020]

Air pollutants are categorized in various ways depending on their characteristics. According to their physical state, they can be gaseous or particulate. While gaseous air pollutants are present in the form of gas or vapor; particulate matters are suspended in the air in solid or liquid form [WHO, 2006]. Depending on their formation, they are classified as primary air pollutants which are emitted directly from sources, and secondary pollutants which are formed in the atmosphere due to the existence of the primary pollutants and chemical reactions [WHO, 2006].

Sources of air pollutants can be categorized in different ways as well. Principally, these pollutants can be emitted either from non-anthropogenic (i.e. natural) sources such as deserts and volcanoes or from anthropogenic sources (i.e. caused by humans) such as industry and transport. Secondarily, sources can be categorized according to their spatial characteristics as point sources (e.g. power plants), line sources (e.g. roads), or area sources (e.g. waste deposit areas) [WHO, 2006; SCHWELA, D., 2009]. Alternatively, they can be categorized according to the related sector (e.g. industrial, transport-related, agricultural sources) or their impact areas (e.g. regional, local sources).

Air pollutants cause several short or long-term health problems: from less harmful effects such as eye, nose, throat, and skin irritations to more severe problems such as respiratory and cardiovascular problems, pregnancy-related problems, and cancer [WHO, 2006; NADADUR, S. S. AND HOLLINGSWORTH, J. W., 2015; MANISALIDIS, I. ET AL., 2020]. In addition to direct health effects, they contribute to the acidification of the ecosystem (e.g. water and soil), higher ozone levels, and eutrophication leading to several environmental and ecological problems [EEA, 2015, 2019a]. In other respects, air pollution damages the built environment and cultural heritage (e.g. due to corrosion, soiling) as well as the economy (e.g. due to health expenditures, crop yield losses) and fortifies climate change since many pollutants are also “climate forcers” [EEA, 2019a].

2.1.1 Air Pollution as a Global Problem

Air pollution is a protracted issue, contrary to the common belief that it is a recent problem. It starts with the use of fire; its smoke is the very first source of air pollution mankind induced [BOUBEL, R. W. ET AL., 1994; MAKRA, L. AND BRIMBLECOMBE, P., 2004; MOSLEY, S., 2014; WHO, 2000]. Although air pollution exists for a long time, its main reasons and dimensions have changed over the centuries. The history of air pollution can be divided into three basic phases: the pre-industrial era (before 1780), the industrial era where the problem escalated (1780 - 1950), and the current era where some actions started to be taken to solve the problem (after 1950) [MOSLEY, S., 2014; BOUBEL, R. W. ET AL., 1994].

In ancient settled societies, the main air pollution problem was indoor air pollution (i.e. household air pollution) -caused by cooking and heating with domestic fires, not having chimneys or good ventilation in dwellings, and using smoke to keep insects away [MOSLEY, S., 2014; MAKRA, L. AND BRIMBLECOMBE, P., 2004; BOUBEL, R. W. ET AL., 1994]. Outdoor air pollution (i.e. ambient air pollution) became an issue with the development of cities [MOSLEY, S., 2014]. In early cities, the main reasons for air pollution were burning wood, pottery, smelting and mining of metals (e.g. lead and copper) which were used immensely for the production of tools, weapons, and coins as well as infrastructure [MOSLEY, S., 2014; MAKRA, L. AND BRIMBLECOMBE, P., 2004]. Consequently, air pollution and its effects have been a concern even for the citizens of preindustrial cities. There are classical writings about how poet Horace mentioned Roman marble buildings turning black due to smoke or how philosopher Seneca's health improved after leaving the polluted atmosphere of Rome [BOUBEL, R. W. ET AL., 1994, p. 3]; [COLBECK, I., 2007] stated in [MOSLEY, S., 2014, p. 145]; [HEIDORN, K. C., 1978] stated in [MAKRA, L. AND BRIMBLECOMBE, P., 2004, p. 645]. Even in the pre-industrial era, the pressure of financial demands overtook environmental concerns and air pollution could not be avoided completely [MAKRA, L. AND BRIMBLECOMBE, P., 2004].

Air pollution in cities worsened with industrialization, as coal replaced wood as the primary energy source resulting in smoke and ash emissions [BOUBEL, R. W. ET AL., 1994]. Mosey [2014] calls this time "the age of smoke" when the air pollution was visible, like a black blanket over industrialized cities. During this era, air pollution caused several problems such as damaging buildings in cities, harming vegetation in a larger area, causing dark days without sunshine, and urban fog [MOSLEY, S., 2014]. These were the common problems in cities of the three main coal producers of that time: the UK (e.g. Manchester, Leeds), the USA (e.g. Chicago, Pittsburg), and Germany (e.g. Ruhrgebiet) [MOSLEY, S., 2014]. In 1842, the first "anti-smoke group" was founded in Britain followed by similar activist groups in the USA and later in Germany [MOSLEY, S., 2014]. As a result, the first local regulations against smoke (i.e. smoke abatements) emerged in these countries around the end of the 1800s [BOUBEL, R. W. ET AL., 1994; MOSLEY, S., 2014]. Nevertheless, air pollution was once again seen as a compromise of economic growth and there was no political or public support for stricter and broader regulations [MOSLEY, S., 2014].

After the Second World War, the air pollution problem started to be tackled. Following several air pollution disasters affecting thousands (e.g. the Donora Smog in the USA, 1948 and London's Great Smog, 1952), the first national air pollution action plans against smog started to be introduced in the USA (Air Pollution Control Act in 1955) and the UK (Clean Air Act in 1956) [MOSLEY, S., 2014]. At the same time, several technological changes showed their effects; electricity and diesel engines replaced steam engines, natural gas replaced coal for heating and automobilization increased [BOUBEL, R. W. ET AL., 1994; WILLIAMS, M., 2009]. These changes and efforts to control air pollution reshaped the air pollution problem. Air pollution changed location and color. The black smoke from the industrial era was defeated, but less visible vehicle emissions (e.g. NO_X and SO_X) replaced them; power generation outside of the city reduced the local smoke but outlying power stations with high chimneys caused regional air pollution problems [MOSLEY, S., 2014; BELL, S. AND MCGILLIVRAY, D., 2008; BOUBEL, R. W. ET AL., 1994; WILLIAMS, M., 2009]. As Mosley [2014] states finely: the world switched from "*the age of smoke*" to "*invisible air pollution*".

Consequently, while the air pollution problem was handled more like a local problem during the 1950s and 1960s, after the 1970s it also began "to be acknowledged as a large-scale issue" [MAAS, R. AND GRENNFELT, P., 2016; WILLIAMS, M., 2009]. This was initiated by the realization of the contribution of transboundary transfer of air pollutants in acidification and the inability of individual countries to solve this problem alone [KUYLENSTIERNA, J. C. I. ET AL., 2002, p. 46; MAAS, R. AND GRENNFELT, P., 2016]. The

Geneva Convention on Long-range Transboundary Air Pollution [UNECE, 1979] is “the first international legally binding instrument” to achieve air pollution control on a large international basis [BOUBEL, R. W. ET AL., 1994; UNECE, 2015, p. 11]. This convention did not only result in broad control and reduction of emissions (e.g. Sulfur causing acidification) but also led to transparent emission and air quality information exchange across countries which was once considered as sensitive information [WILLIAMS, M., 2009, p. 4]. To summarize, between the 1950s and 1980s, in many countries air pollution research evolved, the first organizations and conferences were formed, air quality monitoring and control techniques were developed and air pollution limitations were introduced [MOSLEY, S., 2014]. To illustrate, the WHO Air Quality Guidelines for Europe is published in 1987; Germany’s first national law Federal Emissions Control Act (Bundes-Immissionsschutzgesetz) is published in 1974.

Despite having an extensive history, air pollution stays as a profoundly serious global problem today (see **Figure 2.1**). According to the UN [2018], in 2016 total outdoor air pollution led to 4.2 million deaths (7 million deaths, together with indoor air pollution) worldwide and “*9 out of 10 people living in urban areas lacked clean air*”. The State of Global Air Report [HEI, 2020b] declares air pollution as the fifth leading risk factor for mortality worldwide which makes it riskier than road traffic accidents, malnutrition, alcohol or drug use.

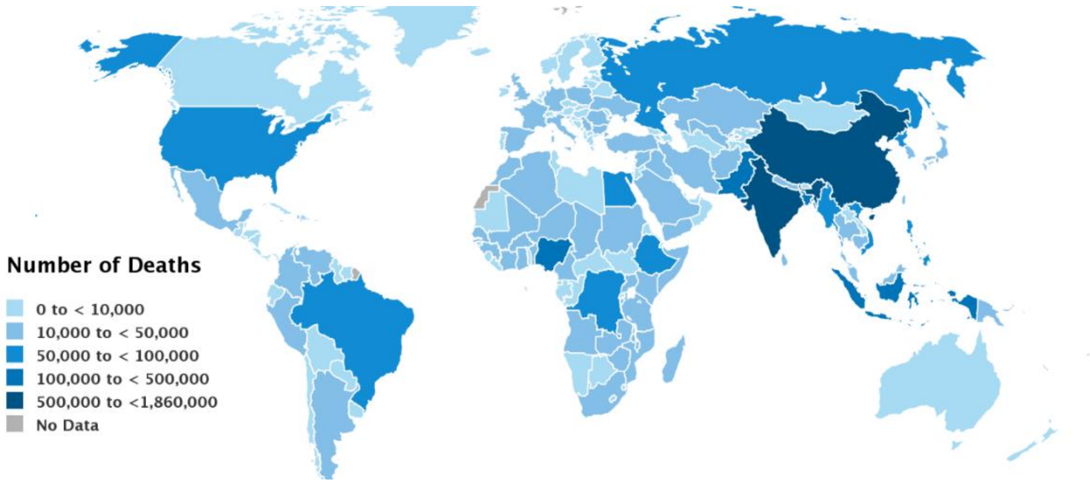

Figure 2.1 Number of deaths attributable to air pollution in 2019 [HEI, 2020a, p. 12]

It should be mentioned here that there have been several improvements in air quality in the last centuries, unlike the case of greenhouse gas emissions. However, while big steps are being taken in many countries, in others economic development has the priority and in some, even indoor air pollution is still a problem. Due to these different approaches, problematic air pollutants vary strongly from region to region. In several countries, PM concentrations have the greatest importance, whereas in others NO_2 is the dominant pollutant, and for some SO_2 is still problematic. To conclude, air pollution is a long-lasting global problem; but the scale, form, and management of this problem differ from region to region. This study deals with ambient (outdoor) air pollution, in Europe geographically, and focuses on road transport-related air pollution in urban areas.

2.1.2 Air Pollution in Urban Areas

Before going into details of road transport-related air pollution in European cities, it is important to understand the characteristics of ambient air pollution in urban areas. Air pollution occurs as a consequence of complex processes. To put it concisely, the level of air pollutant concentrations in urban areas is influenced by the amount of air pollutants emitted from anthropogenic and natural sources, their chemical reactions and formation of secondary pollutants in the atmosphere as well as their dispersion processes in the built environment. The infographic from the European Environment Agency in **Figure 2.2** explains this process; from emissions of pollutants to final pollutant concentrations to which people and the environment are exposed.

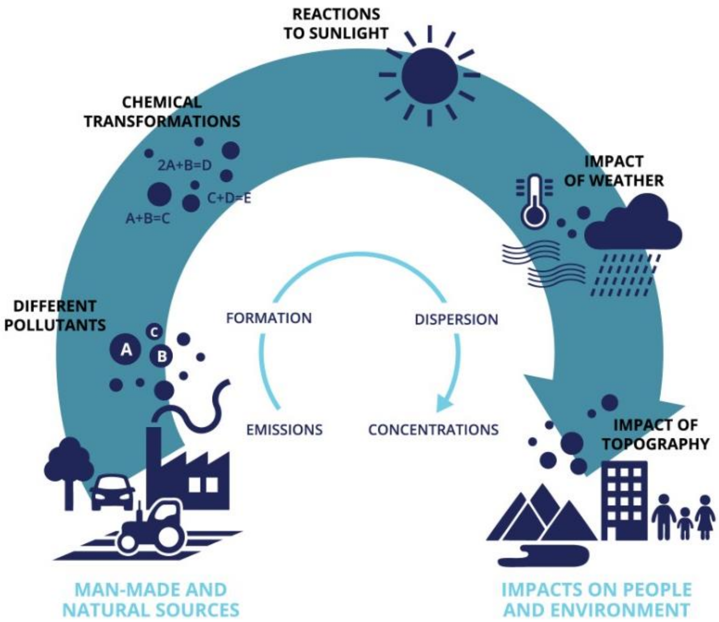

Figure 2.2 Conceptual illustration of air pollution from emissions to exposure [EEA, 2016b, p. 7]

Final air pollutant concentration in an urban area is the difference between the amount of air pollutants emitted (primary pollutant emissions), plus additionally formed air pollutants (secondary pollutant formations) and the amount of pollutants that are removed through the dispersion process [HERTEL, O. AND GOODSITE, M. E., 2009; SALMOND, J. A. AND MCKENDRY, I. G., 2009]. In simple words, the more pollutants are formed and the less they can be dispersed in the atmosphere (vertically and horizontally), the higher the concentrations in a specific location get [SALMOND, J. A. AND MCKENDRY, I. G., 2009].

When primary emissions are considered, the release height of the pollution source is an important factor. Emissions from point sources with tall chimneys (e.g. power plants, urban industries) are emitted to higher levels of the atmosphere, transported to longer distances, and contribute mostly to regional air pollution. On the other hand, “lower emission sources” such as transport, domestic heating, and light industry/commerce dominate the local ground-level air pollution in urban areas in developed/industrialized regions [HERTEL, O. AND GOODSITE, M. E., 2009; BLOSS, W., 2009]. However, the relative contribution of each sector to the total concentration in an urban area as well as the share of regional or local sources may change from pollutant to pollutant and from location to location (see **Chapter 2.2**).

The air pollution problem is especially critical in urban areas due to the densely built environment and lower emission sources such as road vehicles. In addition, total air pollutant concentrations observed in urban areas are the aggregation of regional background concentrations (e.g. agriculture, power plants), urban background concentrations (e.g. heating), and local pollution concentrations (e.g. road traffic and local point sources such as small industry). A commonly used schematic illustration can be found in **Figure 2.3**. However, it should be kept in mind that the Figure illustrates an exemplary aggregation; the share of regional, urban, or local air pollution in total concentrations varies by the pollutant and the location.

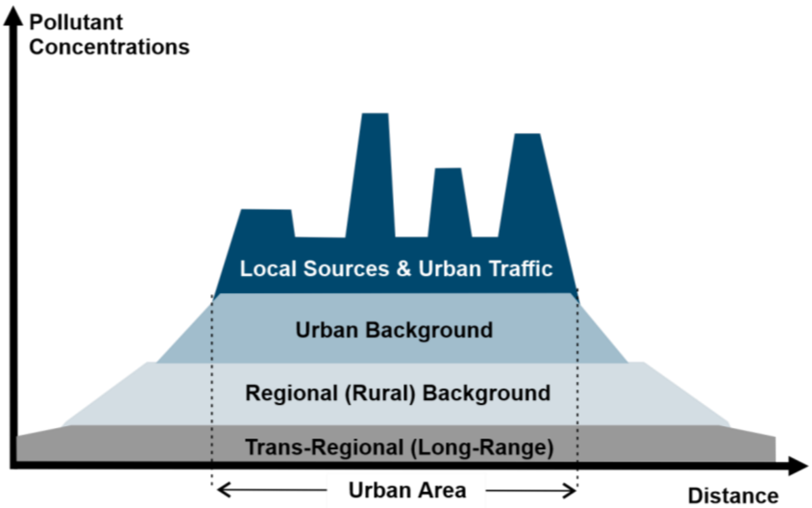

Figure 2.3 A schematic illustration of the contribution of different sources to total air pollutant concentrations in an urban area
adapted from [HERTEL, O. AND GOODSITE, M. E., 2009; NULIS, E. ET AL., 2014; HARRISON, R. M., 2018; WANG, Y. ET AL., 2020]

In addition to the emissions of primary pollutants and the formation of secondary pollutants through chemical processes, the dispersion (i.e. removal) of air pollutants is also very decisive on air pollution levels. For these aspects, the geography, topology, and meteorology of the urban area are important factors [HERTEL, O. AND GOODSITE, M. E., 2009]. Salmond and McKendry [2009] state that the urban atmosphere has a very complex structure and as a result, the relationship between meteorology and urban air pollution can not be explained by one factor; it happens in different scales. While the background state of the atmosphere and pollution is determined by long-range/mid-range transport of pollutants and regional meteorological conditions (e.g. sea breezes), local dispersion conditions are regulated by the built environment and microscale dispersion factors such as wind, turbulence, and built environment [SALMOND, J. A. AND MCKENDRY, I. G., 2009; HERTEL, O. AND GOODSITE, M. E., 2009; WANG, Y. ET AL., 2020].

To summarize, air pollution in urban areas is mainly dominated by emissions from road transport, domestic heating, and local small industries. Other emitters contribute to regional (long and mid-range) air pollution which is added to concentrations in urban areas as background air pollution. On the city scale, chemical reactions and dispersion of pollutants are influenced by geography, topology, and meteorology of the area, whereas air pollutant concentrations in street canyons are mostly affected by local/microscale dispersion conditions.

2.2 Road Traffic Related Air Pollution[1]

The continuous urbanization in all parts of the world generates numerous challenges for all cities, from small urban settlements to mega-cities, since the available space and infrastructure is unable to handle fully the population growth. In 2014 more than half (54 %) of the world's population resided in urban areas (increased from 30 % in the 1950s) and this number is projected to reach 66 % by 2050 [UN, 2014]. Despite the great variety of urban environments and the different challenges that they face, urban mobility is a common issue with high priority.

Transport is a derived demand; it takes place as a result of the need for delivering goods (i.e. freight transport) and for reaching a destination to access a service or to do an activity (i.e. passenger transport). While this accessibility is a great benefit that contributes considerably to economic and social development; transport has several negative effects such as accidents, congestion, and numerous environmental impacts. These effects are called external effects of transport (or external costs of transport, when they are considered in monetary terms) since they are not the primary concern of users' transport decisions, but rather a consequence which in the end affects other people or the whole society [MAIBACH, M. ET AL., 2008, p. 7; BECKER, U., 2016; VERHOEF, E., 1994]. Therefore, the external effects of transport should be considered carefully during the planning, implementation, evaluation, and monitoring of transport services.

According to Maibach, et.al. [2008, p. 18] external impacts of transport can be categorized depending on the problem area as scarce infrastructure, safety, and environment. While there had been some improvements, especially in developed countries, on issues of scarce infrastructure and safety,

[1] Background information summarized in this chapter were collected during the research under the research project "Living Lab Connected Mobility" under the use-case "Eco-sensitive Traffic Management". Sections of this text were originally published in the state-of-the-art report of the project:

CELIKKAYA, N.; PAPAPANAGIOTOU, E.; BUSCH, F. [2016]: Eco-Sensitive Traffic Management. In: Project Consortium TUM Living Lab Connected Mobility. (Eds.) Faber, A., Matthes, F. and Michel, F.: Digital Mobility Platforms and Ecosystems. State of the Art Report, pp. 172–187. [CELIKKAYA, N. ET AL., 2016].

environmental effects gained significant importance globally as a result of unignorably visible effects and higher awareness in society. Negative impacts of transport occur over different segments in the environment. Some are directly linked to landscape, mostly caused by the infrastructure itself; such as land consumption, land sealing, and separation effect on habitats while others are caused by the use of vehicles and fuel such as climate change, air and noise pollution [MAIBACH, M. ET AL., 2008, p. 7; BECKER, U., 2016; VERHOEF, E., 1994]. In this thesis, the focus is on the air pollution caused by road transport vehicles.

2.2.1 Road Vehicle Emissions

All transport vehicles produce emissions in the form of gases, particles, noise, and heat [PALOCZ-ANDRESEN, M., 2013]. When atmospheric emissions are considered, road vehicles emit several different air pollutants as well as greenhouse gases [EEA, 2016b]. Greenhouse gases (GHGs) "*absorb and emit radiation in the atmosphere*" which causes changes in the earth's climate and global warming [IPCC, 2014, p. 1263]. Unlike air pollutants, not all greenhouse gases directly threaten health and therefore they are considered often separately. The three primary GHGs are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) [GWILLIAM, K. ET AL., 2005; IPCC, 2014]. This dissertation focuses on air pollutant emissions, not greenhouse gas emissions.

European Environment Agency (EEA) explains and sums up the emissions by road vehicles as in **Figure 2.4**. The Figure can be associated more with road vehicles in Europe. For example, it does not include lead (Pb) or sulfur dioxide (SO_2) which are two pollutants linked directly to fuel composition and removed from the fuel in Europe [GWILLIAM, K. ET AL., 2004].

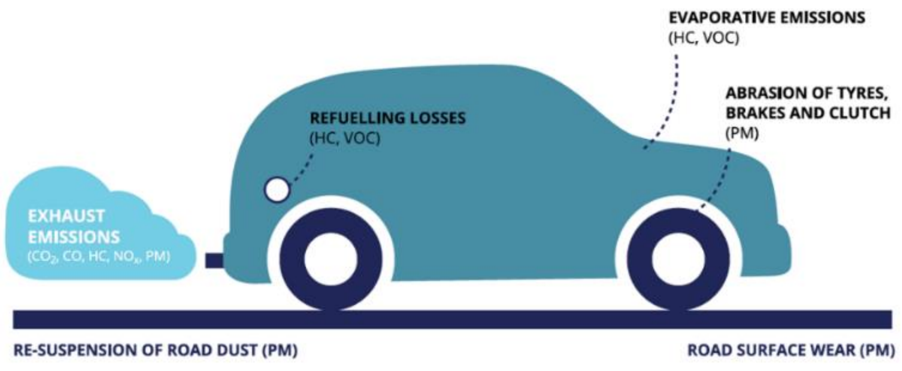

Figure 2.4 Different types of emissions from road vehicles [EEA, 2016b, p. 12]

Vehicle emissions are categorized by the mechanism of production as exhaust and non-exhaust (abrasion, wear, re-suspension, and evaporative) emissions. CO_2, CO, and NO_X are products of the combustion process and are emitted only from the exhaust, whereas Hydrocarbons (HC) can additionally be emitted due to refueling or evaporation [FREY, H. C. ET AL., 2001, p. 5; EEA, 2016b]. Volatile Organic Compounds (VOC) which are emitted as gases occur as a result of refueling and evaporation from vehicles. Particulate matters (PMs) have several different sources like exhaust, abrasion of car parts, and wear from the road surface [EEA, 2016b]. Particulate matters that are emitted from exhaust contributes mostly to smaller particles (i.e. fine particulate matters with aerodynamic diameter <2,5 µm), while particulate matters from abrasion and road contribute mainly to $PM_{2.5}$ and PM_{10} [PANT, P. AND HARRISON, R. M., 2013]. It is also important to note that, like different fuel compositions (e.g. leaded vs. unleaded fuel), different engine types can have different exhaust emissions as well. To illustrate, while an Euro 6 diesel vehicle emits more NO_X and PM; an Euro 6 petrol vehicle emits more CO [EEA, 2016b].

In fact, vehicle emissions are affected by several factors which can be divided into two main categories as technical (i.e. vehicle and fuel related) parameters and operational factors (i.e. related to the vehicle's operation environment and conditions) [CLOKE, J. ET AL., 1998; FREY, H. C. ET AL., 2001]. A summary of these factors can be found in **Table 2.2**.

Technical Factors	**Operational Factors**
• Vehicle Properties (e.g. Class, Age, Mileage, Shape, Size and Weight) • Maintenance Level • Engine Type and Size • Fuel Type and Composition/Content • Exhaust After-Treatment	• Average Speed and Speed Variation • Instantaneous Speed and Acceleration • Starting mode of the vehicle (cold or hot) • Driving Behavior, Gear Selection • Vehicle Load, Use of Air Conditioner • Environment (e.g. Temperature, Gradient, Altitude)

Table 2.2 Example factors affecting road vehicle emissions
adapted from [CLOKE, J. ET AL., 1998; FREY, H. C. ET AL., 2001; MFE NZ, 2008]

Compared to less congested highways and country roads, fuel consumption and thereby emissions are approximately 20 - 30 % higher in urban areas due to different operational factors [PALOCZ-ANDRESEN, M., 2013]. This is another reason, why TRAP in urban areas is even more important and why urban traffic management is a helpful tool for reducing emissions.

2.2.2 Air Pollution in Europe: Trends, Regulations, and Share of Road Transport

In Europe, specifically in the EU, major air pollutant emissions have decreased over the last decades (see **Figure 2.5**) and air quality has improved [EC, 2018, p. 1]. Nevertheless, air pollution is still a major issue and is stated as "*the single largest environmental health risk in Europe*" by European Environment Agency [EEA, 2019a, p. 13]. The three air pollutants that are highly related to health problems in Europe are NO_2, PM, and ground-level Ozone [EEA, 2019a, p. 8].

The European Union considers air pollution as a political concern since the 1980s and communicates this through a number of directives. Similarly, the first WHO Air Quality Guidelines for Europe [WHO, 1987] which is published in 1987 set the basis for European policy and legislation on air quality [WILLIAMS, M., 2009, p. 4–5].

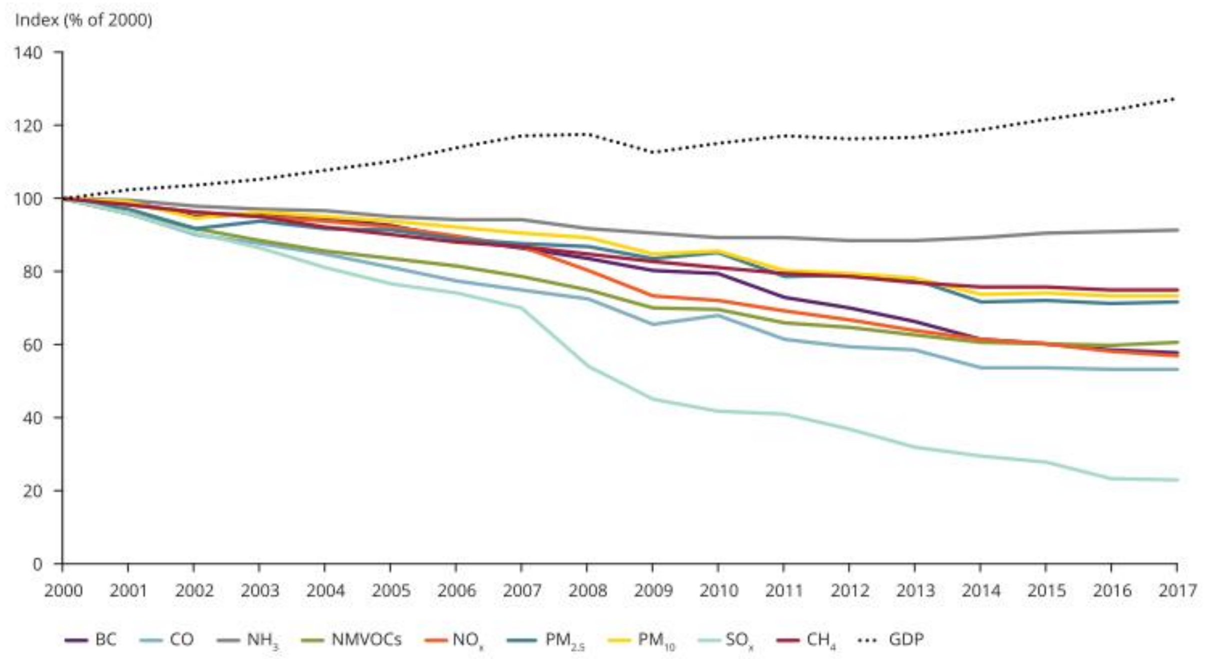

Figure 2.5 Trends in major air pollutant emissions (EU-28), 2000-2017
[EEA, 2019a, p. 19]

Currently, in the European Union, air pollutants are regulated by threshold values that are set by the European Commission (Directive 2008/50/EC) and the values are being updated regularly [EC, 2008]. Given the fact that the severity of health damages depends on the type of air pollutant (i.e. toxicity of the pollutant) as well as the amount and the duration of the exposure [GWILLIAM, K. ET AL., 2005, p. 15]; different pollutants have different regulations - defined by the concentration, averaging period and permitted limit exceedance (i.e. a maximum number of exceedances of the threshold value). EU Standards and WHO Guidelines for the five classical air pollutants can be seen in **Table 2.3**.

	EU Standards (2008)			WHO Guidelines (2005)		
Pollutant	**Value**	**Averaging Period**	**Permitted Exceedances**	**Value**	**Averaging Period**	**Permitted Exceedances**
SO_2	125 µg/m³	1 day	3 times/year	20 µg/m³	1 day	N/A
	350 µg/m³	1 hour	24 times/year	500 µg/m³	10 mins	N/A
NO_2	40 µg/m³	1 year	N/A	40 µg/m³	1 year	N/A
	200 µg/m³	1 hour	18 times/year	200 µg/m³	1 hour	N/A
PM_{10}	40 µg/m³	1 year	N/A	20 µg/m³	1 year	N/A
	50 µg/m³	1 day	35 times/year	50 µg/m³	1 day	3 times/year
$PM_{2.5}$	25 µg/m³	1 year	N/A	10 µg/m³	1 year	N/A
	N/A	N/A	N/A	25 µg/m³	1 day	3 times/year
O_3	120 µg/m³	8 hours	25 days/3 years	100 µg/m³	8 hours	N/A
	Differentiating values					

Table 2.3 Ambient (outdoor) air quality standards for five classical air pollutants
[EC, 2008; WHO, 2006]

In addition to introducing common standards on ambient air quality, European Commission Directive aims to define common criteria for air quality assessment, to ensure publicly available air quality information as well as to promote air quality improvement, maintenance, and cooperation between members [EC, 2008]. Member states have several responsibilities such as assessing air quality regularly and introducing long-term air quality plans as well as action plans that consider short-term measures in case of a threshold exceedance of regulated air pollutants [EC, 2008]. In addition, it is required that information about the amount and location of the excess pollution, type of area and possible origins of the pollution are included in air quality plans [EC, 2008]. The directive also entails that ambient air quality sampling points are located in several representative "*zones and agglomerations*" such as industrial sites, urban background and rural background locations [EC, 2008].

In order to be able to provide this information, numerous air quality measurement/monitoring stations (AQMS) measure ambient air quality in Europe: from urban locations to suburban and rural areas. **Figure 2.6** illustrates these stations in the same visual from **Chapter 2.1.2.** Depending on the major sources of the pollutant, the contribution of regional emissions and urban emissions to total air pollutant concentration can change. Locations with the highest concentration levels are often described as air pollution hotspots. When road traffic related air pollutants are considered (e.g. NO_2), these hotspots are mostly in densely built urban areas with high traffic volumes and congestion.

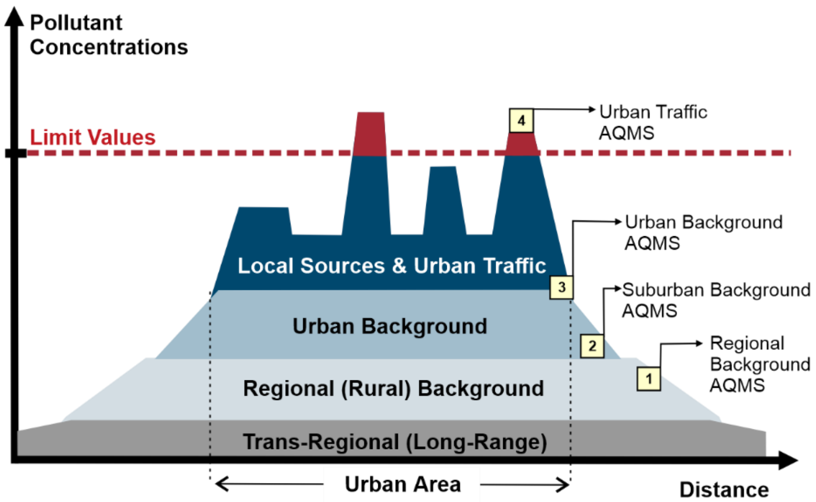

Figure 2.6 Illustration of different locations of air quality measurement stations (AQMS)

Although average air pollutant emissions from road transport are decreasing, the above-given limits are still being exceeded in these hotspots in Europe. This difference is especially high for NO_2 due to the high emission share of road transport. **Figure 2.7** illustrates the NO_2 concentrations from different measurement stations in Europe. It can be seen that most of the observed annual mean concentrations in background stations are below limits, whereas the ones measured at traffic stations largely show a threshold exceedance.

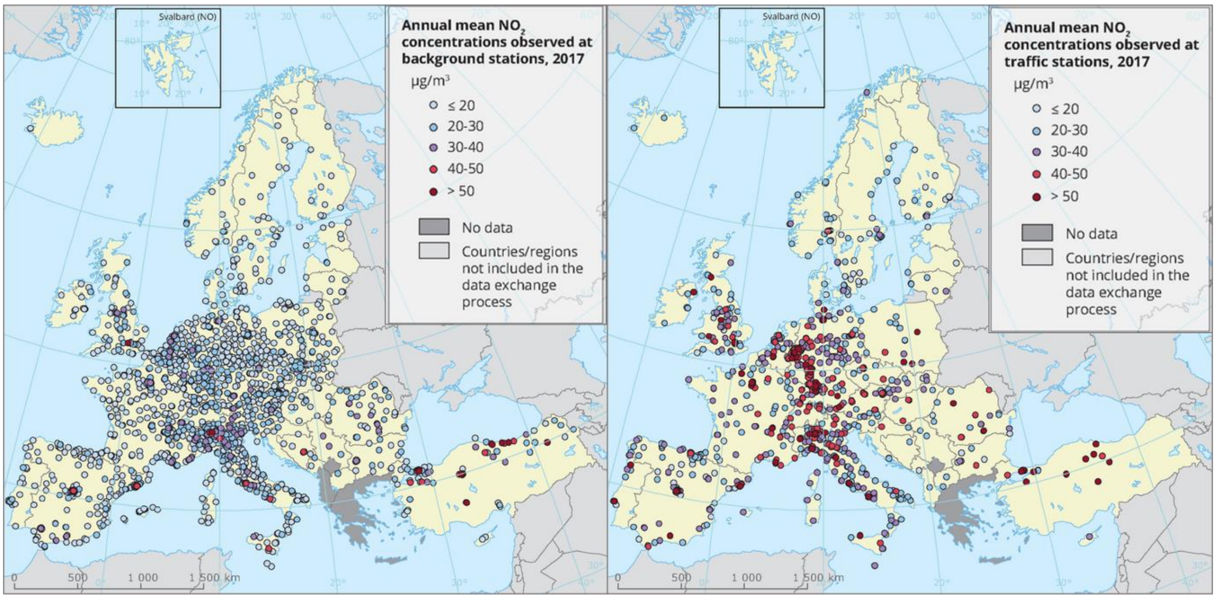

Figure 2.7 Annual mean NO_2 concentrations observed at background and traffic stations in 2017 [EEA, 2019b, 2019c]

When the share of different sectors to air pollutant emissions (primary emissions) is considered, road transport contributes mostly to NO_X emissions in Europe. **Figure 2.8** shows the contributions of sectors in 2017; where road transport has almost 40 % share in NO_X air pollutants. Germany is the largest contributor to NO_X emissions in Europe with a share of approximately 16 % [PINTERITS, M. ET AL., 2020, p. 42–43].

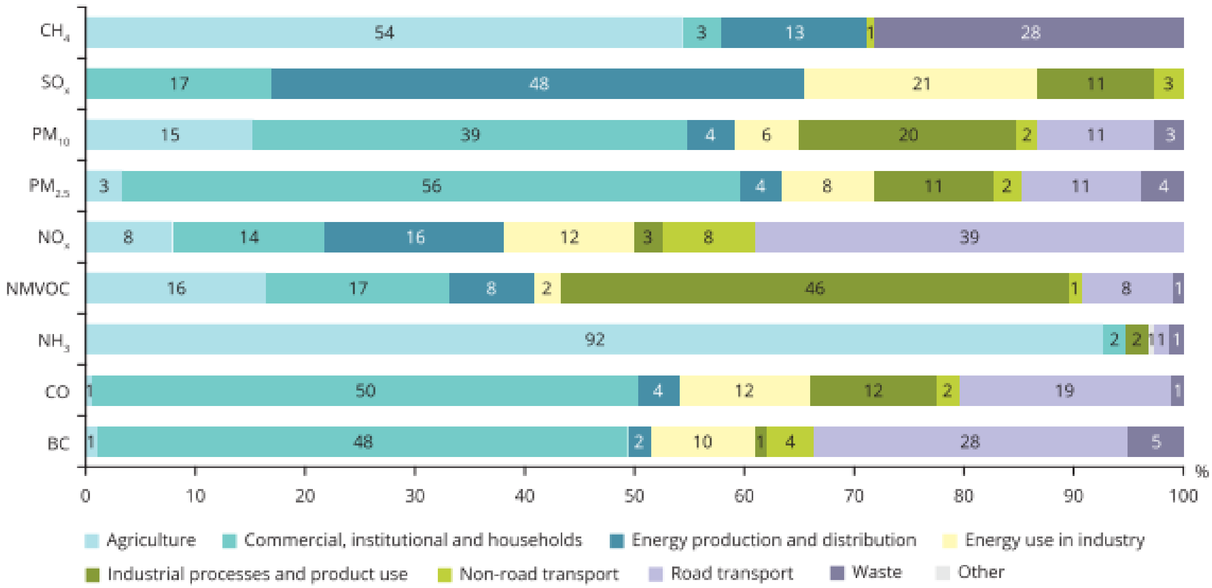

Figure 2.8 The main air pollutant source sectors and their contributions to emissions in EU-28 in 2017 [EEA, 2019a, p. 24]

As a result of these, this study focuses on NO_2 as major road transport related classical air pollutant and NO_X as major road transport related emission. Supportively, Koolen, C. D. and Rothenberg, G. [2019] who analyze the emission trends in Europe, the effectiveness of regulations as well as negative effects of pollutants in combination with a cost-benefit analysis conclude that the reduction of NO_X emissions is "the most urgent and beneficial issue" in terms of air pollution in Europe.

2.2.3 Policy Instruments to Reduce Road Transport Related Air Pollution

There are several policies and policy instruments to reduce air pollution caused by road transport. Policies can be categorized under four main focus areas as planning and regulation, infrastructure and operation, vehicle and fuel technology, and information and awareness. **Table 2.4** represents example policy instruments [BECKER, U., 2016; GWILLIAM, K. ET AL., 2004] for each focus area. It is important to mention that strategies commonly do not utilize only one policy instrument but combines many, especially the ones that are infrastructure or planning related. For instance, if the promotion of non-motorized modes (i.e. walking and cycling) is set as one strategy to reduce road transport related emissions, this can be achieved by the provision of attractive infrastructure, the introduction of supportive regulations, and raising awareness about the advantages of these modes.

Planning and Regulation	**Infrastructure and Operation**	**Vehicle and Fuel Technology**	**Information and Awareness**
• Air quality plans, • Taxations on the road, fuel, or vehicle use • Integrated land-use and transport plans, • Demand management	• Improved public transport services, • Improved infrastructure for non-motorized transport modes, • Traffic management	• Emission Standards, • Vehicle inspection and maintenance, • Promotion of cleaner vehicles and cleaner fuels	• Eco-driving behavior education, • Promotion of environment-oriented organizations

Table 2.4 Focus areas and example policy instruments for reduction of emissions from road transport

The German Federal Road Research Institute (Bundesanstalt für Straßenwesen - BASt) developed a digital database called MARLIS in 2006 (continuously updated since) which contains detailed information about air pollution control measures based on numerous air quality plans from Germany and several other countries [BASt, 2021]. According to the latest report [SCHNEIDER, C. ET AL., 2021], from almost six thousand measures dealing with high NO_2 concentrations covered in the database, a great proportion was focused on traffic restriction measures (around 850) followed by measures focusing on vehicle technology (around 800), public transport (around 700). The same study also points out that a big share of measures that have an above-average NO_2 reduction potential are traffic restrictions (e.g. speed limitations, vehicle access restrictions such as low-emission zones, HDV restrictions, or transit traffic restrictions).

2.3 Electric Road Vehicles[2]

One of the policy instruments to reduce road transport related air pollution is the promotion of cleaner fuels and vehicles. Therewith promotion of e-mobility is one of the most popular topics today. This study focuses on electric road vehicles. Finite fossil fuel supply, increasing crude oil prices, increasing emissions and their perceivable consequences (e.g. climate change, air pollution), as well as strict emission and air quality regulations, are the main motivations to rethink mobility today.

However, it should not be forgotten that e-mobility is not a new concept. The first electric vehicles and combustion engine vehicles were both introduced around the 1880s and electric road vehicles had their first golden age between 1890 and 1912 [MOM, G., 2004]. As a result of the introduction of practical self-starters for gasoline cars in 1912, decreasing costs and mass production of combustion engine cars as well as the availability of oil, electric vehicles have lost their popularity.

Throughout history, several times, alternative transport concepts have been searched for and evolved. GRÜBLER [1990] explains this constant change and evolution in transport with the following sentence: "*The crisis of the old provides the fertile ground for the emergence of the new*." At the end of the 1870s, the world was searching for alternatives to horse-powered transport which was uncomfortable and polluting; like today cleaner alternatives to fossil-fuel vehicles are being searched, to cope with air pollution and climate change [SERRA, J. V. F., 2012, p. 7; MOM, G., 2004, p. 8–9].

2.3.1 Electric Vehicle Technology

Vehicles, or machines in general, run by powertrains that convert energy from an energy source into mechanical energy. There are two main categories of powertrains according to their engines: internal combustion engine (ICE) and electric motor. An electric vehicle (EV) is a vehicle that has at least one electric motor and is partially or fully powered by electrical energy, where the power is drawn either from overhead cables or from mobile energy storage systems (ESS) such as batteries.

ICE converts the chemical energy (present in fuel) firstly into thermal energy which later provides the mechanical (i.e. kinetic) energy to move the vehicle [SERRA, J. V. F., 2012]. In this thermal process, heat

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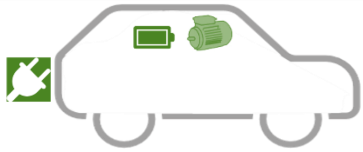
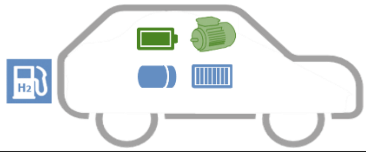
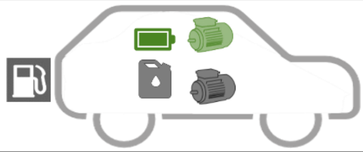
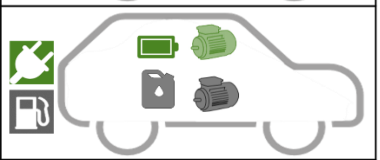
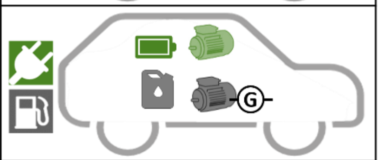
[2] Background information summarized in this chapter were produced within the project "Academic Education Initiative Showcase E-Mobility Bavaria-Saxony" (in German: Bildungsinitiative Schaufenster Elektromobilität Bayern-Sachsen). Sections of this text were originally used in the lecture slides developed under the project:

BUSCH, F.; CELIKKAYA, N. [2014]: Lecture Slides of Transport Planning and Traffic Engineering Concepts for Electric Mobility (PowerPoint Slides). Unpublished manuscript. Technical University of Munich. [BUSCH, F. AND CELIKKAYA, N. 2014].

and air pollutants are emitted. In electric motors, magnetic elements create repelling magnetic fields which generate magnetic forces resulting in a continuous rotational motion. In this way, the electric motor converts electrical energy directly into mechanical energy [SERRA, J. V. F., 2012]. While some electric road vehicles procure this electrical energy from batteries; some acquire it from fuel cells which use fuel (mostly hydrogen) to produce this electrical energy for the electric motor (see **Figure 2.9**).

	Classification	Description	Illustration
ALL-ELECTRIC VEHICLE	**Battery Electric Vehicle (BEV)**	A vehicle where the electric motor (EM) is powered only by an electrochemical battery.	
	Fuel Cell Electric Vehicle (FCEV)	A vehicle where the EM is powered by a fuel cell stack which uses hydrogen from a tank as energy source (additional battery is possible).	
HYBRID ELECTRIC VEHICLE	**Hybrid Electric Vehicle (HEV)**	Any vehicle that is able to use a combination of electrical energy from the EM and combustion energy from the internal combustion engine (ICE). HEVs are powered predominantly from ICE and the battery cannot be charged externally.	
	Plug-in Hybrid Electric Vehicle (PHEV)	PHEV is a hybrid EV which can be powered by an EM and/or by an ICE - together or separately. PHEVs can be charged by plugging into an external source of electric power.	
	Range-Extended Electric Vehicle (REEV)	A range-extended electric vehicle uses EM for propulsion and ICE solely to provide power to the battery (acting like a generator or through a generator) to recharge it and assure that it is not empty.	

Electric Motor (EM) · Battery · Charging · Internal Combustion Engine (ICE) · Fuel Tank
Fuel Cell Stack · Hydrogen Tank · Refueling (Hydrogen) · Refueling (Diesel/Petrol) · Generator

Figure 2.9 Electric road vehicle types
[SERRA, J. V. F., 2012; EEA, 2016a]

Electric road vehicles are divided into two main categories as all-electric vehicles (i.e. pure-electric vehicles, only-electric vehicles, fully-electric vehicles) and hybrid electric vehicles with several sub-classifications (see **Figure 2.9**). All-electric vehicles cover battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs), whereas hybrid electric vehicles cover hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and range-extended electric vehicles (REEVs). In general, hybrid vehicles have several sub-categorizations depending on the drive train configuration (e.g. parallel, series) and their hybridization/electrification level (e.g. micro, mild, full).

Due to not having an ICE and using only an electric motor, all-electric vehicles (BEVs and FCEVs) have zero exhaust emissions [EEA, 2016a]. Hybrid electric vehicles show a wide range in terms of their characteristics such as engine power, battery capacity, or range, resulting in great variety in terms of the share of electric driving and fuel/emission-saving potentials [ZHOU, B. ET AL., 2018; PLÖTZ, P. ET AL., 2020; HUSS, A. ET AL., 2014]. To illustrate, a recent study [PLÖTZ, P. ET AL., 2020, p. 34] found that tailpipe CO_2 emission-saving of PHEVs can range between 15 % and 55 % in real-world operation. Consequently, this thesis focuses on pure EVs that have no tailpipe/exhaust emissions; since their emission-saving potential is not fluctuating. The term zero-emission vehicles (ZEVs) will be used in the document for these vehicles.

Before focusing on the potential of ZEVs for emission reduction and air quality improvement in urban areas, it is useful to understand the main differences between these vehicles and conventional vehicles, to outline their strengths and weaknesses. In the end, these aspects are decisive on acceptance and broader usage. One of the remarkable advantages of ZEVs is the Tank-to-Wheel (TTW) energy efficiency. Due to high engine losses (i.e. heat loss) during energy conversion in a combustion engine, only a portion of the chemical energy from the fuel reaches the wheels as power. On the other hand, when the energy density of the energy source is considered, ZEVs have a disadvantage today. Currently, batteries have lower energy density in comparison to other fuels; they need more space in vehicles and are heavier [EIA, 2013]. Some other aspects are summarized in **Table 2.5**.

Strengths	**Weaknesses**
• Higher Energy Efficiency (TTW)	• Speed and Range
• Regenerative Energy Supply	• Lower Energy Density and Storage Capacity
• Performance (e.g. Acceleration)	• High Costs and Weight of the Battery
• Flexibility in Architecture Design	• Higher Production Costs and Purchase Price
• Less Mechanical Parts and Maintenance Costs	• Charging Duration
• Zero Exhaust Emissions and Low Engine Noise	• Availability of charging stations

Table 2.5 Example strengths and weaknesses of ZEVs in comparison to conventional road vehicles

As mentioned, motivations to use more ZEVs focus mostly on energy-related (e.g. finiteness of fossil fuels, dependencies) and environment-related (e.g. climate change, air pollution) aspects. This thesis focuses on air pollution-related potentials and limits this to vehicle-use-related air pollution. However, the author is aware that in addition to vehicle use, other phases such as fuel and energy production, vehicle and battery production, as well as vehicle and battery disposal/recycling are crucial to consider for a more comprehensive environmental impact analysis (e.g. a life-cycle analysis) of electric road vehicles.

When air pollution resulting from vehicle use (i.e. local emissions) is taken into account, ZEVs offer a noteworthy potential as a result of not having an internal combustion engine and resulting exhaust emissions. They do not produce exhaust-related air pollutants such as CO, NO_X, HC, and PM as well as CO_2 greenhouse gas (See **Chapter 2.2.1**). However, it should be kept in mind that even ZEVs do still contribute to non-exhaust-related particulate matter emissions (mostly PM_{10}) which result from abrasion of breaks or tires, road surface wear, and road dust resuspension [REQUIA, W. J. ET AL., 2018;

TIMMERS, V. R.J.H. AND ACHTEN, P. A.J., 2016]. This is another reason, why this dissertation focuses on the potential of ZEVs in reducing NO_2 concentration – in addition to NO_2 being the major road transport related air pollutant in Europe (see **Chapter 2.2.2**).

2.3.2 Trends and Incentives for E-mobility in Europe

The share of electric vehicles (EVs) and the popularity of battery electric vehicles (BEVs) is increasing gradually in Europe. In the 27 EU countries, the share of EVs in newly registered vehicles increased from 0,01 % to 10,7 % between the years 2010 and 2020 [EEA, 2021a] (**Figure 2.10**). In 2020, Sweden had the highest percentage of electric passenger cars in total new car registrations with around 34 %, whereas Germany was the leading country in terms of the absolute number of newly registered electric passenger cars with almost 400.000 registrations [EEA, 2021b].

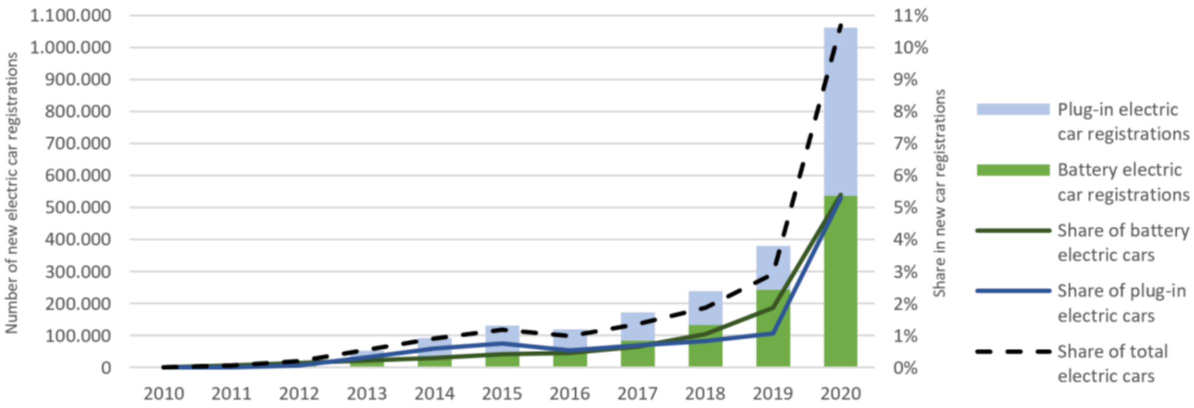


Figure 2.10 New registrations of electric vehicles in Europe [EEA, 2021a]

Numerous financial and non-financial incentives for the promotion of e-mobility are being implemented in several countries. In Europe, EVs are promoted at different levels; through several EU legislations, national incentives, and/or local actions [EEA, 2016a, p. 59–61]. EEA [2016a] summarizes measures that promote electric vehicles in four categories:

- Purchase Subsidies: co-funding new purchases, purchase-related tax exemptions or reductions, reductions or exemptions in registration tax or import tax, etc.
- Ownership Benefits: annual circulation tax exemptions or reductions, reduction of electricity or energy costs for charging, tax-deduction opportunities for individuals and companies, etc.
- Financial Support for EV-Industry: promotion of research and development, support for installation of EV charging infrastructure, etc.
- Local Incentives: free parking places or charging opportunities, access to bus lanes, road toll fee reduction or exemption, access to restricted areas in city centers, etc.

As an example, the promotion of e-mobility in Germany starts with the national e-mobility development plan [Bundesregierung, 2009] where goals and strategies were set, and continued with the government program on e-mobility where measures were defined. In 2015, the Electric Mobility Act (EmoG) came into effect, which sets the basis for local incentives for EVs. As one control mechanism, specific number plates for electric vehicles are introduced. With this number plate, local governments became able to implement and monitor EV-related privileges such as parking priorities, use of special vehicle lanes, or exceptions from access/transit restrictions. According to the latest report from the Federal Ministry for Digital and Transport [HARENDT, B. ET AL., 2018, p. 35], most of the local authorities implemented parking privileges for EVs (50 - 65 %), whereas only a few considered the use of bus lanes and/or exemptions from driving restrictions (3 %).

The latest Sustainable Mobility Strategy [EC, 2020] sets the goals for mobility and transport in Europe. The strategy paper states the importance of emission reduction: "*By far, the most serious challenge facing the transport sector is to significantly reduce its emissions and become more sustainable.*" [EC, 2020, p. 1]. It aims to reduce emissions from the transport sector by 90 % by 2050 and sets several milestones including road transport-related ones, such as [EC, 2020, p. 2–3]:

- "at least 30 million zero-emission vehicles will be in operation on European roads" by 2030,
- "nearly all cars, vans, buses as well as new heavy-duty vehicles, will be zero-emission" by 2050.

To reach this, it is pointed out that all policy instruments should be used at the same time, starting from increasing the share of low- and zero-emission vehicles in the fleet and promoting cleaner fuels to achieve a modal shift towards sustainable transport modes such as public transport, active modes and implementing monetary measures for the internalization of external costs such as "polluter pays" [EC, 2020].

2.4 Traffic Management[3]

Another policy instrument to reduce road transport-related emissions and resulting air pollution is traffic management since driving conditions of vehicles (operational factors) in urban areas highly

[3] Background information summarized in this chapter were collected during the research under the research project "Living Lab Connected Mobility" under the use-case "Eco-sensitive Traffic Management". Sections of this text were originally published in the state-of-the-art report of the project:

CELIKKAYA, N.; PAPAPANAGIOTOU, E.; BUSCH, F. [2016]: Eco-Sensitive Traffic Management. In: Project Consortium TUM Living Lab Connected Mobility. (Eds.) Faber, A., Matthes, F. and Michel, F.: Digital Mobility Platforms and Ecosystems. State of the Art Report, pp. 172–187. [CELIKKAYA, N. ET AL., 2016].

influence vehicle emissions (see **Chapter 2.2.1**). Traffic management aims to mitigate the negative impacts of traffic not only on the environment, but also on safety, traffic flow, and economic efficiency [MAIER, F. ET AL., 2008] by influencing and balancing transport demand and supply through sets of appropriate short-, medium- or long-term measures [FGSV, 2011].

Typically, traffic management measures look to reduce (or redistribute) demand and increase capacity. The three main strategies for traffic management can be summarized as traffic avoidance, traffic shift, and traffic control [FGSV, 2003]. The strategy of traffic avoidance aims to reduce the travel demand; shifting traffic intends to redistribute traffic in time, in space as well as between traffic modes and traffic control aims to optimize current traffic flow by influencing mainly the supply through traffic control actuators such as traffic lights.

Based on the working mechanisms of its measures, traffic management can be separated into main categories as static traffic management where long-term measures are in focus (e.g. introducing a reduced-speed area in the city center), and dynamic traffic management which emphasizes short-term measures for specific traffic situations (e.g. variable message signs that show different speed limits according to the traffic situation) [FGSV, 2011]. The field of avoiding traffic is almost completely served by measures of static traffic management while controlling traffic mostly relies on short-term measures provided by dynamic traffic management. Shifting traffic, however, is the field in which both static and dynamic measures cooperate closely. This thesis focuses on dynamic traffic management strategies.

2.4.1 Dynamic Traffic Management

According to FGSV [2003], dynamic traffic management (DTM) consists of influencing the current traffic demand and the available transport supply through the coordination of measures according to the situation, in order to achieve the best possible level of mobility for a specific period. For every traffic situation that may occur, a specific strategy has to be developed in advance and should be ready for implementation. The term *traffic situation* depicts the current traffic state including problems, events, and other relevant situations. A *strategy* is a predefined action plan for taking a traffic management measure (or combination of measures) with the purpose of improving the defined (initial) situation. The combination of a situation and the corresponding strategy is defined as a *traffic management scenario* [FGSV, 2003].

Since the time to select the traffic measures is limited in real-time, dynamic traffic management strategies are developed offline using mainly traffic simulation to reproduce the situation and evaluate the impact of each strategy. The plausible measures are then listed to be used later by the operators at the Traffic Management Center (TMC). The implementation of the measures can be summarized in 6 steps (**Figure 2.11**): the essential step is to observe the network condition which is necessary to identify the situation and problems in real-time. When a problem is identified, the provided list of possible strategies is evaluated and the best one will be implemented. The impact of the implemented strategy is also monitored to make the necessary changes, when needed. **Figure 2.11** illustrates the system architecture of dynamic traffic management strategy planning and implementation.

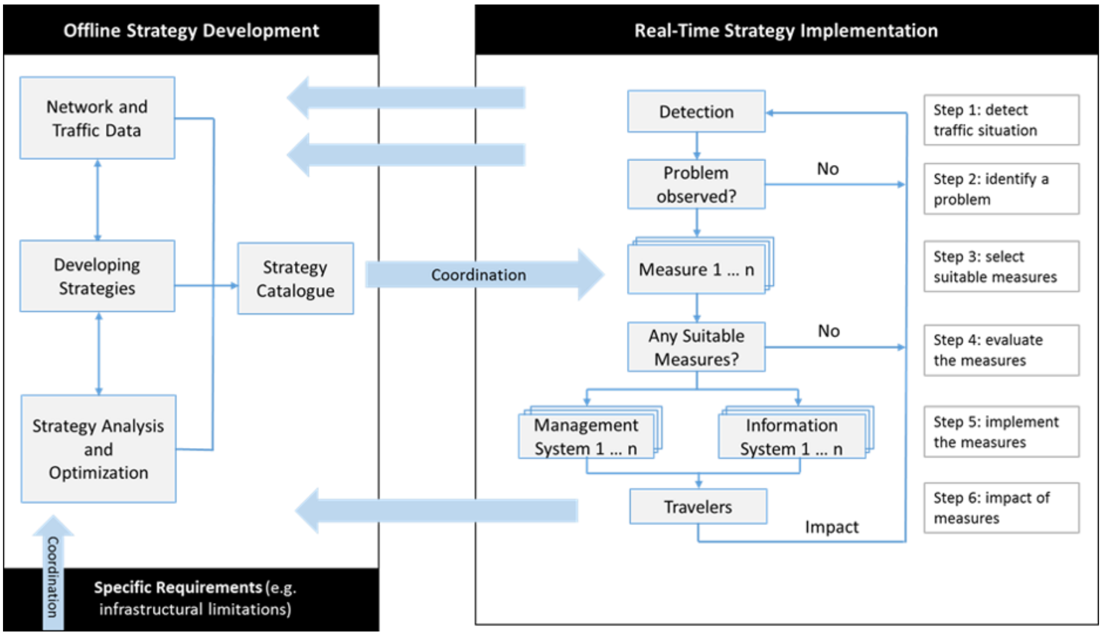


Figure 2.11 System architecture of traffic strategy planning and implementation adapted and translated from [FGSV, 2003]

Because of the wide range of dynamic traffic management measures that can be implemented, a number of categories can be defined in order to distinguish and choose between them. A measure can influence the movement of travelers before (pre-trip) or during (on-trip) the trip. Moreover, measures can be compulsory (regulation and control measures) or voluntary, where just information or a recommendation is provided. Measures can be sent to all travelers (collective measures) or to individual users (e.g. dynamic navigation systems).

Table 2.6 which is based on [FORNAUF, L., 2015, p. 23] and [FGSV, 2003, p. 11–13] shows a categorization of dynamic traffic management measures depending on the traffic mode with example measures. Private transport measures focus typically on optimizing the current traffic flow, while public transport measures focus on improving provided services. In addition, traffic management typically aims to give incentives to travelers to use more efficient modes (e.g. use car-sharing instead of a private car). Furthermore, measures in favor of cyclists and pedestrians can be adopted to make these sustainable modes more attractive and safer.

Examples of traffic management measures that can affect the network rapidly include those that can have a direct impact on the capacity of the network, such as traffic signal control (e.g. intersection control or ramp metering), variable speed limits, and lane closure/opening. On the other hand, examples of measures that affect the transport demand or the route choice by providing traffic information (pre-trip or on-trip) include variable message signs for alternative routes, park and ride information, and real-time traffic information on the internet.

Private transport measures	Public transport measures
• Rerouting of traffic streams • Allowance of temporary special lanes • Variable speed limits • Ramp metering • Dynamic adjustment of available parking spaces • Dynamic toll system • Pre-emption of emergency vehicles	• Redistributing public transport passengers • Rerouting public transport vehicles • Public transport prioritization • Increase of capacity of a line • Introduction of special lines, lanes, and stops • Increase in accessibility and attractiveness • Adjusting ticket prices
Multi-modal and inter-modal measures	**Non-motorized transport measures**
• Information about all modes and measures • Influencing the mode choice • Shifting the start of the trip • Changing the use of transport areas • Mobility pricing • Information about available car-sharing vehicles	• Prioritization of cyclists at intersections • Prioritization of pedestrians at intersections • Temporary special lanes for cyclists • Temporary pedestrian areas • Information about available bike-sharing systems

Table 2.6 Example measures for dynamic traffic management,
adapted and translated from [FORNAUF, L., 2015, p. 23] and [FGSV, 2003, p. 11–13]

2.5 Summary

Air pollution, which has been a problem for centuries, has several negative effects on health, the environment, and the economy. Although there have been improvements, it is still one of the leading mortality factors in the world and the largest environmental health risk in Europe. Air pollution is regulated by legal threshold values in Europe and around the world. For this, air pollutant concentrations are monitored in several locations. Air pollution is especially critical in urban areas due to high population, building and traffic density, poor ventilation conditions as well as the dominance of low emission sources such as road transport. A major air pollutant caused by road transport is NO_2 whose concentrations often exceed threshold values in urban centers in Europe.

There are several measures to cope with road traffic related air pollution problems: ranging from regulations and planning instruments to new vehicle/fuel technologies. Road vehicle emissions are influenced by the technical properties of vehicles such as engine and fuel type as well as operational factors such as speed, acceleration, and driving conditions.

One policy instrument is the promotion of electric vehicles. Especially ZEVs have high emission reduction potential and their share on EU roads is increasing constantly. ZEVs have some limitations such as range, charging infrastructure, and costs but also increasing potential through intensified research and development, stricter emission regulations, increasing charging opportunities, the introduction of several incentives, and increasing environmental awareness. In terms of emissions, the focus is on the promise of CO_2 reduction today. However, it is also important to analyze how much these vehicles can contribute to reducing local air pollution in urban areas caused by road transport.

The literature review shows zero-emission vehicles (ZEVs) have higher air pollutant reduction potential (by being emission-free at the tailpipe) compared to other electric vehicle types (i.e. hybrid vehicles), especially for NO_2 which is the most critical road-traffic-related air pollutant in Europe (answering *Research Question 1*).

Another air pollution-related measure is traffic management, which can improve operational conditions to reduce road vehicle emissions. Reducing environmental effects of transport is one of the goals of traffic management which is to be achieved by managing transport demand to use transport capacity effectively. Several researchers such as WISMANS ET AL. [2011] and BOLTZE AND TUAN [2016] point out the importance of considering the term capacity not only as traffic characteristics; but also to include other sustainability aspects (i.e. externalities of transport) such as environmental capacity which can cover air pollution.

The terms “Environmental Traffic Management” and “Environmental Capacity” have been discussed since the 1940s within the context of air pollution and noise problems [MCKEE, W. A. AND MATTINGLY, M. J., 1977]. For example, in 1977, McKee and Mattingly concluded that a static environmental traffic management which only redirects/relocates vehicles in an urban network was not a solution to the pollution problem in London and recommended long-term measures such as improving emissions of motor vehicles and travel behaviors of residents [MCKEE, W. A. AND MATTINGLY, M. J., 1977].

> *“…It is as though environmental traffic management in the circumstances we have witnessed attempts to treat symptoms rather than the causes of environmental decline. Where the roads and land are built up and public expenditure severely limited, it seems easier to change the forms of the vehicles and the manner in which they are used than to change the road system… From such point of view, noise and pollution might be best attacked with national legislation reducing the emissions of all kinds of motor vehicles…”*

Agreeing on the idea of the cruciality to aim reducing emissions in addition to managing or redistributing emissions, this thesis focuses on a combined consideration of the two policy instruments against air pollution: cleaner vehicles and environmental traffic management. Environmental traffic management includes all applications aiming to reduce the negative environmental effects of traffic by reducing, shifting, and redistributing demand (see **Chapter 2.4**) such as the introduction of low-emission zones, congestion charging, or promoting non-motorized transport modes and public transport.

Today environmental traffic management is possible in a dynamic manner, which can adaptively regulate demand and environmental capacity, without changing the road system completely. Dynamic environmental traffic management measures and integrating electric vehicles with zero tailpipe emissions (ZEVs) into these measures can offer several advantages. On one hand, short-term relocation of emissions can be avoided; on the other hand, a shift to cleaner vehicles can be encouraged in the long term. In the following chapter, the concept of dynamic environmental traffic management will be explained in detail.

3. State of the Art: Dynamic Environmental Traffic Management[4]

Environmental traffic management (ETM) is a phrase used for traffic management applications that focus on one specific goal of traffic management: reducing the negative environmental effects of road transport where the focus is mainly on coping with emissions today. It is important to note here that, there is no single terminology for these traffic management applications. Some other used phrases are environmentally-sensitive traffic management [NULIS, E. ET AL., 2014; FGSV, 2014], eco-sensitive traffic management [CELIKKAYA, N. ET AL., 2016], environment-responsive traffic control [BOLTZE, M. AND KOHOUTEK, S., 2010], environment-oriented traffic management [VMZ, IVU, LK Argus, 2012] or emission minimizing traffic control [HIRSCHMANN, K. AND FELLENDORF, M., 2009]. Dynamic traffic management systems focusing on air pollution reduction are mentioned as dynamic environmental management (DETM) in this document.

In DETM, specific measures that aim to reduce road vehicle emissions and improve air quality (especially in hotspots where pollutant concentration thresholds are exceeded) are activated according to the air pollution situation, for a specific location, and for a defined time period [FGSV, 2014]. By using dynamic measures, it aims to offer a midway solution by contributing to emission reduction and helping to comply with air pollution regulations while still using the road network as efficiently as possible – which is not always possible with static measures [FGSV, 2014; BOLTZE, M. AND KOHOUTEK, S., 2010; LUDES, G. ET AL., 2010]. Examples of these traffic management measures are dynamic re-routing, temporary driving restrictions for heavy-duty vehicles, dynamic metering, temporary speed limitations and/or signal control coordination/optimization [FGSV, 2014; BOLTZE, M. AND KOHOUTEK, S., 2010; DIEGMANN, V. ET AL., 2020].

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[4] Sections of this text were originally published in following papers:

CELIKKAYA, N.; PAPAPANAGIOTOU, E.; BUSCH, F. [2016]: Eco-Sensitive Traffic Management. In: Project Consortium TUM Living Lab Connected Mobility. (Eds.) Faber, A., Matthes, F. and Michel, F.: Digital Mobility Platforms and Ecosystems. State of the Art Report, pp. 172–187. [CELIKKAYA, N. ET AL., 2016]

CELIKKAYA, N.; FULLERTON, M.; FULLERTON, B. [2019b]: Use of Low-Cost Air Quality Monitoring Devices for Assessment of Road Transport Related Emissions. In: Transportation Research Procedia 41, pp. 762–781. DOI: 10.1016/j.trpro.2019.09.125. [CELIKKAYA, N. ET AL., 2019b]

CELIKKAYA, N.; GERSTENBERGER, M. [2019]: Comparison of Traffic Situation Based and Instantaneous Emission Models for Emission Calculation for Dynamic Traffic Management. Poster Presentation in 98th Annual Meeting of the Transportation Research Board January 13–17, 2019. Extended Abstract Paper Number 19-04744. Washington, D.C., 2019. [CELIKKAYA, N. AND GERSTENBERGER, M., 2019].

The main difference between DETM and other dynamic traffic management systems is the integration of an environment module into the existing traffic management system (**Figure 3.1**) which is responsible for the consideration of the environmental situation (e.g. air pollution concentration) and the activation of traffic management measures [FGSV, 2014]. All dynamic traffic management measures resulting in reduced vehicle emissions can have positive air quality-related impacts (e.g. dynamic green waves, dynamic speed limits). The distinction of DETM from others is that the air quality is not only a consequence of the improved traffic situation but a trigger of traffic management measures. DETM measures can be activated solely due to the environmental (i.e. air quality) situation (**Figure 3.1**).

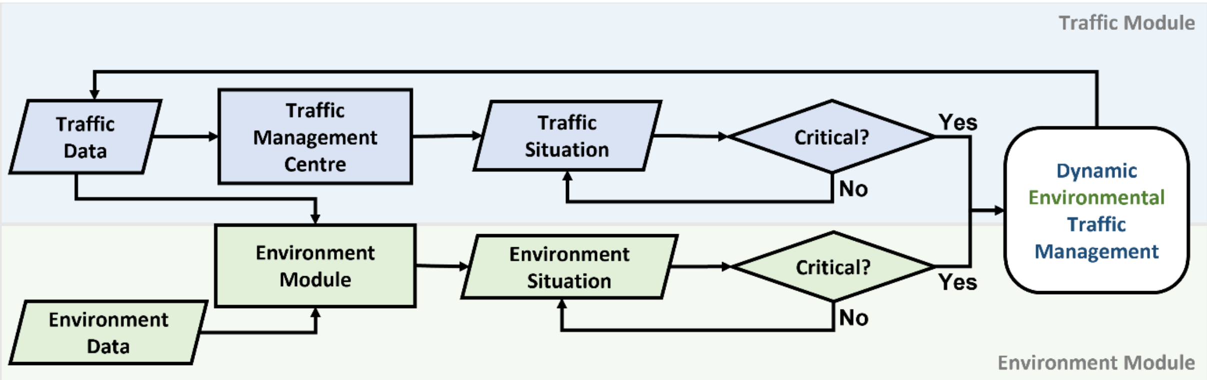

Figure 3.1 Integration of environment module into dynamic traffic management for DETM adapted and translated from [FGSV, 2014]

According to German Road and Transport Research Association (FGSV), requirements of a DETM system are assessment of the air pollution levels (current and/or expected), evaluation of the effectiveness of air pollution reduction measures, monitoring of the impacts as well as documentation of data for future planning decisions [FGSV, 2014]. Technical facilities needed to implement a DETM system are: infrastructure for data supply (e.g. detectors), infrastructure for dynamic traffic management (e.g. adaptive LSA, variable message signs), structural data (e.g. road network, buildings), and software (e.g. tools for traffic and air quality modelling or meteorological prognosis) [FGSV, 2014].

In line with traffic management strategy implementation steps (See **Chapter 2.4**, **Figure 2.11**), the procedures of DETM can be summarized in four main steps:

1. **Situation Assessment**: The first step is the assessment of the traffic and air pollution situation. Depending on the system this can cover only an assessment of the present situation, or it can additionally contain an assessment of the future situation (i.e. prognosis). The present situation can be observed by detection methods, when possible. For cases/locations where detection is not possible, it can be predicted by modelling techniques, which are also used to estimate future situations. In addition, this step requires the detection of traffic and/or air pollution-related problems and their possible reasons.

2. **Selection of Measures**: Second main step is the identification of possible traffic management measures, in accordance with the results of the first step. If there is more than one possible measure, through a pre-analysis, the most effective measure can be selected. This analysis can be done by using modelling techniques or with the help of empirical data.

3. **Implementation of Measure(s)**: The third step is the operational implementation of the measures. This procedure includes the activation and deactivation of measures.

4. **Tracking:** Finally, the effects of implemented measures should be evaluated and the whole process (e.g. description of the initial situation, detected problems/reasons, comparison of measures, implementation) should be documented.

Figure 3.2 illustrates a generic DETM system approach where the above-mentioned implementation steps and used methods can be seen. As outlined in the figure, situation assessment and problem detection can be done in different ways. Traffic and air pollution situations can be collected directly from detectors (measured input) or can be modelled where detection is not available (modelled input).

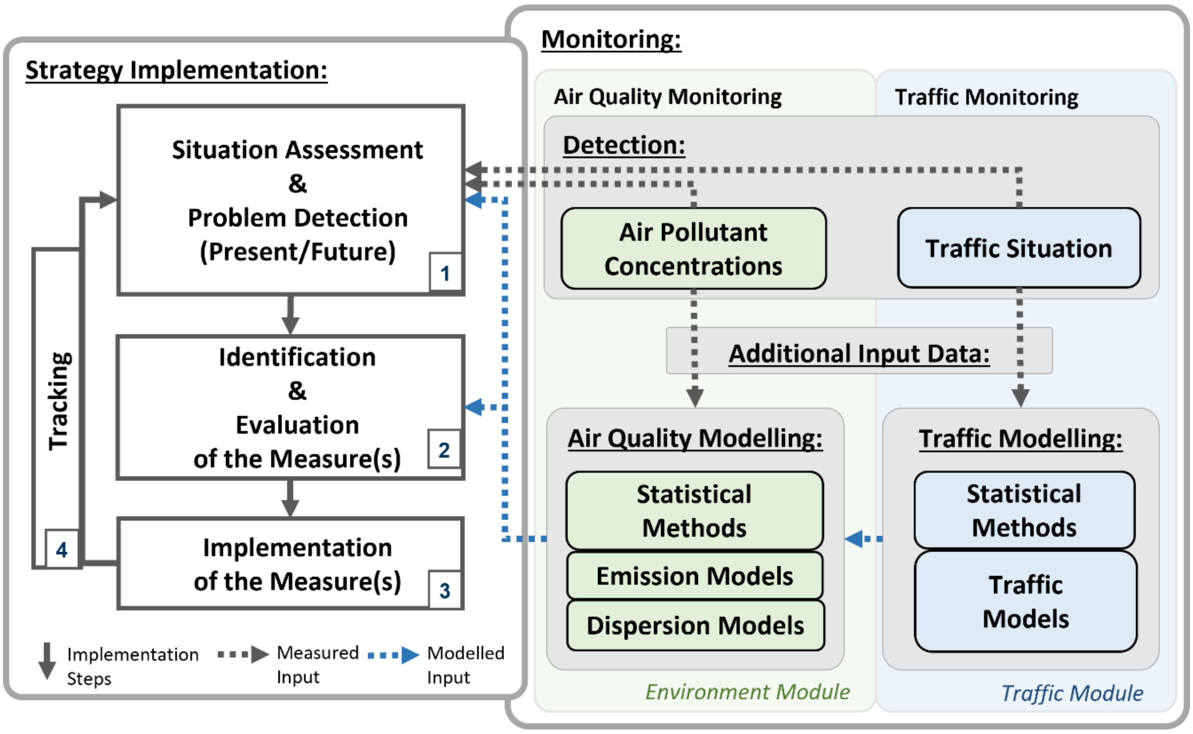

Figure 3.2 Main components of DETM

For modelling of air pollution in traffic-related studies, there are two main approaches. Air pollution can be estimated by using empirical data and statistical approaches where factors influencing pollutant concentration are defined according to observed data and used for the estimation of future air pollution levels [BOLTZE, M. AND KOHOUTEK, S., 2010]. While this approach can explain these factors well and offer a good prediction quality, it does not provide detailed information on spatial distribution [BOLTZE, M. AND KOHOUTEK, S., 2010]. Another way is to use air pollution modelling. Existing DETM systems and studies use one or a combination of these air quality assessment methods and modelling approaches [BOLTZE, M. AND KOHOUTEK, S., 2010; HÜLSMANN, F., 2014]. There are uncertainties in currently used assessment methods resulting from highly aggregated, inaccurate or missing input data on traffic and/or environment data [BOLTZE, M. AND KOHOUTEK, S., 2010; XU, J. ET AL., 2018].

The whole process of continuous situation assessment (through detection, data management and modelling) is highlighted as air quality monitoring and traffic monitoring in **Figure 3.2**. Monitoring of air pollutant concentrations and traffic situations does not only provide input for the first step of DETM (situation assessment) but also for the second step which is the identification and evaluation of measures.

To sum up, as highlighted in **Figure 3.2**, a DETM system can be considered in two main components as strategy implementation and monitoring behind it. There is not one single DETM system that is applied for all urban areas with air pollution problems today. These systems can use an extensive range of input data and can accommodate numerous models, depending on their availability for the operator. As a result, there are several different systems that use different combinations of detection and modelling approaches [DIEGMANN, V. ET AL., 2020]. In addition, on the implementation side, examples can differ according to applied measures and operational methods depending on the problem in a specific area and available infrastructure [DIEGMANN, V. ET AL., 2020; FGSV, 2014].

The following chapters will first give an overview of monitoring methods (**Chapter 3.1** and **Chapter 3.2**) and later illustrate examples of DETM applications from Germany (**Chapter 3.3**).

3.1 Traffic Monitoring

3.1.1 Traffic Detection

Automated traffic detection is a vital component of traffic management which provides numerous information that helps to optimize the traffic in road networks. The purpose of traffic detection can be summarized in two categories as short-term traffic management such as vehicle detection, incident detection, adaptive signal control, ramp-metering, and information services as well as long-term offline traffic management and planning purposes such as design and evaluation of transport measures, acquisition of statistical traffic data [KLEIN, L. A. ET AL., 2006; FGSV, 2019].

The Federal Highway Administration (FHWA) defines traffic detectors in two main groups as in-roadway sensors which are installed into the pavement such as inductive-loop detectors and magnetometers and over-roadway sensors that are mounted nearby such as cameras, infrared sensors, and radar detectors [KLEIN, L. A. ET AL., 2006]. In addition to local traffic detection methods, there are also technologies for linear detection [FGSV, 2019] that are generated from vehicles and provide information about specific vehicles as well as traffic conditions such as Bluetooth sensors and floating car data (FCD).

Local Detection			Linear Detection
In-roadway	Over-roadway		
• Inductive-Loop Detectors • Magnetic field Sensors	• Infrared Detectors • Ultrasonic Detectors • Acoustic Sensors	• Radar Detectors • Laser Detectors • Video Cameras	• Bluetooth Data • Floating Car Data

Table 3.1 Main traffic detection technologies
adapted from [KLEIN, L. A. ET AL., 2006; FGSV, 2019]

Detection technologies have advantages and disadvantages in terms of their detection capabilities (e.g. detection of vehicle presence, vehicle count, vehicle speed, queue length, vehicle type, vehicle weight or detection at multiple lanes, etc.); their installation, operation, and maintenance costs as well as their accuracy and sensitivity to environmental conditions (e.g. temperature, rain, visibility, etc.). To illustrate, while in-roadway detectors have challenges with installation and maintenance, they are insensitive to weather conditions whereas over-roadway sensors are more flexible but may be affected by environmental conditions [KLEIN, L. A. ET AL., 2006].

Different detection technologies have different application areas depending on their detection capabilities. For example, detectors that can measure traffic volume, density, and speed as well as vehicle classes are needed for temporary shoulder lane use on highways. On the other hand, for local adaptive traffic control, detectors that can capture the presence, queue length, and time gap are required [FGSV, 2019].

3.1.2 Traffic Flow Modelling

Models are used "*for predicting the output from a real system, under various conditions that are specified by the input data, without actually using the real system to make this prediction*" [BARCELÓ, J., 2010, p. 2]. Transport models are commonly used for several purposes; from the development of long-term transport/land use plans to traffic state estimation and short-term predictions as well as to assess externalities (e.g. safety, emissions) or impacts of traffic management measures [KESSELS, F., 2018].

The two main components of transport models are transport demand (behavior of travelers) and transport system (network and supply) [BARCELÓ, J., 2010]. Transport demand can be modelled in two major ways: in an aggregated way by estimating the number of trips between origin and destination zones (trip-based models) or in a more detailed way by considering different activities of defined traveler groups or individual travelers that generate demand (i.e. activity-based models) [BARCELÓ, J., 2010]. Transport systems can also be modelled in different levels of detail. Some models simplify the network as links (streets) and nodes (intersections) while others use a detailed representation (number of lanes, intersection design, curves, etc.) of the road network [BARCELÓ, J., 2010, p. 8–10]. Similarly, other supply-related aspects (e.g. traffic control, public transport capacities) can be considered with different precision degrees in models.

Modelling of the temporal and spatial distribution of the demand on the network is done by traffic flow models. Similar to demand and supply, traffic flow can be modelled in different levels of detail, dependent on the scope. The two main possibilities are modelling traffic flow in an aggregated way by considering vehicles in groups and using aggregated temporal/spatial features (macroscopic) or by modelling each vehicle separately and using detailed temporal/spatial representations (microscopic) (see Error! Reference source not found.). A third intermediate way (mesoscopic) is to combine m icroscopic and macroscopic aspects in different ways (e.g. in terms of spatial/temporal details, vehicle dynamics or interactions) for traffic flow modelling [BARCELÓ, J., 2010, p. 33].

- **Macroscopic Traffic Flow Models**: In macroscopic models, traffic flow is considered as a continuous flow and is often associated with fluid dynamics. Traffic flow is defined with aggregated parameters such as average traffic volume, average speed, and density, which represent the collective behavior of the system. According to the methodology used, there are numerous sub-clusters such as kinetic wave models, high-order models, etc. [KESSELS, F., 2018; BARCELÓ, J., 2010]. These models can simulate large areas with low computation needs but can only provide aggregated values. They are traditionally used for strategic planning.

- **Microscopic Traffic Flow Models**: Microscopic traffic flow models simulate each vehicle individually and consider their interaction with each other by taking vehicles' longitudinal and lateral driving behaviors into account (i.e. car-following and lane-changing behaviors). According to the methodology they can be subcategorized as cellular-automata models, safe-distance models, etc. [KESSELS, F., 2018; BARCELÓ, J., 2010]. These models can provide precise information (e.g. individual vehicle trajectories) and have the advantage of offering a detailed analysis of the traffic. However, they have numerous parameters to adjust which makes them complex and time-consuming to calibrate. They also need more computation time, in comparison to macroscopic models. They are traditionally used for operational planning.

Generic type	**Type of input data**	**Output data**	**Typical application area**	**Example modelling tool**
Macroscopic traffic flow models	Travel behavior, demand Land use, demography Simplified network Speed limit Impedance	Aggregated traffic data (e.g. average speed, volume, density, etc.)	Development plans, Transport master plans, Comprehensive impact analysis	PTV VISUM SIDRA AIMSUN
Microscopic traffic flow models	Traffic demand Detailed network Detailed signalization Driving behavior Speed distribution Acceleration distribution	Detailed traffic data (e.g. travel time, delay, queue length, etc.), Individual vehicle trajectories	Signal control optimization, Traffic safety analysis, Detailed analysis of intersections	PTV VISSIM SUMO CORSIM PARAMICS AIMSUN

Table 3.2 Macroscopic and microscopic traffic flow models adapted from [Barceló, J., 2010; Kessels, F., 2018]

3.2 Air Quality Monitoring

The European Ambient Air Quality Directive (AAQD) defines air quality assessment as "*any method used to measure, calculate, predict or estimate*" air quality levels [EC, 2008, p. 5]. An important part of this assessment is conducted by measuring pollutant emissions from sources (e.g. emission measurements of vehicle exhaust or chimneys) and by measuring the final pollutant concentrations that affect people and the environment [UBA, 2004; CHANDRAPPA, R. AND CHANDRA KULSHRESTHA, U., 2016]. With the first one, conformity to emission standards; with the latter, conformity to ambient air quality standards is examined. For ambient air quality monitoring, measurements can be divided into two main categories as follows [UBA, 2004; EC, 2008; MFE NZ, 2009]:

- **Fixed measurements** that are conducted at particular locations, are expected to use standard/reference measurement methods and meet high data quality standards. This type of detection is carried out mainly to determine compliance with the regulations.
- **Indicative measurements** that can use non-standard methods or specialized sampling equipment and are expected to meet less strict data quality objectives. This type of detection is carried out mostly for screening or research purposes.

The European AAQD suggests that fixed measurements must be done in areas where thresholds are exceeded and they can be supported by additional indicative measurements as well as modelling techniques in order to have a more comprehensive understanding of the pollution problem [EC, 2008, p. 2]. The directive sets different data quality objectives for fixed and indicative measurements as well as for the modelling of different pollutants [EC, 2008, p. 14]. In this thesis, the term 'air quality monitoring' is used to define this whole assessment process, a combination of measurement and modelling techniques. The following chapters give more information on air quality measurement (i.e. air quality detection) as well as modelling approaches and techniques used today, focusing mainly on road-transport-related purposes.

3.2.1 Air Quality Detection

In Europe, fixed measurements are done at official air quality monitoring stations (AQMS). For these, the European AAQD defines reference measurement methods for each pollutant and suggests member states to use these or similar verified methods for air quality measurements [EC, 2008]. In addition, the directive describes several criteria for "*macroscale and microscale*" location selection for fixed measurements. To illustrate, measurement sites should be representative (e.g. should not be dominated by one source), should be selected by considering possible pollution exposure of the citizens, and the airflow around the station should be free and not blocked.

According to the directive, AQMS can use continuous measurement methods (i.e. active sampling) and/or discontinuous measurement methods (i.e. random/passive sampling), depending on the air pollutant [EC, 2008]. Continuous measurement stations analyze and deliver air quality data automatically by drawing air into the station. Such detection devices deliver detailed data, can be controlled remotely, and need fewer human interventions; but they are expensive and have high maintenance/operational requirements. In addition to these high-precision measurement stations, diffusive/passive sampling can be used for fixed measurements, where air pollutants are collected on filters, and later analyzed in laboratories. Passive sampling is useful since the tools are cheaper, portable, and do not need a power supply or data transmission; but they have longer reaction times (days to weeks) and therefore are more suitable for the detection of long-term pollution trends (not short-term peak concentrations). To summarize, continuous measurement devices provide air quality data with a higher temporal resolution, whereas discontinuous measurement methods help to increase the spatial resolution of the air quality data [VARDOULAKIS, S. ET AL., 2003; MFE NZ, 2004; UBA, 2004; CHANDRAPPA, R. AND CHANDRA KULSHRESTHA, U., 2016].

Today, there are also low-cost measurement devices available that can provide additional continuous information on air quality for a larger area at fewer costs due to being portable. With the increasing availability of low-cost sensors in the market in the last couple of years, several studies have been conducted to analyze the performance and precision of these sensors by comparing them to a reference high-precision measurement device under several conditions (e.g. laboratory, indoors, and outdoors). Studies show that the correlation between low-cost and conventional sensors is higher in laboratory tests (due to controlled conditions) and lower in field tests [BRODAY, D. M., 2017; RAI, A. C. ET AL., 2017; SOUSAN, S. ET AL., 2017]. Studies highlight the sensitivity of low-cost sensors to environmental conditions and the importance of the frequent on-field calibration of sensors to improve the quality of the results [CASTELL, N. ET AL., 2017; BRODAY, D. M., 2017; RAI, A. C. ET AL., 2017].

3.2.2 Air Quality Modelling

Air quality modelling is an important part of monitoring due to several reasons. To begin with, not every location has a fixed precise measurement station and highly comprehensive indicative measurements are demanding. In addition, detection alone does not help to understand the sources, possible future trends, or solutions to air pollution. Consequently, air quality modelling does not only help with the assessment of air quality but also with forecasting and management of air quality.

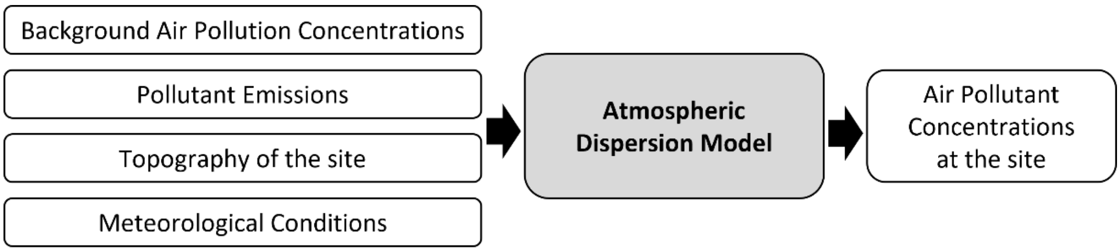

Figure 3.3 Overview of air quality modelling
adapted from [MFE NZ, 2004, p. 4; CHANDRAPPA, R. AND CHANDRA KULSHRESTHA, U., 2016, p. 88]

Figure 3.3 gives a general overview of air quality modelling which covers the collection of the relevant data and utilization of an atmospheric dispersion model to estimate final ground-level air pollutant concentrations in a specific area. The output of air quality models can be used to assess several aspects such as the size of the population that is exposed to air pollution as well as environmental and health impact assessments. As seen in the figure, the four main input data for the dispersion model are background air pollution concentration levels, the amount of direct emissions from pollution sources as well as topographical/local (i.e. built environment) conditions of the area and meteorological conditions.

For the evaluation of road traffic-related air pollution, emission models are utilized to estimate the amount of emitted pollutants from road transportation. This information is later used as one of the input data for dispersion models which are utilized to estimate final air pollution concentrations at the modelled site. The following sub-chapters give detailed information on these two modelling procedures.

Road Transport Emission Modelling

As explained in **Chapter 2.2.1**, road transport vehicle emissions are influenced by technical and operational factors. Therefore, for an accurate emission calculation for road transport, in addition to knowing the traffic volumes, also information on traffic compositions and conditions is needed. Traffic composition describes the technical factors by vehicle types (e.g. trucks, cars, and motorbikes), engine and fuel types (e.g. petrol, diesel, and electric) as well as emission classes of vehicles (e.g. Euro 1, Euro 2, etc.) whereas traffic condition covers operational factors such as average speeds, congestion levels and road infrastructure (e.g. gradient). The level of data needed can change depending on the level of detail that the emission model requires/can process.

Road transport emission models focus mainly on exhaust emissions (see **Chapter 2.2.1**). By the calculation of exhaust emissions, a distinction is made between “hot emissions” and “cold-start emissions” [BARLOW, T. J. AND BOULTER, P. G., 2009, p. 3]. During parking, the temperature of a vehicle’s engine and exhaust system is similar to the temperature of its ambient air; while driving, the temperature of the engine and exhaust increases gradually and becomes stable at an operational level [BOULTER, P. G. AND LATHAM, S., 2009]. Emissions produced during this warm-up phase are called “cold-start emissions”, whereas emissions from the vehicle during full operational temperatures are called “hot-exhaust emissions” [BARLOW, T. J. AND BOULTER, P. G., 2009].

Emission models can be classified according to their general types as aggregated emission factor models, average speed models, traffic situation models, multiple linear regression models, and instantaneous emission models [HÜLSMANN, F., 2014; BARLOW, T. J. AND BOULTER, P. G., 2009].

- **Aggregated emission factor models** operate with a single emission factor that represents a particular vehicle type and a driving condition (e.g. urban roads, rural roads, motorways). The emission factors are calculated as mean values from measurements of vehicles with pre-defined driving cycles. This approach offers emission factors only for these defined situations which are covered by the model [BOULTER, P. G. ET AL., 2007].

- **Average speed emission models** are based upon the assumption that average emission factors for a certain pollutant and a specific type of vehicle vary according to the average speed during a trip. They do not differentiate between different driving dynamics on a link which results in the same emission factors for all links with the same average speed. As an example, the emission model COPERT provides emission factors for driving on urban roads, rural roads, and motorways as a function of average speed [BOULTER, P. G. ET AL., 2007; BARLOW, T. J. AND BOULTER, P. G., 2009]. To illustrate, COPERT is mostly used by many national governments to calculate road transport emissions [TISTA, M. ET AL., 2019].
- **Traffic situation models** link emissions and fuel consumption to vehicle categories (considering the vehicle type, engine type, and emission class) operating in a specific traffic condition. These models are suitable for local applications (e.g. emission estimation for individual link segments), but they can also be used for inventories of regions or countries [HÜLSMANN, F., 2014; BARLOW, T. J. AND BOULTER, P. G., 2009]. One example which is regularly used, especially in Europe, is the handbook of emission factors for road transport (HBEFA).
- **Multivariate regression models** consider the relationship between driving dynamics and emission rates. Based on measurements of vehicles on specified test cycles, for each pollutant and vehicle category, a separate regression model is created which is taking different influencing factors of driving dynamics (e.g. speed-time profiles, number of stops per km, acceleration) into account [BARLOW, T. J. AND BOULTER, P. G., 2009].
- **Instantaneous emission models** are typically used at a microscopic scale as they can illustrate vehicle operation in detail. Vehicle operation is defined in different driving modes like idle, acceleration, deceleration, and cruise. By using the data such as second-by-second driving cycle, road gradient, driving resistance, and losses in the transmission system, the engine power and emissions at a given time can be calculated for individual vehicles [BARLOW, T. J. AND BOULTER, P. G., 2009]. One example that is commonly used in Europe is the Passenger Car and Heavy-duty Emission Model (PHEM).

Table 3.3 shows an overview of the characteristics of these emission calculation approaches. It is important to note here that, emission factors in less detailed models (i.e. emission inventory models) are mostly aggregated from detailed vehicle-based models (e.g. HBEFA and CORPERT databases are based on PHEM). Furthermore, there are emission models available that can be used in different levels of detail such as MOVES that can be used in macroscopic, mesoscopic, and microscopic scales [SHEKARRIZFARD, M. ET AL., 2016; EPA, 2012].

Generic type	Type of input data	Typical application	Example Emission Modelling Tool
Aggregated emission factor models	Area and Road type	Emission inventories	NAEI: National Atmospheric Emissions Inventory (UK)
Average speed models	Average trip speed	Emission inventories, Dispersion Modelling	COPERT: Computer Program to calculate Emissions for Road Transport
Traffic situation models	Road type, Speed limit, LOS, Gradient	Emission inventories, Environmental Impact Assessments, Area-wide Assessments of UTM, Dispersion Modelling	HBEFA: Handbook of emission factors for road transport
Multivariate regression models	Driving pattern	Emission inventories, Dispersion Modelling	VERSIT+: Verkeers Situatie Model
Instantaneous emission models	Driving cycle, Gradient	Detailed temporal and spatial analysis of emissions, Dispersion modelling	PHEM: Passenger Car and Heavy-duty Emission Model

Table 3.3 Road transport emission models
adapted from [HÜLSMANN, F., 2014; BARLOW, T. J. AND BOULTER, P. G., 2009; BOULTER, P. G. ET AL., 2007]

As can be seen in **Table 3.3**, for emission calculation within the context of urban traffic management (UTM), mostly traffic situation-based emissions models are utilized today. The main advantages of these models are being fast and efficient. However, they also have disadvantages due to the simplification of traffic situations into a few level-of-service (LOS) categories; resulting in not covering each specific operational condition which is an important factor for detailed emission calculation. To illustrate, after on-board emission measurements, the statistical relationship analysis of emissions with operational factors FREY ET AL. [2001, p. 270–282] finds out that emissions are strongly related to "*time spent in acceleration*" and therefore emission reduction potentials of measures (e.g. signal optimization) increases with reducing the time spent in acceleration. Instantaneous models can capture such detailed aspects but need higher computational times. Several studies [ALAM, A. ET AL., 2014; KRAJZEWICZ, D. ET AL., 2016] point out the importance of microscopic emission modelling by using drive-cycle information for air quality assessment.

Atmospheric Dispersion Modelling

The amount of air pollutants that reach to the population depends on their dispersion in the ambient air (see **Chapter 2.1.2**) and dispersion modelling is the key aspect of air quality modelling. Consequently, dispersion models are tools to calculate air pollutant concentrations and to evaluate if air pollution is (or will be) a problem in a specific area. In addition to finding the problem, atmospheric dispersion models can be used to determine the source of the air pollution problem as well as to evaluate possible air pollution reduction measures [DE VISSCHER, A., 2014]. That is why they are an important component of DETM and are being utilized not only for situation assessment but also for the identification and evaluation of traffic management measures (see **Figure 3.2**).

There are numerous dispersion modelling tools available. According to the methodology (i.e. mathematical principles) used, they can be divided into six main groups and explained in simple terms as follows [ZANNETTI, P., 1990; VARDOULAKIS, S. ET AL., 2003; HOLMES, N. S. AND MORAWSKA, L., 2006; DE VISSCHER, A., 2014; CHANDRAPPA, R. AND CHANDRA KULSHRESTHA, U., 2016]:

- **Gaussian Plume Models** calculate downstream air pollution concentrations from a pollution source by considering its height, the amount of produced emissions, and constant wind conditions (speed, direction) for short time intervals (e.g. hours). Therefore, they are called "*steady-state*" models. These models are widely applied. They are simple and fast due to using a single formula to calculate dispersion; but less accurate (e.g. for low wind speeds and distances more than 10 - 20 km) compared to more complex models [DE VISSCHER, A., 2014; LEELŐSSY, Á. ET AL., 2014].

- **Lagrangian Models** assume that particles emitted from a source follow a path in relation to wind conditions and this path is updated every time step (i.e. they model the trajectory of the pollutants). Their computation time increases with the number and/or length of trajectories considered. Consequently, they can be very accurate up to thousands of kilometers with few sources or very efficient for short-range calculations with many sources [DE VISSCHER, A., 2014; LEELŐSSY, Á. ET AL., 2014].

- **Gaussian Puff Models** do not assume constant wind conditions (*non-steady-state*) and simulate emissions in the form of puffs which can change direction when wind conditions change. They are more accurate than Gaussian Plume models; can model low wind conditions and perform well up to 200 km distances. Since they consider the trajectory of a plume, they are a combination of Gaussian and Lagrangian approaches [DE VISSCHER, A., 2014; LEELŐSSY, Á. ET AL., 2014; ZANNETTI, P., 1990].

- **Eulerian Models** consider the modelled area in grids and calculate concentrations for each grid. Similar to Lagrangian models, they simulate the movement of pollutants but consider the transport of pollutants between cells (i.e. they use a fixed reference system, unlike Lagrangian models). Their accuracy and computational requirements change with the grid size (i.e. resolution). Some hybrid models use the Lagrangian approach for near-source dispersion and aggregate it into an Eulerian grid to simulate large-scale dispersion [ZANNETTI, P., 1990; DE VISSCHER, A., 2014; LEELŐSSY, Á. ET AL., 2014].

- **Computational Fluid Dynamics (CFD) Models** are the most detailed dispersion model type (e.g. complex geometry, fine grid resolution, small-scale turbulence calculation). Thus, the technique used is computationally more intensive. They are more reliable for detailed analysis of the dispersion and suitable for small-scale applications [VARDOULAKIS, S. ET AL., 2003; DE VISSCHER, A., 2014; LEELŐSSY, Á. ET AL., 2014].

- **Box Models** are the models that simulate air dispersion by considering the modelled area as a box. These models simplify meteorological conditions inside the box and thereby can focus on detailed pollutant movements and chemical reactions. Box models are mostly used for modelling well-defined environments such as street canyons, tunnels, or indoor areas; for other applications (where the studied area and meteorological effects are more complex) they are often combined with the above-mentioned modelling approaches [HOLMES, N. S. AND MORAWSKA, L., 2006; TAN, Z., 2014; CHANDRAPPA, R. AND CHANDRA KULSHRESTHA, U., 2016].

In addition to the methodology, dispersion modelling tools can also be categorized according to other aspects such as their scale, possible source types to model, and considered air pollutants [HOLMES, N. S. AND MORAWSKA, L., 2006]. **Table 3.4** illustrates some examples.

Example dispersion modelling tool	Generic type	Model scale	Modelled source types	Street canyon
CALPUFF	Gaussian Puff Model	Regional	Area, Line, Point	
IMMIS^{net}	Gaussian Plume Model	Regional, Local	Area, Line, Point	
AERMOD	Gaussian Plume Model	Regional, Local	Area, Line, Point	
GRAL	Eulerian-Lagrangian Model	Regional, Local	Line, Point	
CALINE 4	Gaussian Plume Model	Local	Line	
OSPM	Gaussian Plume and Box Model	Local	Line	X
IMMIS^{cpb}	Canyon Plume and Box Model	Local	Line	X
PROKAS_V+B	Gaussian Plume and Box Model	Local	Line	X
SIRANE	Gaussian Plume and Box Model	Local	Line, Point	X
MISKAM	CFD Model	Local	Line, Point	X

Table 3.4 Example dispersion models
[VARDOULAKIS, S. ET AL., 2003; HOLMES, N. S. AND MORAWSKA, L., 2006, p. 52–54; CALPUFF, 2011; SOULHAC, L. ET AL., 2011; Lohmeyer, 2021; IVU Umwelt, 2020]

Dispersion Modelling in Road Transport

For road transport-related air quality modelling, dispersion models that cover line sources can be used (see **Table 3.4**.). Models that can simulate the dispersion and transformation of air pollutants in urban street environments in detail, by considering specific aspects such as surrounding buildings, and wind flows in street canyons, are called street canyon models [VARDOULAKIS, S. ET AL., 2003; HOLMES, N. S. AND MORAWSKA, L., 2006]. From the example tools in **Table 3.4**., the ones that can model street canyons in detail are marked.

Specific conditions in street canyons can be summarized as follows [BERKOWICZ, R. ET AL., 1997; VARDOULAKIS, S. ET AL., 2003; HOLMES, N. S. AND MORAWSKA, L., 2006; MIAO, Y. ET AL., 2014]. The dispersion of pollutants is highly influenced by the canyon geometry (length, width, height) and wind conditions inside the canyon (speed, direction) which are different from the roof-top conditions. Depending on the geometry and wind conditions, air pollution concentrations can differentiate between different locations in the canyon (e.g. two sides of the street). Along with these two factors, the wind flow in a canyon is also influenced by vehicle-induced turbulence (VIT). Especially in low wind speeds, due to the reduced ventilation, this turbulence becomes a dominant dispersion factor. In addition to the dispersion process, chemical processes in canyons (e.g. formation of secondary pollutants, especially conversions between NO_2 and NO) are different than in large-scale areas. Consequently, street canyon models consider one or more of these aspects.

The main input data requirements for street canyon modelling are (in line with the ones for general atmospheric dispersion modelling, see **Figure 3.3**) road traffic emission data and relevant traffic data, background air pollution concentrations, meteorological conditions as well as street geometry (i.e. built structure). Some important points considering the input data are [VARDOULAKIS, S. ET AL., 2003]:

- Most of the street canyon models use emission factors (g/km per vehicle) or emission rates (g/km per time interval). These factors are one important source of the input data uncertainties and need to be updated regularly. In addition, detailed data on traffic and fleet composition at specific street canyons are rarely available and usually, generalized vehicle compositions are used. This can be improved to increase accuracy.
- Urban background concentrations can be gathered from nearby AQMS, can be obtained from larger-scale AQ models, or acquired by using roof-top measurements at the studied area.
- Meteorological data is generally available. The level of detail of these data can depend on the used model. An important point is to be cautious while using weather data from airports because local conditions (especially wind) at street canyons can be quite different.

Modelling pollutant dispersion from traffic in urban areas is complex and difficult due to inhomogeneous pollutant emission from vehicles (unlike industry or heating) and the existence of numerous several factors to be considered such as different atmospheric layers, buildings, and traffic-induced turbulence [SOULHAC, L. ET AL., 2011]. Consequently, as SOULHAC, L. ET AL. [2011] and VARDOULAKIS, S. ET AL. [2003] state, there are two main options available: either to use CFD models which are very detailed but need high computational times or to use less detailed operational models that simplify the urban geometry and meteorology (e.g. box models and/or Gaussian plume models) which should be calibrated due to being dependent on empirical assumptions. Today, for urban traffic-related studies (e.g. hotspot detection, monitoring, evaluation of measures, sensitivity analyses) mostly operational dispersion models are utilized [VARDOULAKIS, S. ET AL., 2003].

3.2.3 Air Quality Modelling Examples Focusing on Road Transport

As covered in previous chapters, there are several possibilities to model air quality; from several techniques for the estimation of road transport emissions to different atmospheric dispersion models. A review of literature related to monitoring air pollution from road transport by using models can be found in **Table 3.5**. Depending on the research focus and availability of tools, there are numerous model combinations (including mixed combinations of microscopic and macroscopic approaches) available to estimate the impacts of road transport on emissions and/or pollutant concentrations.

Author / Title	Goal	Traffic Flow Model	Emission Model	Dispersion Model
[BIGAZZI, A. ET AL., 2010] Traffic Data for Local Emissions Monitoring at a Signalized Intersection	"Assessment of the accuracy of local emissions monitoring based on traffic data and models, with a focus on air pollution responsive dynamic traffic management (DTM) systems"	Microscopic model VISSIM	Multivariate regression model VERSIT+	No Model Instead: Comparison to AQMS data
[HUNG, N. T. ET AL., 2010] Air pollution modeling at roadsides using the Operational Street Pollution Model — a case study in Hanoi, Vietnam	"Application of a dispersion model to cities where model input data and data from air quality monitoring stations are limited or of varying quality, for the estimation of air pollution at street level."	No model Instead: Macroscopic data from surveys, local traffic measurements	Estimated emission factors for Hanoi, adapted from the average speed model COPERT	Gaussian plume box model OSPM
[SCORA, G. ET AL., 2011] Real-time roadway emissions estimation using visual traffic measurements	"Development of an emission estimation methodology to provide real-time link-based emission information, by using a computer vision-based methodology."	No Model Instead: Vehicle trajectories (classified by vehicle types) from video-based traffic monitoring	Instantaneous model CMEM and MOVES	No Model
[HÜLSMANN, F., 2014] Integrated agent-based transport simulation and air pollution modelling in urban areas — the example of Munich	"Development of an integrated air pollution modelling approach to analyze transport policies, especially large-scale scenarios"	Mesoscopic model MATSim	Emission calculation tool, based on the traffic situation-based model HBEFA	Gaussian plume box model OSPM
[DIAS, D. ET AL., 2014] Impact of road transport on urban air quality: GIS and GPS as a support for a modelling framework	"Application of an integrated approach for quantifying emissions from road transport in urban areas and its spatial and temporal distribution based on GIS and GPS"	Microscopic model VISSIM	Average speed model TREM	Gaussian model URBAIR + GIS for visualization
[SCHÖLLNHAMMER, T. ET AL., 2014] Effects of electric vehicles on air quality in street canyons	"Evaluation of the potential effects of the increasing number of electric vehicles in Germany on air quality and estimation of the necessary EV share to comply with the EC limit values: based on two example street canyons"	No Model: Instead: Existing traffic situation with estimated future EV shares	Traffic situation-based model HBEFA	Canyon plume box model $IMMIS^{luft}$
[GHAFGHAZI, G. AND HATZOPOULOU, M., 2015] Simulating the air quality impacts of traffic calming schemes in a dense urban neighbourhood	"Investigation of the effects of traffic calming measures on NO_X emissions and NO_2 concentrations using air quality modelling"	Microscopic model VISSIM	Instantaneous model MOVES in microscopic scale	Gaussian plume box model OSPM
[GORI, S. ET AL., 2015] Emission dynamic meso-simulation model to evaluate traffic strategies in congested urban networks	"Development of a method to estimate pollutant emissions considering the daily variations of traffic flow conditions to evaluate the results of traffic management strategies in wide congested urban networks"	Mesoscopic model DYNAMEQ	Average speed model COPERT	No Model

Author / Title	**Goal**	**Traffic Flow Model**	**Emission Model**	**Dispersion Model**
[KRAJZEWICZ, D. ET AL., 2016] Benefits of using microscopic models for simulating air quality management measures	"Design of a software tool to predict the effects of large-scale traffic management measures on emissions and to evaluate measures"	Microscopic model SUMO	Instantaneous model PHEMlight	No Model
[VALLAMSUNDAR, S. AND LIN, J., 2016] Modelling air quality and population exposure levels to PM emissions from motor vehicles in Gold Coast Region, Chicago	"Assessment of microenvironmental exposure to air pollution (e.g. outdoor, indoor, or in-vehicle) based on dynamic population information combined with air quality data from emission and dispersion models"	No Model <u>Instead:</u> Data from traffic detectors	Average speed model MOVES in macroscopic scale	Gaussian plume model AERMOD
[SHEKARRIZFARD, M. ET AL., 2016] Validation of a puff dispersion model: air quality simulation for new highway infrastructure	"Validation of air quality modelling through the evaluation of the potential air quality impacts of a new highway extension"	No Model <u>Instead:</u> Traffic counts	Average speed model MOVES in macroscopic scale	Gaussian puff model CALPUFF
[PRADA, F. P. AND MONZON, A., 2017] Identifying traffic emissions hotspots for urban air quality interventions: the case of Madrid City	"Proposal of a macroscopic air quality diagnosis tool based on the combination of transport, emission, and population density GIS models for a comprehensive transport emission assessment"	A macroscopic traffic model	Average speed model COPERT	No Model <u>Instead:</u> Emission exposure based on population density
[RUSHTON, C. ET AL., 2018] City-wide emissions modelling using fleet probe vehicles	"Demonstration of a new methodology to model emissions using instantaneous vehicle emission modelling, GIS and capturing vehicle behavior using global positioning system"	No Model <u>Instead:</u> Vehicle trajectories from (GPS & GIS) probe vehicles	Instantaneous model PHEM	No Model
[GÓMEZ-PÉREZ, C. A. AND ESPINOSA, J., 2018] Evaluation of pollutants dispersion in an urban traffic scenario in Medellín	"Detailed analysis of emissions in a mobility network with simulation tools for the identification of pollutant dispersion in an urban area and therefore air quality improvement"	Microscopic model SUMO	Traffic situation-based model HBEFA	CFD model Ansys-Fluent

Table 3.5 Example road transport related air quality modelling studies

Studies highlight several aspects of air quality modelling in road transport. First of all, the availability of detailed and reliable data on traffic, air quality, and local meteorology is a crucial aspect. Especially the information about the local fleet composition is highlighted; due to vehicle type having an important effect on emissions and measures focusing on fleet change (e.g. vehicle restrictions) having a higher impact on air quality compared to other measures [BIGAZZI, A. ET AL., 2010; HUNG, N. T. ET AL., 2010; SCORA, G. ET AL., 2011; HÜLSMANN, F., 2014; GORI, S. ET AL., 2015].

Another aspect is the importance of traffic and emission monitoring with a higher temporal resolution, especially for the assessment of dynamic traffic management measures. Using vehicle trajectories that can represent vehicle dynamics/speed profiles and utilizing microscopic (instantaneous) emission models is gaining popularity. In addition to utilizing microscopic traffic flow models, using vehicle trajectories through detection (e.g. GPS, video monitoring) is coming out as a strong alternative; either to be used in microscopic emission models or to validate microscopic traffic flow models [SCORA, G. ET AL., 2011; DIAS, D. ET AL., 2014; GHAFGHAZI, G. AND HATZOPOULOU, M., 2015; KRAJZEWICZ, D. ET AL., 2016; RUSHTON, C. ET AL., 2018]. Microscopic models are computationally more tiring and used mostly for hotspot analysis, but KRAJZEWICZ ET AL. [2016] show that larger-scale analyses can become more common through combined traffic and emission models.

Finally, studies highlight the complexity and importance of dispersion processes and emphasize using dispersion models. Results show that the impacts of road transport measures on final pollutant concentration levels are not directly proportional to the increase or decrease in road transport emissions [GHAFGHAZI, G. AND HATZOPOULOU, M., 2015; SHEKARRIZFARD, M. ET AL., 2016; HÜLSMANN, F., 2014]. These conclusions imply the importance of detailed monitoring approaches on traffic and air quality situations for DETM applications.

3.3 DETM Application Examples

In this section some DETM examples and studies from Germany will be presented to illustrate how these systems are applied, evaluated, to which degree DETM contributes to reductions in emissions and air pollutant concentrations as well as what lessons can be learned. For each study, a piece of short background information, followed steps, data detection methods, traffic management measures, and their impacts will be explained briefly. While the first two examples are research-oriented and not in operation, the last three examples are in operation. Detailed descriptions of these applications can be found in related project reports as well as in special reports of the German Road and Transport Research Association [FGSV, 2014] and the German Federal Highway Research Institute [DIEGMANN, V. ET AL., 2020] on DETM.

Hagen

One of the first examples of DETM in Germany is in Hagen [BOLTZE, M. AND KOHOUTEK, S., 2010; FGSV, 2014] which was developed under a research project. The motivation in Hagen is high NO_2 and PM_{10} levels in inner-city streets caused by the road traffic and testing of possible measures to consider for the Air Quality Plan [LUDES, G. ET AL., 2010]. The methodology applied is the analysis of existing trends (traffic, weather, and emissions), defining influencing parameters, implementing a control algorithm, simulation of possible impacts using recorded data as well as a test implementation on the field [LUDES, G. ET AL., 2010].

Data collection is done for a whole year to eliminate seasonal effects. Air pollution measurements are conducted at three urban traffic AQMS and one urban background AQMS. Atmospheric data is collected from 3 different weather stations. Traffic data is gathered from automatic and manual counting. After the first data analysis, one hotspot is detected where NO_2 and PM_{10} levels were frequently exceeded [LUDES, G. ET AL., 2010]. A pre-analysis of emissions by using traffic data and a macroscopic emission model showed that 55 % of the total NO_X emissions were caused by heavy-duty vehicles (HDVs) in this hotspot, although they were only 4,5 % of the total traffic volume. Consequently, the selected DETM measure is dynamic re-routing of HDVs [LUDES, G. ET AL., 2010]. It is also seen from air quality measurements that NO_2 concentrations were highly affected by meteorological parameters. Thus, different activation criteria are defined which take wind, radiation, and emission levels into consideration for the control algorithm [LUDES, G. ET AL., 2010].

A model-based potential analysis with different HDV reduction rates (i.e. acceptance rates) showed that the DETM measure does not contribute to a reduction in yearly average values but in the number of limit exceedances for NO_2 and PM_{10}. It is also seen that for NO_2 limit exceedances, DETM was as effective as static restrictions; but the success was highly dependent on the acceptance of the measure by HDV drivers [LUDES, G. ET AL., 2010]. Later, the DETM system was tested on the field, and pollutant concentrations for each scenario were calculated (ex-ante) by dispersion modelling. In line with the pre-analysis, it is seen that DETM brought around 2-3 $\mu g/m^3$ reduction in NO_2 hourly average concentrations and 6-8 times fewer exceedances of the hourly thresholds [LUDES, G. ET AL., 2010]. The study shows in general that DETM can be as effective as static measures and can avoid emission-relocation but it is not expected to be highly effective on reducing yearly average concentrations alone. To achieve a long-term reduction, more comprehensive larger scale measures are suggested. In addition, the study recommends additional concepts for DETM to increase compliance rates (e.g. early routing information, strict control) [LUDES, G. ET AL., 2010].

Braunschweig

The air quality action plan of Braunschweig was prepared in 2007 as a result of limit-excesses of NO_2 and PM_{10} concentrations [Stadt Braunschweig, 2007, p. 9–10]. In connection with the plan, a DETM project started in 2009. In the first phase, the goal was to analyze, develop, and test a DETM system [UVM-BS, 2010]. In the second project phase (2010 - 2012) developed DETM system was enhanced and with the third phase (since 2015) it became operatable [DIEGMANN, V. ET AL., 2020, p. 17–18]. However, until now the measures were only activated for research and development purposes [DIEGMANN, V. ET AL., 2020, p. 28]. The traffic module in the Braunschweig traffic management center (TMC) consists of VIBSmt (traffic monitoring) and SITRAFFIC Scala (for activation and deactivation of measures); the environment module is the air quality monitoring tool $IMMIS^{mt}$ [UVM-BS, 2010, p. 3–6].

In the DETM development phase, one hotspot was defined. Air quality data were collected from official AQMS and measurement containers; traffic data were gathered from passive infrared detectors, test rides, and videos; meteorological data were obtained from airport weather stations [UVM-BS, 2010]. Pre-analysis of collected data showed that there were only NO_2 exceedances at the hotspot (no PM_{10} excess) during the analysis period [UVM-BS, 2010]. Later, possible traffic management measures were defined and tested by using a macroscopic traffic model to understand their NO_2 reduction potentials.

Results indicated that the highest reduction was possible by respectively: temporary restriction of HDVs and temporary traffic metering [UVM-BS, 2010, p. 16]. Due to the risk of relocating emissions and congestion on alternative routes with such a restriction, the second measure metering (reducing traffic volumes by adjusting green times) was selected to test on the field [UVM-BS, 2010]. Field tests showed that the number of stops and emissions could be reduced without causing new hotspots.

With the second phase, the study area was enlarged, detection methods and models were improved, a prognosis function was introduced and the DETM activation with threshold exceedance as well as an improvement of information systems were aimed [UVM-BS, 2012]. As activation criteria, hourly NO_2 concentration levels were selected and a tool for the activation mechanism was developed [UVM-BS, 2012]. By checking modelled annual mean NO_2 levels, several hotspots in the urban area were defined and possible DETM measures were selected for each hotspot. Finally, the effectiveness and impacts of these measures were evaluated in a larger area by using models. Air pollutant concentrations are calculated by hourly meteorological data, background pollutant concentrations, and average traffic volumes [UVM-BS, 2012, p. 42]. Results indicate that all DETM measures contributed to the desired reduction in hotspots (3 - 15 % reduction in total NO_X concentrations). However, they all, more or less, lead to an increase in concentrations on alternative routes [UVM-BS, 2012, p. 45–47]. The study concludes that dynamic temporary measures can reduce air pollution, can cause less re-location effects (compared to static measures), and suggests supporting DETM with a user-information concept about the measures and their environmental impacts [UVM-BS, 2012, p. 59].

Wittenberg

In Wittenberg, there are two AQMS: one is for urban background AQMS and the other one is an urban traffic AQMS [DIEGMANN, V. ET AL., 2020, p. 44]. The air quality problem and DETM motivation in Wittenberg is the limit-excess of PM_{10} daily average concentrations in the second station, due to high shares of through traffic (13 %) and high HDV percentage (7,7 %) [FGSV, 2014]. Consequently, this area around the urban traffic AQMS is the selected hotspot for the DETM system and the applied traffic management measure is a temporary re-routing of HDVs.

In Wittenberg, the traffic module and the environment module in DETM are not linked yet and the activation and deactivation are done manually. Air quality modelling consists of statistical analysis (multilinear regression analysis for the prognosis of daily average PM_{10} values) and an air quality modelling tool which includes an emission model and a dispersion model. Input data are measurements from AQMS, meteorological data, and the street network. The model gives expected PM_{10} levels for the next day and a five-day trend. If the next-day-prognosis shows a threshold exceedance (defined as greater than 50 µg/m^3), the HDV-Routing measure is activated.

The impact of the measure on air pollution is calculated by using PROKAS. Results show that the measure could lead to some reduction in the number of limit-excess (-7 %) but could not reduce yearly average air pollutant concentrations significantly. Furthermore, it is seen that this measure can increase emissions (NO_X and PM_{10}) on the alternative route. Model results show that the DETM measure can reduce pollutant concentrations slightly for the hotspot, whereas the same amount of concentrations is increased on the alternative route [DIEGMANN, V. ET AL., 2020, p. 84–85].

Erfurt

DETM in Erfurt is developed, similar to other examples, in several phases starting with a research project in 2011. The main goal of the DETM approach in Erfurt is to improve the air quality in the inner city and to control the traffic inflow from ring roads and distributor roads to this area. In the first phase (2011 - 2013), within the framework of the research project, the feasibility of a DETM system on an example of two hotspots was checked [DIEGMANN, V. ET AL., 2020, p. 29]. In the second phase (2013 - 2015) the study area was enlarged with metering on an additional distributor road and in the third phase, it is aimed to complete the concept with all 11 distributor roads.

The traffic module of DETM consists of three software systems: a traffic analysis and prognosis model (PTV OPTIMA), traffic and air quality monitoring/data management software (pwpTMPlatform), and a traffic computer center (SITRAFFIC Scala) for the application of measures. Input data are detector data, traffic events/situations, parking space availability, as well as meteorological conditions and air pollutant concentrations [DIEGMANN, V. ET AL., 2020, p. 34–38]. In Erfurt air quality measurements are done at 6 locations; 3 of them are close to the 2 hotspots (2 urban traffic AQMS and one urban background AQMS). Emission calculations are conducted macroscopically, by using an HBEFA-based model. Currently, air quality prognosis is not included but it is planned for the third phase.

There are two measures activated according to traffic situation (defined by the level of service) and hourly NO_2 concentrations. If the concentration level is greater than 50 $\mu g/m^3$, traffic information is given (e.g. please use P&R) and if it is greater than 60 $\mu g/m^3$, traffic metering is activated [DIEGMANN, V. ET AL., 2020, p. 39]. Pilot studies show that measures could improve traffic flow at hotspots (i.e. less stop & go) and reduce NO_2 concentrations by up to 7-8 % for the two hotspots. In addition, no significant dislocation of traffic could be observed. However, the peak hours were observed to be longer. With the applied measure, travel times were only slightly increased, and the congestion is kept on well-ventilated street canyons instead of environmentally sensitive urban street canyons.

Potsdam

Potsdam introduced an air quality and action plan in 2007 as a result of detected PM_{10} and NO_2 threshold exceedances and proposed many strategies to overcome this problem. One of the measures is to develop and integrate a DETM system into the existing traffic management system [FGSV, 2014; VMZ, IVU, LK Argus, 2012]. The DETM is operational in Potsdam since 2012 for the reduction of NO_2 and PM_{10} limit exceedances. The system covers six hotspots and several measures such as the improvement of the traffic flow by green waves, short-term traffic volume control at traffic signals (i.e. traffic metering) on the border of hotspots as well as informing users about traffic conditions, emission levels, and related changes in the network [FGSV, 2014]. The main strategy is to keep congestion on well-ventilated street canyons outside of the city center instead of urban street canyons.

Traffic detection is done by several field detectors, traffic data is aggregated into 30-minute intervals, and traffic situations for HBEFA are calculated by the traffic control center by using the fundamental diagram. The environment module is IMMIS^{mt}. Input data are traffic data (through SITRAFFIC Scala), traffic situation from the traffic module, air pollutant concentrations from AQMS as well as meteorological data from several locations [DIEGMANN, V. ET AL., 2020, p. 42]. DETM Measures are activated according to the traffic situation as well as NO_2 concentrations.

The first results show that there was a reduction in traffic volumes and queue lengths which contributed to a reduction in air pollutant concentrations and the number of threshold exceedances. To illustrate, at one traffic station in one of the hotspots, a yearly average NO_2 emission level that did not exceed the limit was observed for the first time [LH Potsdam, 23.01.2013; LH Potsdam, 13.03.2014].

Summary

An overview of the above-mentioned examples in terms of their goals and scopes as well as utilized traffic/air quality detection and modelling tools can be found in **Table 3.6**. To sum up briefly:

- The examined DETM examples focus mostly on exceedances of the NO_2 threshold values.
- While the first DETM examples concentrate on improving the air quality in one hotspot, the latter examples take a more comprehensive approach and deal with the air pollution problem in multiple hotspots.
- Dynamic traffic flow metering is the most applied DETM measure, followed by dynamic HDV re-routing.
- Activation criteria for measures, as expected from DETM, always include the air pollutant concentrations; in some cases, traffic situations and in one case meteorological conditions. When NO_2 is considered, the activation threshold is based on hourly or half-hourly concentration values, changing between 50 - 180 µg/m^3.
- For traffic monitoring mostly detectors; for air quality monitoring mostly nearby air quality measurement stations (AQMS) are utilized.
- Modelling approaches, tools, and data utilized change from application to application, however, the macroscopic approach is adopted mostly for traffic, emission, and dispersion modelling. Models are used mainly for screening and evaluation of traffic management measures; only a few DETM examples include traffic or air quality forecasting/prognosis.

City	Hagen	Wittenberg	Braunschweig	Erfurt	Potsdam
Start Year	2006	2007	2009	2011	2012
Application	Research and Field Test	Regular Operation	Research and Field Test	Regular Operation	Regular Operation
Scope	One Hotspot	One Hotspot	Multiple Hotspots	Multiple Hotspots	Multiple Hotspots
Motivation	NO_2 Limit Exceedances	PM_{10} Limit Exceedances	NO_2 Limit Exceedances	NO_2 Limit Exceedances	NO_2 Limit Exceedances
DETM Measure	HDV Re-routing Metering	HDV Re-routing	HDV Re-routing Metering	Information Metering	Information Green Wave Metering
Activation Criteria	Hourly NO_2 Concentration and Meteorology (measured)	Daily PM_{10} Concentration (modelled)	*Hourly NO_2 Concentration (modelled)	Hourly NO_2 Concentration (measured) and Level of Service (modelled)	Half-hourly NO_2 Concentration (modelled) and Level of Service (measured)
Activation Threshold (Air Quality)	180 µg/m^3 (hourly)	50 µg/m^3 (daily)	*80 µg/m^3 (hourly)	Information: 50 µg/m^3 (hourly) Metering: 60 µg/m^3 (hourly)	Information: 80 µg/m^3 (half-hourly) Green Wave and Metering: 90 µg/m^3 (half-hourly)
Traffic Detection	Detectors and Manual Counting	Detectors	Detectors	Detectors FCD	Detectors
Air Quality Detection	4 AQMS: 3 Urban Traffic (1 in hotspot) 1 Urban Background	2 AQMS: 1 Urban Traffic (hotspot) 1 Urban Background	2 AQMS: 1 Urban Traffic (hotspot) 1 Urban Background	3 AQMS: 2 Urban Traffic (hotspots) 1 Urban Background	3 AQMS: 2 Urban Traffic (hotspots) 1 Urban Background
Model Use	Evaluation (Ex-post)	Screening Prognosis Evaluation	Screening *Prognosis Evaluation	Screening and Prognosis (Traffic) Evaluation (Emissions)	Screening Evaluation
Additional Input Data	Meteorology Built Structure	Meteorology Road Network Built Structure	Meteorology Road Network Built Structure	Meteorology Road Network Built Structure Traffic Events, Parking	Meteorology Built Structure
Traffic Modelling		Macroscopic (5-min interval) OPTIMA	Macroscopic (60-min interval) ViBS	Macroscopic (5-min interval) OPTIMA	Macroscopic (30-min interval) and MFD
Air Quality Modelling	Emission and Dispersion Models	Statistical Model Emission Model Dispersion Model	Emission and Dispersion Models	Emission Model	Emission and Dispersion Models
Statistical Model		Multilinear Regression PROFET			
Emission Model	Macroscopic exhaust emissions based on HBEFA + non-exhaust PM KFZEMISS	Macroscopic exhaust emissions based on HBEFA + non-exhaust PM PROKAS	Macroscopic exhaust emissions based on HBEFA + non-exhaust PM IMMIS^{em}	Macroscopic exhaust emissions based on HBEFA + non-exhaust PM	Macroscopic exhaust emissions based on HBEFA + non-exhaust PM IMMIS^{em}
Dispersion Model	Canyon-Plume-Box Model (CPB) IMMIS^{luft}	Combination of Gaussian Plume and Box Models PROKAS	Combination of Gaussian Plume and Canyon-Plume-Box Model (CPB) IMMIS^{net} & IMMIS^{cpb}		Combination of Gaussian Plume and Canyon-Plume-Box Model (CPB) IMMIS^{net} & IMMIS^{cpb}
Prognosis		Traffic Air Quality	*Traffic *Air Quality	Traffic *Air Quality	

*planned aspects

Table 3.6 DETM application examples from Germany - Summary

3.4 Conclusions

The main conclusions obtained from the state-of-the-art analysis can be divided into two areas as strategical conclusions which are related to the strategy implementation component of DETM and general methodological conclusions which focus on the monitoring component of DETM.

Strategical Conclusions (Strategy Implementation)

- There is not one implementation method for DETM. Depending on the problem and available resources; DETM systems can focus on different pollutants (mostly NO_2), cover one or more hotspots, implement different measures, or use various monitoring methods. FGSV [2014] states exemplary factors affecting the complexity of a DETM system as the size of the considered area, the presence of situation prognosis, and consideration of one single measure or combination of different measures.

- Exemplary environmental traffic management measures principally try to keep traffic in well-ventilated street canyons where building density is low by metering or re-routing traffic and thereby to reduce the congestion in narrow inner-city street canyons. In contrast to static traffic management, the DETM approach has advantages: it does not limit the accessibility of an area completely and does not cause a long-term relocation of emissions to other areas. However, studies and examples show that DETM measures can also cause short-term spatial relocation (e.g. alternative routes or queuing areas) or temporal relocation (e.g. longer peak hours) of the traffic and emissions. Therefore, the availability of "suitable relocation areas" is an important factor for the applicability and effectiveness of DETM measures.

- Exemplary DETM applications indicate that these systems help reducing short-term pollutant concentrations and the number of threshold exceedances, but they are not that effective in reducing annual average air pollutant concentrations. Consequently, depending on the severity of the air pollution problem, either DETM measures should be supported with static measures, or they should be stricter. In addition, DETM examples show that the reduction of overall traffic volumes and restriction of vehicle types with higher emissions (e.g. HDVs) at hotspots are more effective than lighter measures. This emphasizes the significance of traffic demand and traffic composition in air pollution concentrations. Consequently, it is important to consider DETM as a part of the overall air pollution control and when needed combine it with static measures such as travel demand management, promotion of public transport, non-motorized transport and cleaner vehicles.

- Considering EVs, and in particular ZEVs, the literature review shows that until now these vehicles have neither been broadly considered nor promoted in the context of DETM. The privileges given to these vehicles are mostly financial benefits as national incentives and only parking privileges as local incentives. From the reviewed studies on road traffic and local air quality (see **Table 3.5**), only one study [SCHÖLLNHAMMER, T. ET AL., 2014] dealt with the question of how the increasing EV shares can affect NO_2 and PM_{10} concentrations in street canyons. The results show that EVs have more potential for NO_2 reduction (compared to PM_{10}) and at least a 40 % EV rate in the vehicle fleet is needed for compliance with annual average air quality standards for NO_2. When DETM examples from Germany are reviewed (see **Table 3.6**), it is seen that DETM measures considering EVs have not been considered until now.

Methodological Conclusions (Monitoring Methods)

- Air quality and traffic monitoring are crucial not only for DETM strategy implementation steps (see **Figure 3.2**) but also for other applications that focus on road transport related air pollution. Detection of pollutant concentrations and traffic situations on the field is one way for monitoring. When traffic is considered, the detection and the number of observations are usually not a problem. City-wide automatic detection methods provide sufficient data in most cases but do not provide detailed information on vehicle type or fleet composition. When air quality is considered, data coverage is a problem - spatially and temporally. Data gathered from precise AQMS provide point information and are thusly spatially limited, whereas sampling methods (which can cover a larger area) cannot provide information for short-term evaluations (e.g. hourly). Low-cost monitoring tools offer potential for area-wide continuous measurement of air pollutants, but their potential is still being investigated.
- Due to the above-mentioned reasons, situation assessment in DETM is often supported by modelling. Modelling of road-transport related air quality covers three main aspects: traffic, emission, and dispersion modelling. Each aspect can be conducted in several ways and there are numerous tools available. It can be summarized that there are three major possibilities: utilizing detailed microscopic models which can be time-consuming (in terms of data collection, calibration, and computation) but more accurate; using macroscopic models which are fast and efficient but may not capture complex relationships and require aggregation of input data; or mesoscopic models which can find a middle way between the two options. This is the case for all three modelling aspects: traffic, emission, and dispersion. It is important to note here that usually macroscopic models are derived from detailed information gathered from microscopic ones (e.g. emission model HBEFA is based on PHEM; dispersion model PROKAS is based on MISKAM).
- As the whole modelling chain covers three different aspects and, in many cases, also different tools, there is room for uncertainties in the air quality modelling approach. These can result from aggregation levels or inaccuracies of the input data; from features of the model used (e.g. mathematical principles, covered aspects, scale, etc.) to the utilization of the modelling tool (e.g. settings, calibration). When traffic input data is considered, Diegmann, V. et al. [2020] states that 5-minute intervals are optimal for modelling in DETM and in addition to conventional detectors, other technologies can be used to gather more detailed information on the fleet composition. In terms of emission modelling, mostly situation-based models are used for traffic-related purposes due to their efficiency. However, they consider pre-defined traffic compositions and aggregate operational conditions into pre-defined traffic situations

although these aspects have a high impact on emissions. From the reviewed studies on road traffic-related air pollution (Table 3.5), only two use microscopic traffic and emission modelling: [Ghafghazi, G. and Hatzopoulou, M., 2015] and [Krajzewicz, D. et al., 2016]. For environment monitoring, Diegmann, V. et al. [2020] suggests input data at 30 to 60-minute intervals. Dispersion modelling in road traffic is mostly conducted with operational street canyon models, also due to their efficiency. From the reviewed studies (see Table 3.5), only one used CFD-based dispersion modelling [Gómez-Pérez, C. A. and Espinosa, J., 2018].

To summarize, DETM is a meaningful tool to reduce air pollutant concentrations from road transport, especially for peak concentrations at hotspots. The effectiveness of DETM measures can be enhanced further by providing more information to users, achieving higher compliance rates, and supporting DETM with higher-level static measures such as the promotion of cleaner vehicles, public transport, and non-motorized transport modes to ensure long-term effectiveness. Furthermore, monitoring methods play an important role in the effectiveness and evaluation of DETM measures. Existing monitoring methods can be improved by using spatially and temporally detailed, comprehensive, and disaggregated traffic and air quality input data; by utilizing accurate prediction tools that are being updated and calibrated constantly. Current developments in the technology and transportation fields such as the rise of cleaner vehicles, new traffic/air quality detection techniques, better computation opportunities for microscopic models as well as digitalization are offering new opportunities for DETM.

3.5 Research Need

In line with the literature review and the above-mentioned conclusions, two aspects are defined for further research in this dissertation. The first and main research need which is the focus of this thesis is related to the strategy implementation; the latter deals with the methodological research need.

Strategical Research Need: Evaluation of the Integration of ZEVs into DETM

DETM examples indicate the importance of vehicle composition in a hotspot on air pollution levels and on the decision about traffic management measure(s) to apply. DETM measures are not highly effective in reducing total emissions (or annual air pollution concentrations), but they improve traffic flow and efficiently redistribute emissions in urban areas to reduce emission/air pollution peaks at hotspots. That is why the availability of alternative less-critical routes or areas to direct/distribute traffic is particularly important.

Emerging developments in clean vehicle technologies and policies can substantially help to reduce overall emissions of road transport in urban areas and offer new possibilities for DETM. ZEVs can reduce the “emission dislocation pressure” on DETM measures. Since these vehicles do not have local tailpipe emissions, they can be freely re-routed or can be freed from dynamic restrictions (e.g. driving restrictions to a hotspot). Exempting ZEVs from DETM measures would also reduce the number of vehicles that are affected by the measure (e.g. queuing at a metering point or causing increased traffic volumes on alternative routes) and thus reduce overall emissions and improve the effectiveness of DETM measures. Furthermore, integrating ZEVs into DETM systems and giving exemptions can help to meet long-term ambitious international, national, and local goals such as reaching "*30 million zero-emission vehicles in operation on European roads by 2030*" [EC, 2020, p. 2–3] (see **Chapter 2.3.2**).

Methodological Research Need: Microscopic Monitoring of Air Quality in Hotspots

According to the literature review, in ideal conditions (e.g. high data availability and computational resources), detailed detection and modelling techniques can give comprehensive air quality monitoring for hotspots. From reviewed studies, only one study [GHAFGHAZI, G. AND HATZOPOULOU, M., 2015] used a complete microscopic modelling approach (including dispersion modelling) with a focus on the effects of static traffic calming scenarios on air quality. Not many sources could be found on air quality monitoring for the evaluation of dynamic measures (i.e. DETM measures) with complete microscopic detection and modelling approach.

With recent developments in portable low-cost detection devices, it can become possible to gather more comprehensive air quality data. Although it is not yet commonly used or proven, these technologies may offer the potential to be integrated into DETM. Thereby, they can help to fill the information gap in air quality monitoring and contribute to a better assessment. Although several studies report on the performance of low-cost sensors and monitoring devices, there is little information about how they react to different levels of road transport related emissions and therefore if they can be used as an additional data source for traffic related studies and particularly for DETM.

Due to operational and computational reasons, existing DETM systems use macroscopic/mesoscopic modelling approaches for traffic, emission, and dispersion modelling. Although this approach is convenient for city-wide monitoring, hotspots which are the focus of most DETM systems can be monitored in detail microscopically. Such an approach can solve the problems with aggregation in modelling approach and can lead to better evaluation of dynamic traffic management measures by covering operational factors affecting vehicle emissions.

This methodological research need sets the foundation of *Research Question 2* (see **Chapter 1.2**): What type of air quality monitoring (i.e. air quality measurements and modelling) approach is advantageous for the evaluation of DETM measures? Is a macroscopic or a microscopic monitoring approach advantageous for the evaluation of ZEV-related measures in DETM?

Consequently, it is aimed firstly to analyze the methodological research need, in order to be able to evaluate the possibilities better and decide on the final methodology for the main strategical research. **Chapter 4: Experimental Methodological Research** focuses on the methodological research need (*Research Question 2*). In line with the results from the previous chapter, **Chapter 5: Development of a DETM Approach** illustrates how the DETM system is designed and executed in this dissertation. Finally, **Chapter 6: Integration and Evaluation of ZEVs in DETM** deals with the main strategical research need (covering *Research Questions 3 to 7*).

4. Experimental Methodological Research

As a result of the research need assessment presented in **Chapter 3.5**, it is decided to evaluate a microscopic hotspot-monitoring approach with a focus on DETM to determine its advantages, disadvantages, and opportunities. This methodological research contains two aspects:

Evaluation 1: Microscopic detection of air pollutant concentrations by using low-cost devices,

Evaluation 2: Microscopic air quality modelling with detailed traffic, emission, and dispersion models.

For these two purposes, a test case area in Munich is selected. The selected area is located near an official urban traffic AQMS, where the highest annual average NO_2 concentration values are recorded within Germany (Landshuter Allee Station).

4.1 Description of the Test Case Area

There are six official AQMS available in and around Munich (**Figure 4.1**). The stations represent different zones (see **Chapter 2.2.2** and **Figure 2.6**) [LfU, 2017, p. 8].

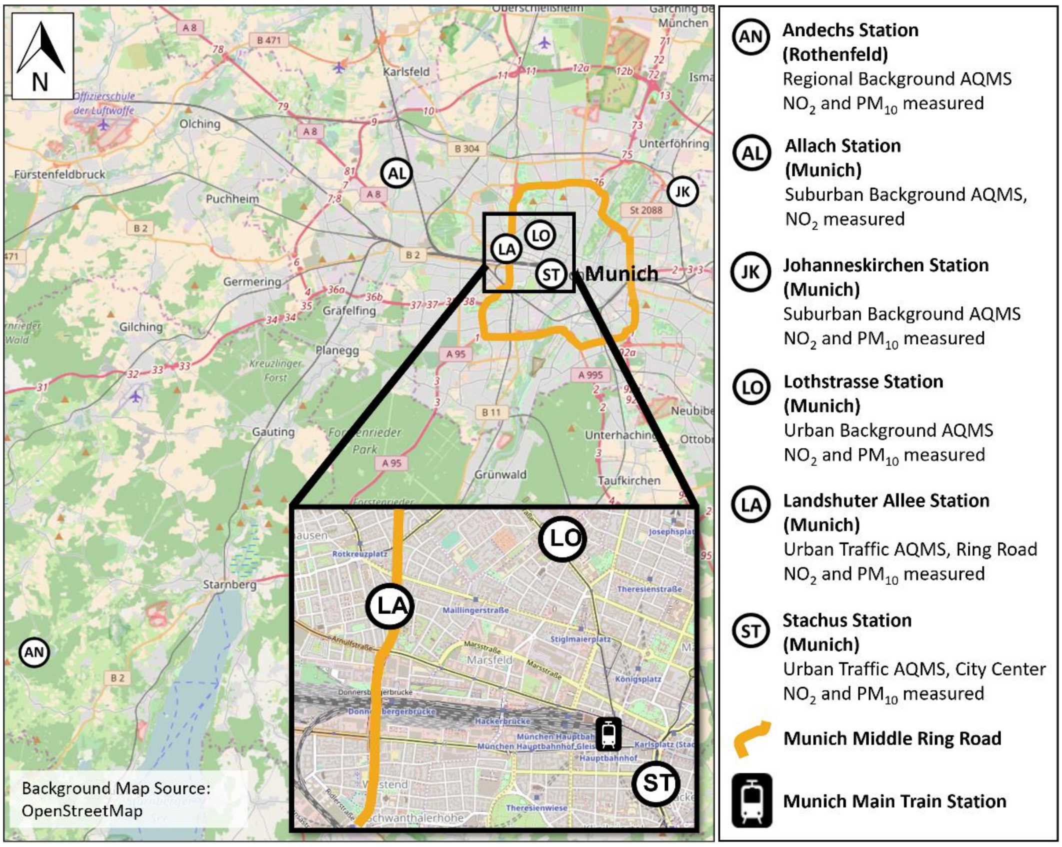

Figure 4.1 Air quality monitoring stations around Munich

The test case area (approximately 1 km^2) incorporates not only the AQMS Landshuter Allee (LA-Station) but also the surrounding area to cover different road and traffic situations as well as street canyon types for air quality measurements and modelling (**Figure 4.2**). The area includes a part of the ring road (Landshuter Allee) which is a separated carriageway with two lanes per direction and a speed limit of 50 km/h. In front of the monitoring station, the ring road is routed through a tunnel. There is one main intersection where the ring road is perpendicular to an urban distributor road (Nymphenburger Strasse) which is a single-carriageway with two lanes per direction and a speed limit of 50 km/h. Furthermore, there are several residential roads (single-carriageway with one lane per direction and a speed limit of 30 km/h) in the area. To summarize, the selected area covers different road types, road sections with different gradients, number of lanes and speed limits, and intersections with and without signalization.

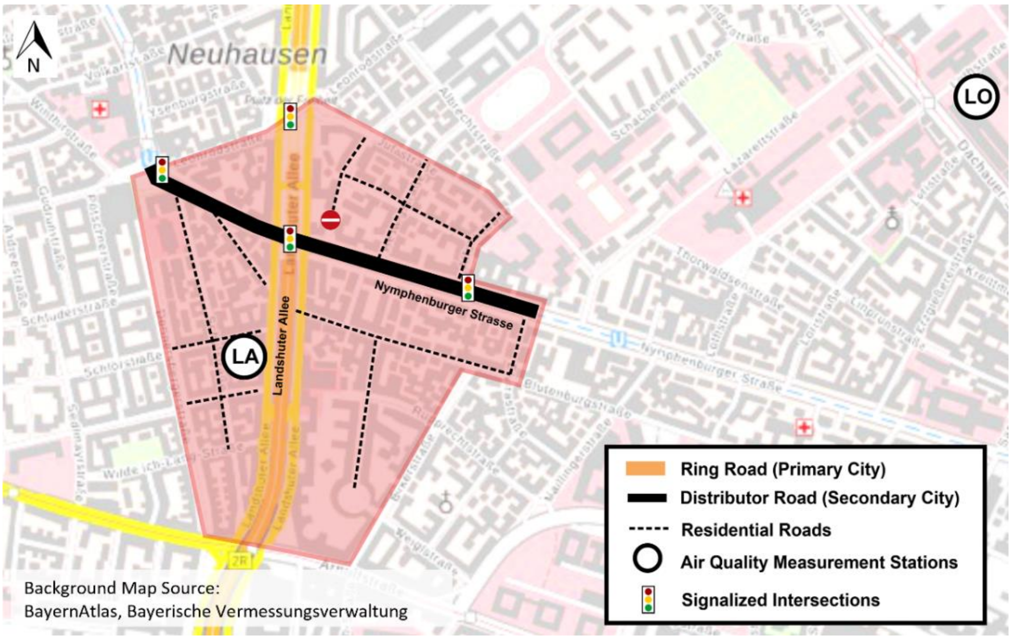

Figure 4.2 Test case-area

The primary goal of the experiment is to measure air pollution concentrations in several locations by using low-cost devices in addition to AQMS (**Evaluation 1**) and to compare the results of these measurements with the results of the detailed air quality modelling approach (**Evaluation 2**). For this, firstly, a mini model prototype is developed to test the planned detailed modelling approach with artificial data on a very small section of the study area. This prototype has shown that the coupling of microscopic traffic and emission calculation models works properly although it is computationally demanding, compared to the macroscopic approach. Utilized detailed CFD dispersion model is proven to provide spatially and temporally very detailed dispersion information. However, the modelling process was computationally so demanding that it was very difficult to use it for the whole test-case area within the scope and capacities of this study. As a result, it is decided to continue with an operational dispersion model and to focus on a comparison of microscopic and macroscopic emission modelling under the evaluation of the microscopic air quality modelling approach (see **Chapter 4.3**).

4.2 Testing of Low-Cost Sensors as Additional Air Quality Monitoring for DETM[5]

This chapter investigates the utilization of low-cost devices as an additional data source for air quality assessment through a case study in the city of Munich (**Evaluation 1**) to understand if they can contribute to a comprehensive and detailed air quality detection in urban areas (with a focus on road traffic). The main goal is to use and test low-cost air quality devices to assess their potential in providing frequent and extensive air quality data for monitoring traffic-related air pollution. For the field measurements, ten prototype air quality monitoring devices are used. Since the devices were optimized for particulate matter detection and not for NO_X at the time of the experiment, the investigation was conducted with the measurement of PM_{10} concentrations.

There are three main methods for the measurement of particulate matter (PM) concentrations: gravimetric, microbalance, and optical [AMARAL, S. ET AL., 2015]. A large part of available low-cost sensors for PM use smaller optical particulate counters (OPCs) and use the light scattering method [CRILLEY, L. R. ET AL., 2018]. Similarly, the used prototype devices are equipped with low-cost PM sensors which are laser particle counters that can detect particles of different sizes based on the scattering of the light. According to the Bavarian Environment Agency [LfU, 2017, p. 10], official air quality measurement stations in Munich use light absorption and gravimetric measurement principles for PM_{10} measurements. Due to the dissimilarity of the measurement principles and scopes of the devices, it is not expected from low-cost devices to give exact values with the high precision air quality monitoring stations. The goal is to measure and detect reasonable trends in PM_{10} levels for a greater area.

According to the literature research (**Chapters 2.2** and **3.2**) and the correlation analysis (**Chapter 4.2.2**), it is expected that data gathered from devices with low-cost sensors show four main trends:

- Higher PM_{10} values in case of higher background PM_{10} levels,
- Higher PM_{10} values in case of lower wind speeds,
- Higher PM_{10} values at locations where traffic volumes are higher,
- Higher PM_{10} values on the days that traffic volumes are higher.

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[5] Sections of this text were originally published in the paper:

CELIKKAYA, N.; FULLERTON, M.; FULLERTON, B. [2019b]: Use of Low-Cost Air Quality Monitoring Devices for Assessment of Road Transport Related Emissions. In: Transportation Research Procedia 41, pp. 762–781. DOI: 10.1016/j.trpro.2019.09.125. [CELIKKAYA, N. ET AL., 2019b].

4.2.1 Methodology

First of all, a preliminary analysis is conducted by using historical data, to analyze the influences of different factors such as weather and traffic conditions on PM_{10} concentrations as well as to select the proper study area and time period. Before the field measurements, the devices were calibrated by the low-cost device supplier. For calibration, devices were placed next to an official urban background AQMS (LO-Station, **Figure 4.1**) for several weeks before the field measurements. Machine learning algorithms were used to provide a model for each of these devices that can map raw measured values to corrected values. Detailed information on the calibration can be found in [CELIKKAYA, N. ET AL., 2019b].

Finally, measurements are carried out for the evaluation of low-cost monitoring devices and to collect data for a subsequent microscopic modelling approach. Several data are collected on three different days at ten locations in the test-case area (for details, see **Chapter 4.2.3**):

- **Air Pollution Data:** PM_{10} concentrations are obtained from nearby AQMS and low-cost devices. Each device incorporates in addition to a PM_{10} sensor, peripheral hardware for sending the values over a Wi-Fi access point to a central server. It has a digital output and a built-in fan. The device can send information at different intervals but was set for the measurements to output high-frequency data giving around 300 data points per hour (every 12 seconds). For both calibration and measurement periods, mobile phone network to Wi-Fi routing was used with standalone dongles or mobile phone "tethering" functionality to overcome the lack of Wi-Fi connection. For continuous data output, each device was connected to a power bank and was installed in a box (**Figure 4.3**).

Figure 4.3 Installation setting of devices

- **Weather Data:** The hourly weather information from the German Weather Service's (DWD) station at the airport (approx. 40 km away from the test case area) were used. In addition, a wireless digital weather station was installed at the main campus of the Technical University of Munich (approx. 3 km away from the test case area, at roof level) to collect the local weather conditions (outdoor temperature, humidity, air pressure, wind speed, and wind direction) in the city center (see **Figure 4.4**).

- **Traffic Data:** For subsequent modelling purposes and plausibility testing of the sensor results, it is important to have information on road transport. Consequently, various traffic data were collected. For the main streets, data from loop detectors were provided by the City of Munich; for residential streets without detectors, manual traffic counts were conducted to complete the data on traffic volumes (see **Figure 4.4**).

4.2.2 Preliminary Analysis

For a preliminary analysis, the historical air quality data (PM_{10} daily average values) from the stations in and around Munich is used for the year 2016 (from 02.01.2016 to 30.12.2016)[6]. Air quality data from official AQMS are publicly available in Germany on the website of the German Environment Agency (Umweltbundesamt, UBA). Firstly, daily PM_{10} concentrations of five AQMS in Munich are compared. It is seen that the urban traffic stations, as expected, have the highest concentrations. From the two urban traffic AQMS, LA-Station had the highest values and was selected as the hotspot of the test case area for further analysis.

Afterwards, the daily average PM_{10} values from LA-Station for the year 2016 are compared according to different months and days. It is seen that concentrations range highly in colder months compared to warmer months. When different days are compared, workdays showed higher mean values and ranges than weekends and public holidays. To see the influence of meteorology, data on average daily weather conditions for the same time period is gathered, which is also publicly available on the website of The German Meteorological Service (Deutscher Wetterdienst, DWD). According to the correlation analysis between daily PM_{10} values and meteorological parameters, the highest correlation is seen with wind speed (r= - 0.372), followed by the daily average air pressure, daily average temperature as well as rain and snowfall. In addition, the influence of traffic is considered. The traffic data (provided by the City of Munich) is from a loop detector located in front of the LA-Station (see **Figure 4.4**). The correlation analysis of PM_{10} values and daily traffic volumes showed a significant positive relation (r= 0.303). Furthermore, the correlation between daily PM_{10} values of different stations is investigated. The highest correlation for LA-Station is seen with LO-Station (r= 0.835) which is the closest urban background AQMS (see **Figure 4.1** or **Figure 4.2**). Consequently, PM_{10} values from LO-Station were used as an insight into the portion of urban background pollutant concentrations at LA-Station. In order to understand the contribution of road traffic to total PM_{10} concentration at LA-Station, concentration values in LO-Station are extracted for each data point. The results showed that the estimated average

[6] Since the PM_{10} values are extremely high in the new year evening, due to fireworks, 01.01.2016 and 31.12.2016 are extracted from the dataset.

daily contribution of road traffic is around 8 µg/m³. As expected; it is higher on workdays compared to weekends and holidays.

To summarize, this preliminary statistical analysis showed that PM_{10} levels at urban traffic AQMS in the test area are highly correlated with respectively the PM_{10} values from the closest urban background station, wind speed, and traffic volumes. Therefore, it is decided to perform the field measurements not in winter or summer months to exclude additional influencing factors (e.g. domestic heating, ice-salting, etc.) and not only on weekdays but also on weekends to cover diverse traffic-related emission levels. Detailed information on the preliminary analysis can be found in [CELIKKAYA, N. ET AL., 2019b].

4.2.3 Measurements

For the experiment, there were ten devices with low-cost sensors available (**Figure 4.4.a**). One device was placed at Olympiapark (Location D) which is one of the nearest green areas to test sensors at low emission levels and to have reference values to compare with the two urban/suburban background stations (reference urban background AQMS). This device will be referred to as "the reference urban background device" in this chapter (**Figure 4.4.b**).

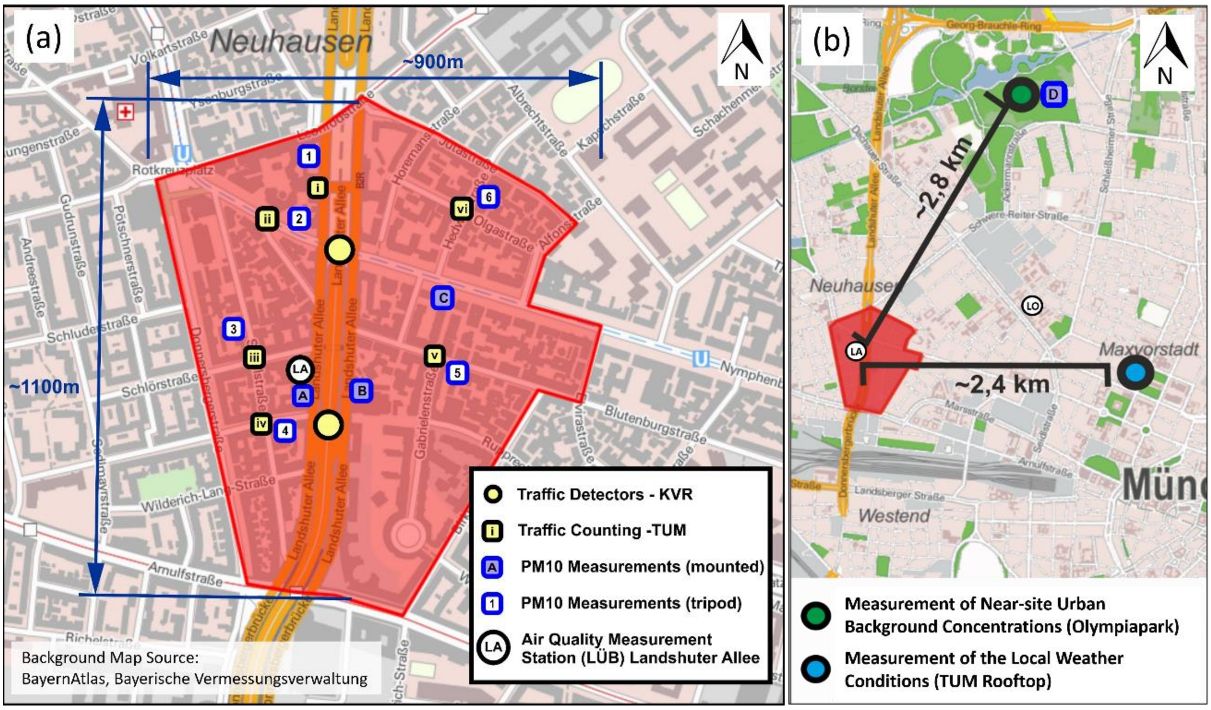

Figure 4.4 Location of the utilized devices and detectors (a), Locations of the reference urban background device and the installed digital weather station (b)

Considering the importance of the street canyon geometry on air pollutant dispersion, the remaining nine devices are distributed to different traffic-related locations (**Figure 4.4.a**) according to: traffic volumes on the streets (i.e. next to the ring road, distributor roads, and residential roads), type of street canyon (i.e. at narrow or wide canyons) as well as the direction of the street canyon (i.e. west-east or south-north direction). Where manual traffic counts were made, the devices were placed with tripods (Locations 1 to 6). At locations where no manual traffic counting was needed (Locations A, B, C), they were mounted on existing infrastructure (e.g. street lights, road signs). Example photos can be found in **Figure 4.5**. **Figure 4.5.a**. shows the device located next to the existing LA-Station (the reference urban traffic AQMS), which will be referred to as "the reference urban traffic device" (at Location A) in this chapter.

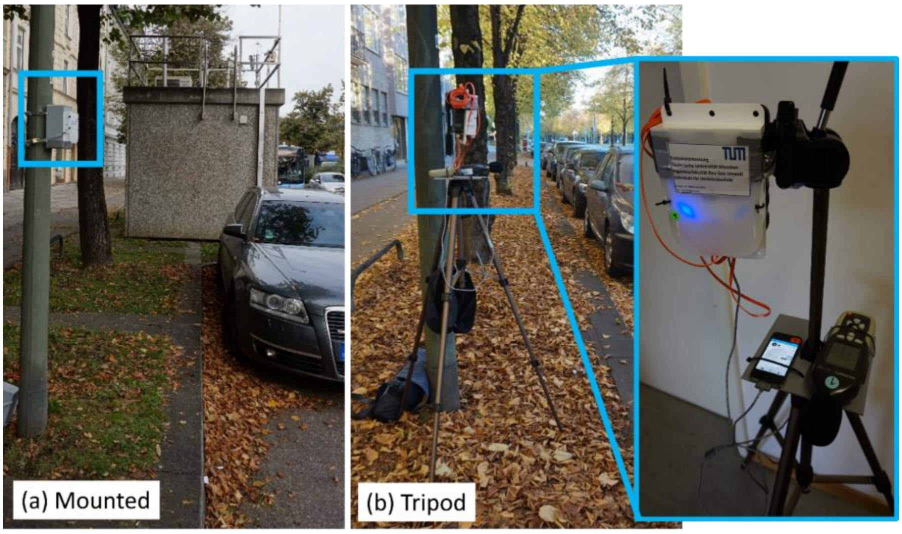

Figure 4.5 Two different installation settings of the devices

According to the Manual of Ambient Air Monitoring in Germany [EICKELPASCH, D. AND EICKELPASCH, G., 2004] which is in line with European Guidelines [EC, 2008], the measurement locations should be open for enough airflow. Devices should not be right next to barriers, should be 1,5 to 4 m above the ground, should be at least 25 m away from busy intersections, and at least 4 m away from the middle of the closest lane [EICKELPASCH, D. AND EICKELPASCH, G., 2004, p. 21]. For the placement of the devices, these criteria were considered.

The field measurements (traffic volumes, weather and air pollutant conditions) at the test case area are done on three days in October, each day for four hours (**Table 4.1**). During the measurement period, there were several technical problems faced which resulted in missing data for the final evaluation (e.g. device at Location B was not operating). In addition, due to some technical problems, not all locations started to measure punctually at the beginning of the measurement period. As a result, for the final analysis, data from the last three hours of the measurements (the time period in which complete data could be received from all locations) is used.

Day	Measurement Period	Analysis Period	Description
10.10.2017	15:00 – 19:00	16:00 – 19:00	Tuesday, Evening Peak
12.10.2017	06:00 – 10:00	07:00 – 10:00	Thursday, Morning Peak
15.10.2017	06:00 – 10:00	07:00 – 10:00	Sunday, Off Peak

Table 4.1 Description of the measurement time

As mentioned in the introduction, it is expected from device outputs to be in line with the PM_{10} concentration trends obtained from reference AQMSs as well as with background concentrations, wind speeds, and traffic volumes. The following paragraphs explain these trends on measurement days.

<u>PM_{10} Concentrations from AQMSs:</u> In **Figure 4.6** hourly PM_{10} concentration values from four official AQMS on these three days can be found (measurement periods on each day are highlighted). It can be seen that on Tuesday most of the stations show (except the one at Stachus) slightly increasing values; on Thursday all stations show a peak around 08:00 AM and on Sunday all show a decreasing trend. Suburban and urban background concentration levels are measured respectively at JK-Station and LO-Station.

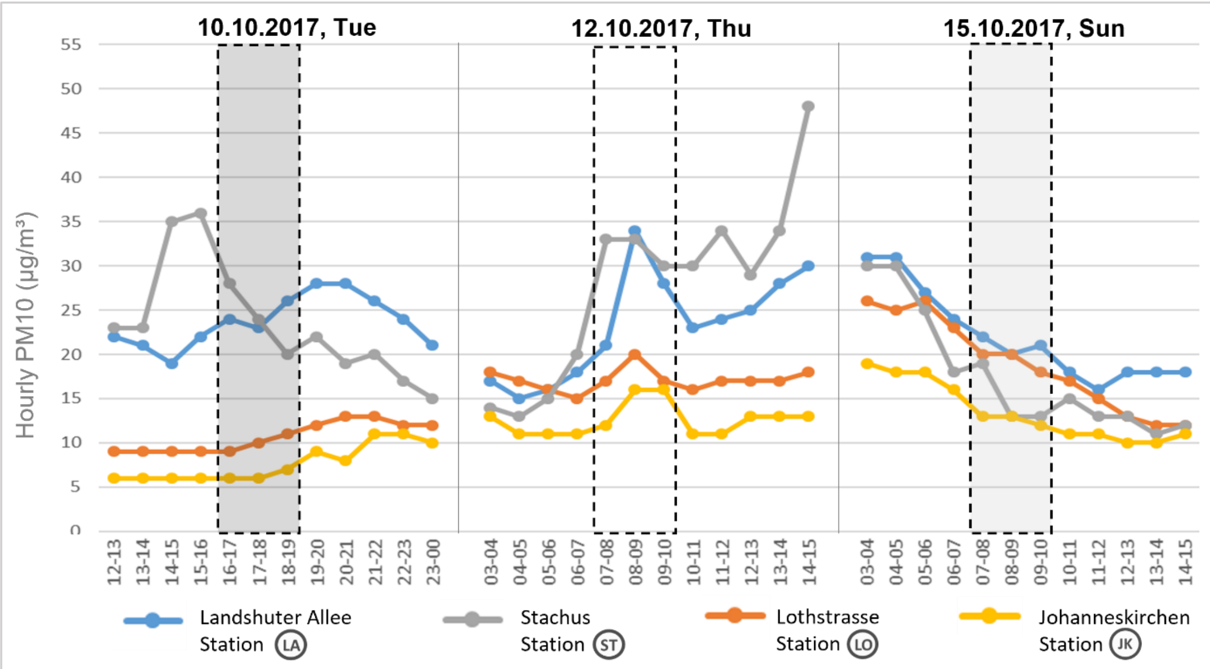

Figure 4.6 Trends in PM_{10} concentrations at AQMS on the measurement days

<u>Wind Conditions:</u> Wind speeds on three measurement days are all below 3 m/s, which is quite low. While on Tuesday the wind speeds decreased during the measurement period (from 2,5 to 1,5 m/s), they rose on Thursday (from 0,5 to 2,0 m/s), and on Sunday the lowest wind speed is observed which was stable below 0,5 m/s.

<u>Traffic Volumes:</u> When hourly traffic volumes of different measurement locations are analyzed (**Figure 4.7**), it can be seen that Location A has the highest and Location 1 has the second highest traffic volumes (both located next to the ring road) followed by Location 2 and Location C (located next to the distributor road). As expected, traffic volumes on residential streets (Locations 3, 4, 5, 6) are noticeably less on all three days and all locations have the lowest values on Sunday. From the provided traffic data, there was missing data for one loop detector for the first day (Tuesday) which resulted in a data gap for three locations.

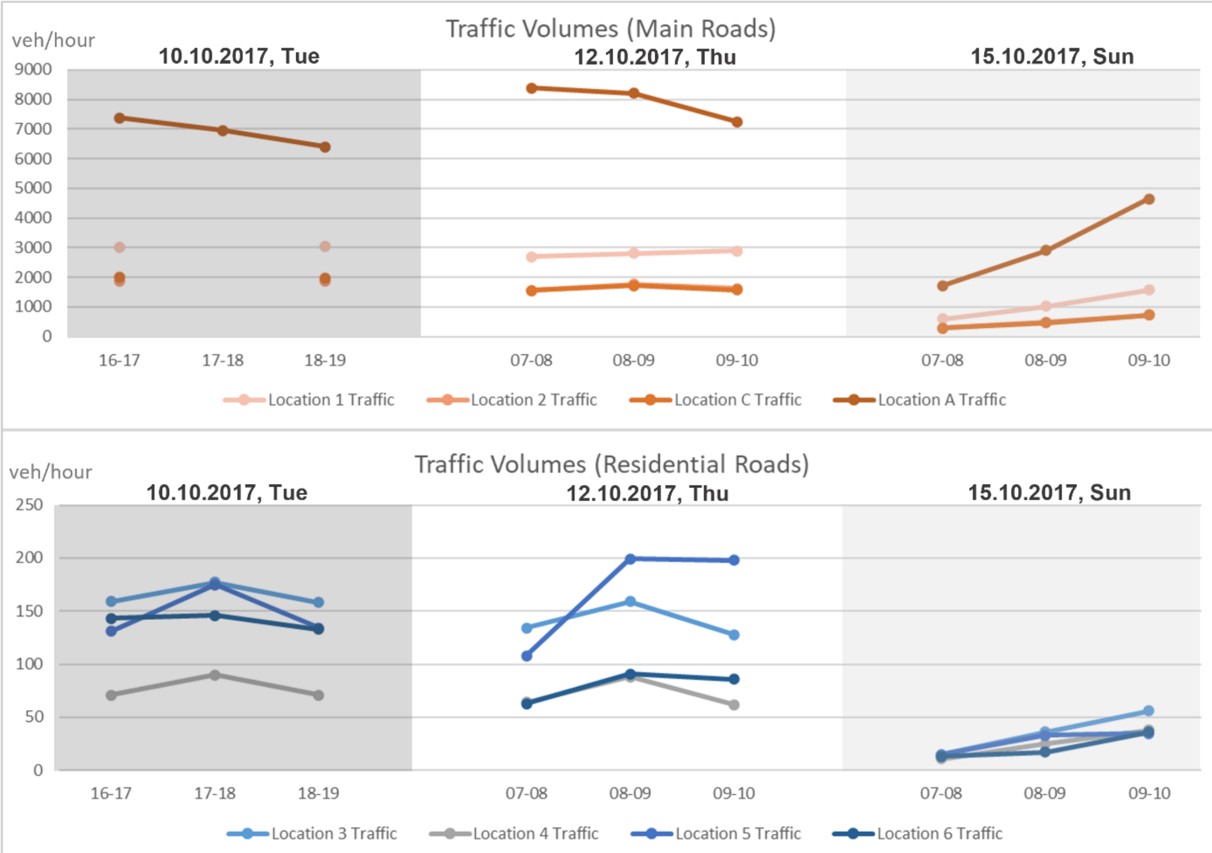

Figure 4.7 Traffic volumes from main and residential roads

4.2.4 Results

The study aims to compare air pollution trends measured by AQMSs and by low-cost devices as well as to see the reactions of the devices to changes in three relevant indicators: background pollutant concentrations, wind speeds, and traffic volumes. First of all, the values from reference devices and reference stations are compared. The results from the reference urban traffic AQMS (LA-Station) and the reference traffic device (at Location A) display that device values are lower than the AQMS values and the peaks are less pronounced (**Figure 4.8**). However, the trends for each day and between the days are matching (exact values can be found in [CELIKKAYA, N. ET AL., 2019b]). According to the measurements from the two reference urban/suburban background reference AQMSs (LO-Station, JK-Station), the urban background concentration levels are lower on Tuesday compared to the other two measurement days (**Figure 4.9**). The reference urban background device at Location D (Olympiapark), on the other hand, shows similarly low values for all three days and does not reflect these different concentration levels between the measurement days. This can be explained by the location of the reference device (in an urban park) where less air pollutant concentrations from urban/suburban background could reach.

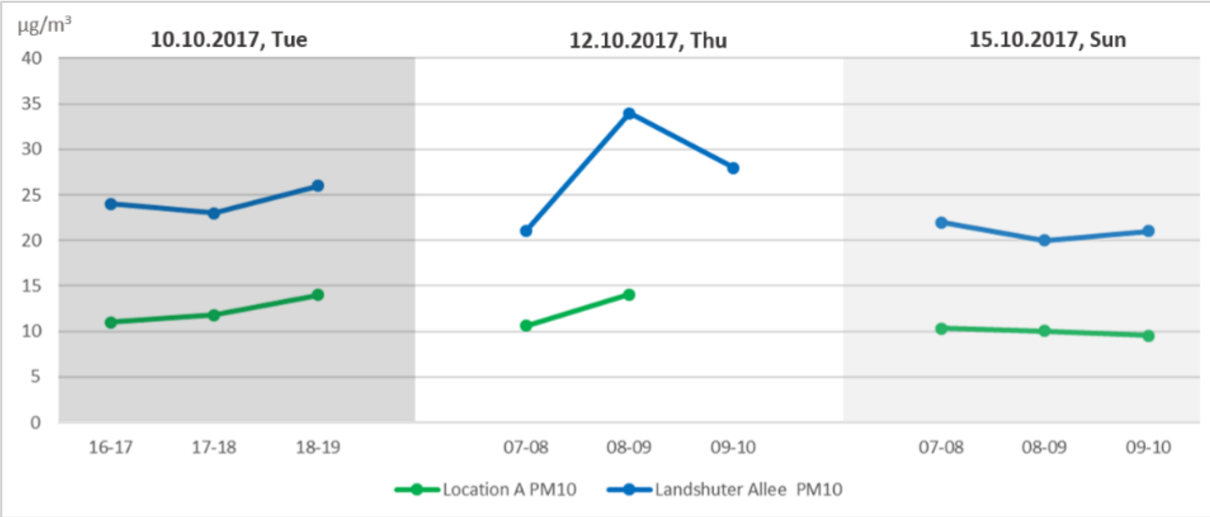

Figure 4.8 Comparison of PM_{10} concentrations measured at the reference urban traffic AQMS to the reference traffic device at Location A

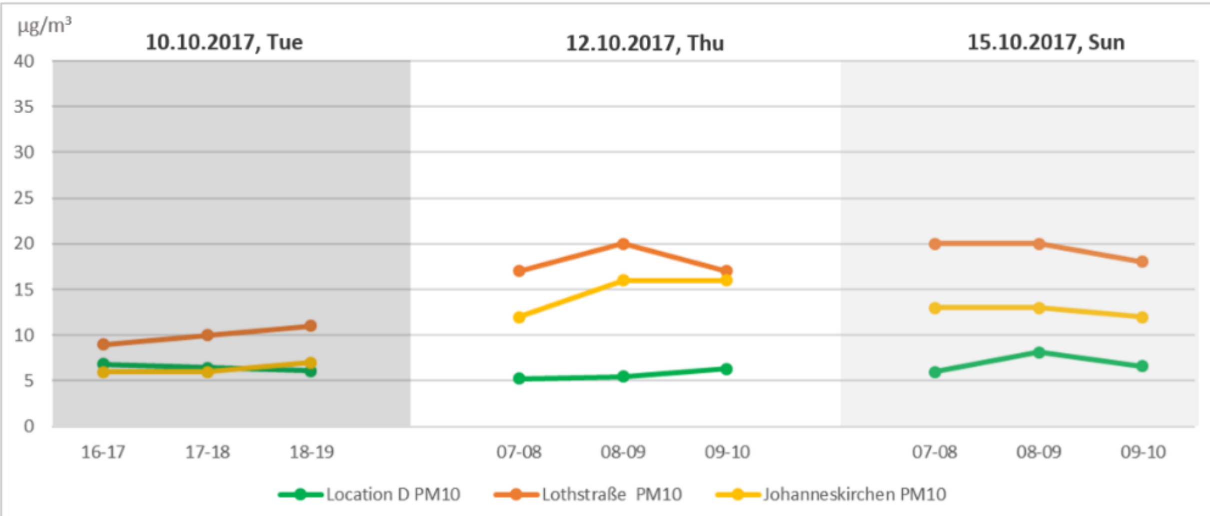

Figure 4.9 Comparison of PM_{10} concentrations measured at the reference urban background AQMS to the reference urban background device at Location D

When the values from the two reference devices are considered (**Figure 4.8** and **Figure 4.9**), the results demonstrate that the reference traffic device (Location A) measured, expectedly, higher concentration levels compared to the reference urban background device (Location D).

As a next step, PM_{10} concentrations measured by devices from different locations with different traffic volumes are compared (**Figure 4.10**). The results did not reflect remarkably high concentration levels for the locations with high traffic volumes (e.g. Location A) and only slightly lower PM_{10} values at residential streets could be observed. In addition, although traffic volumes were considerably less on Sunday (**Figure 4.7**), the devices delivered quite similar PM_{10} values for all three days and all locations.

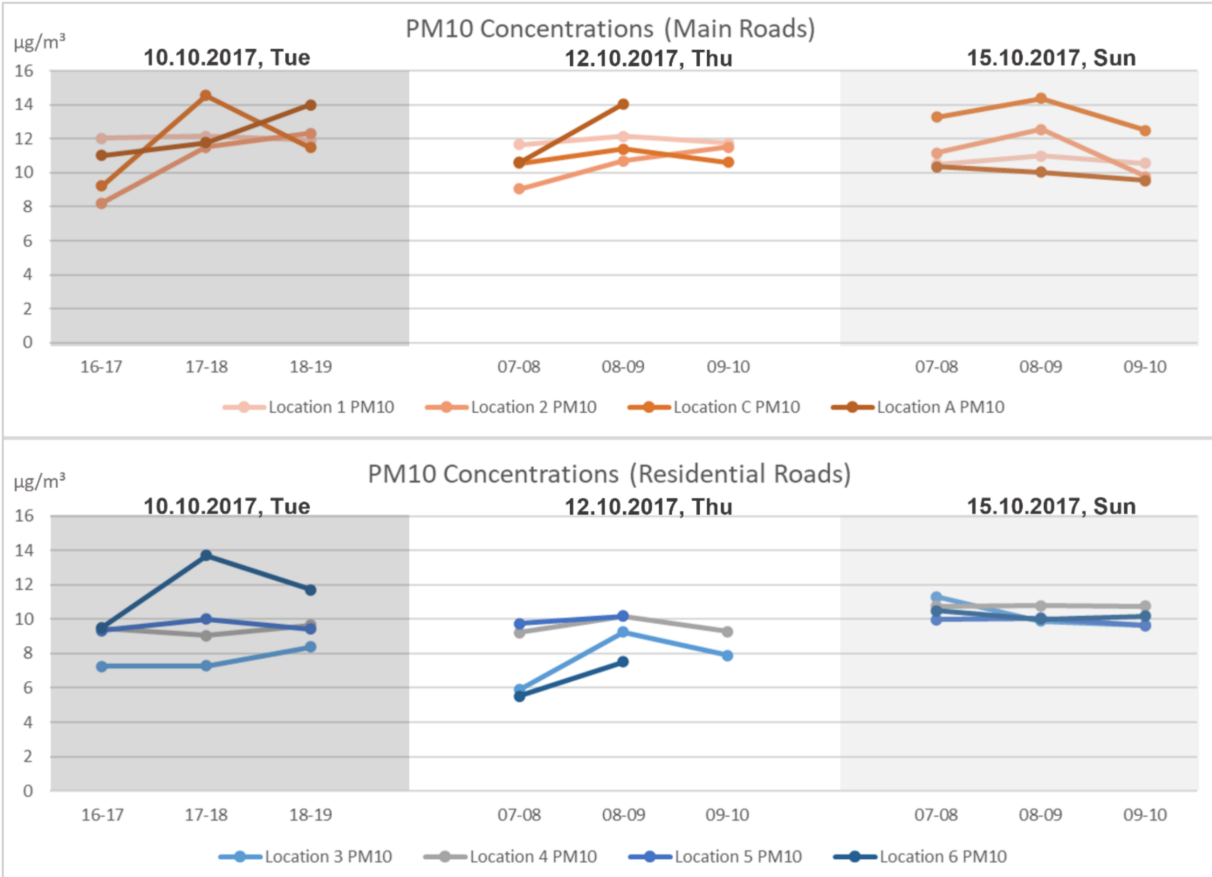

Figure 4.10 PM_{10} concentrations from main and residential roads

The daily trends seen in Munich from all official AQMSs (see **Figure 4.6**) can be slightly seen in values from low-cost devices (**Figure 4.10**). An interesting outcome is that devices placed in residential streets show high homogeneity on the last measurement day (15.10.2017, Sunday) which can be explained by concentrations being less influenced by local traffic volumes and wind conditions (both quite low on that day). On the other hand, the first measurement day (10.10.2017, Tuesday) has the lowest urban background levels and highest wind speeds which could result in lower concentrations, especially in residential areas. Yet, the PM_{10} values from the devices are not particularly lower on this day, compared to other days.

4.2.5 Conclusions

The results show that the absolute values from the reference urban traffic device (Location A) and the reference urban traffic AQMS (located next to each other) were not matching during the measurement period, despite the calibration process. However, the trends were matching to a certain degree which is the focus of this experiment. The second reference device for urban background concentrations which was placed at Olympiapark (Location D) delivered the lowest values for all three days which meets the expectations (other devices are located near traffic areas). However, absolute concentration values and trends did not match the two official urban background AQMSs. The reference device displaying similarly low values for all three days can be related to the location of the device in the park.

In general, due to the limited number of hourly values and measurement locations, the results are hard to interpret statistically and the question of whether the differences are down to highly local factors or measurement errors could not be answered. Some trends can be seen on a small scale, whereas some expected trends were not visible. What can be said with some certainty (based on the reference devices) is that the absolute values from devices were significantly shifted lower than real values and sensors' reactions to changes and peaks were not as strong as expected. For example, although traffic volumes differed notably between the locations as well as between measurement days, no big change could be seen in sensor values. It is hard to say whether this is due to traffic's limited impact on PM_{10}, other dispersion-related factors, or a lack of measurement accuracy. This can be a result of differences in environmental conditions during the calibration and measurement periods as well as lower PM_{10} concentration levels at the calibration station LO-Station, compared to the measurement area around LA-Station. Furthermore, the effects of environmental conditions, especially, temperature and humidity on these types of sensors have been already noted in **Chapter 3.2.1**.

There were two reasons to use hourly values in this study. Although the sensors measure at high frequency, combining many data points into an average increases measurement quality and clarity by removing noise. Furthermore, reference values from AQMS that are used for comparison are only available hourly. This makes it difficult to assess the measurement accuracy or plausibility of devices for any shorter time period. Consequently, the results of this experiment suggest having longer measurement periods to increase the sample size of hourly data for a comprehensive comparison.

Although the calibration process yielded good results, the absolute values during the measurement phase were significantly shifted, when compared to the official AQMSs. As discussed above, this may be due to the different seasonal weather conditions between the calibration and measurement periods as well as the difference in PM_{10} levels between the two locations. This can be solved by selecting measurement locations with similar conditions to calibration locations; or by calibrating devices under diverse conditions (most easily achieved by calibrating for a longer period). This also supports the information from previous studies that frequent in-situ calibrations are needed. It is worthwhile keeping up with changes in sensor technology to try and achieve better results already at the raw data level.

It is also important to note that due to complex relationships between meteorological conditions, the built environment, traffic and pollution levels, it is not easy to interpret results in relation to one factor at a time. This implies again the importance of including dispersion modelling (which takes these complex factors into account at once) in the air quality monitoring process for a better interpretation of point measurement results from low-cost devices. In this way, it can be better understood, why in particular locations and times pollutant concentrations are higher or lower than expected.

4.3 Comparison of Emission Modelling Approaches for DETM[7]

This chapter tackles the second part of the methodological research need: the assessment of a microscopic air quality modelling approach (**Evaluation 2**). The utilization of a microscopic traffic model in this dissertation is settled due to the focus on dynamic traffic management. Furthermore, the usage of a detailed dispersion model (CFD) is already eliminated at the first model prototype because of computational limitations under the scope of this thesis (see **Chapter 4.1**). Consequently, this experiment concentrates on the comparison of two emission modelling approaches for road transport related air quality assessment (with a focus on DETM): the macroscopic approach by using traffic-situation based emission models and the microscopic approach by using instantaneous emission calculation models. The main goal is to understand especially for which situations these two approaches deliver different results; how the differences between the model results change for different road types and traffic situations as well as different temporal and spatial aggregation levels of the input data.

4.3.1 Methodology

For the comparison, the second measurement day from the test-case study is selected: the modelled period is between 6 AM and 10 AM on a Thursday, 12. October 2017 (**Table 4.1**). The study period covers the morning peak hour when traffic volumes gradually increase from 6 AM on. It is aimed to have a representation of different congestion levels in the model by selecting this period.

For traffic modelling, PTV VISSIM (Version 9) is used. During the development of the traffic flow simulation model, speed limits and traffic volumes of the street sections within the network, as well as public transport in the area, pedestrian flow at intersections, and realistic signal plans are considered. Traffic volumes and turning rates at intersections are estimated (in 15-minute time intervals) by using data from existing loop detectors for major roads and from manual counts for residential roads for the simulation period (see **Chapter 4.2.1**). The traffic flow simulation model was run with three different random seeds to include stochasticity in the traffic situation. Comparing the average traffic volumes from the simulation to the field data, a Root Mean Square Percentage Error (RMSPE) between 0,07 and 0,14 could be reached.

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[7] Sections of this text were originally published in poster form in:

CELIKKAYA, N.; GERSTENBERGER, M. [2019]: Comparison of Traffic Situation Based and Instantaneous Emission Models for Emission Calculation for Dynamic Traffic Management. Poster Presentation in 98th Annual Meeting of the Transportation Research Board, January 13–17 2019, Extended Abstract Paper Number 19-04744. Washington, D.C. [CELIKKAYA, N. AND GERSTENBERGER, M., 2019].

For microscopic emission modelling PHEM is used. PHEM is an engine-based emission model, where emissions are calculated in relation to the engine performances (i.e. engine maps) [HAUSBERGER, S. AND REXEIS, M., 2017; SO, J. ET AL., 2018]. Being able to use different emission maps, the model can illustrate all combinations of vehicle speeds, accelerations, road gradients, and vehicle payloads [HAUSBERGER, S. AND REXEIS, M., 2017]. The emission data comes from calibrated real measurements from individual vehicles. They are later aggregated to representative average vehicles for each vehicle category (defined by the vehicle type, engine type, and emission class) [HAUSBERGER, S. AND REXEIS, M., 2017]. The user can evaluate a specific vehicle model by providing data on engine load/engine speed or by using these average vehicle values [HAUSBERGER, S. AND REXEIS, M., 2017]. For this experiment, PHEM (Version 12.01) is used in "advance mode". In PHEM-Advance, the user provides vehicle trajectories (in this study provided from microscopic traffic simulation) together with the fleet composition and the model calculates emissions by using average vehicle values [HAUSBERGER, S. AND REXEIS, M., 2017]. In this modelling approach, only tailpipe emissions (hot) are calculated.

For macroscopic emission modelling, HBEFA is utilized. HBEFA uses the information provided by the PHEM model as "base emission factors" for the calculation of aggregated emission factors, [KELLER, M. ET AL., 2017b]. For HBEFA, PHEM values which are already characterized by vehicle type, engine type (petrol or diesel), and emission class (e.g. Euro 1, Euro 2, …, Euro 6) are aggregated to average traffic situations. The categorization of traffic situations in road traffic is done by area type (urban or rural), road type (e.g. motorway, distributor/collector road, residential access road), speed limit, and level of service (LOS). For this study, HBEFA Version 3.3 is used which provides emission factors for several vehicle categories (passenger cars, light commercial vehicles, heavy-duty vehicles, busses, and motorcycles) [KELLER, M. ET AL., 2017a]. This update of HBEFA includes emission factors for the improved diesel Euro 6 engines with Real Driving Emissions (RDE) which are the new regulations for vehicle emission tests. It is important to note here that, only hot emission factors from HBEFA are used for this analysis.

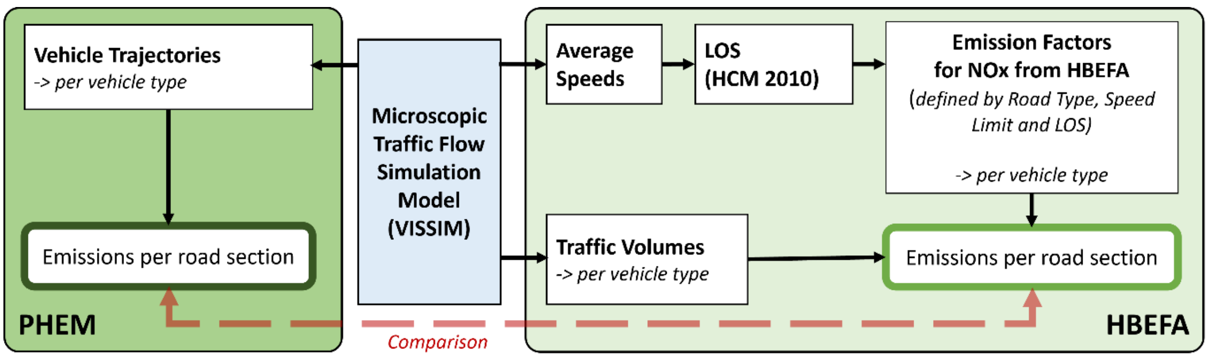

Figure 4.11 Methodology for emission calculation with VISSIM, PHEM, and HBEFA

For emission calculation comparison, VISSIM Model outputs are generated to be used as ground-truth data for both microscopic and macroscopic emission models (see **Figure 4.11**). For the PHEM model, exported vehicle trajectories are split into defined sections to have emission values per road section.

For the HBEFA model, required data on traffic volumes and average speeds are exported from VISSIM directly per each road section.

Figure 4.12 shows how the road network of the study area is divided into different road sections; classified as main roads (M), tunnel sections (T), distributor roads (D), and residential roads (R). For the main roads, tunnel, and distributor roads, driving directions are taken into account separately for emission calculations. For residential roads, no distinction between driving directions has been made. The length of road sections included in the analyses varies between 50 m (section R6) and 280 m (section R12). The average length of road sections is 120 m. Tunnel sections are the only road sections with a gradient, where it is +4 % for T3SB and -4 % for T3NB.

Figure 4.12 Microscopic traffic flow simulation network

HBEFA uses traffic volumes per road section (separately for passenger cars, light commercial vehicles, and heavy-duty vehicles) as one input data (**Figure 4.11)**. In addition to this data, HBEFA requires a level of service for each road section (given as four qualitative definitions: LOS 1, 2, 3, 4). Since it is not explicitly defined by HBEFA, for this analysis they are calculated by using Highway Capacity Manual [TRB, 2010] and average speeds per road section (details in **Chapter 4.3.2**). The reason for using HCM is the possibility to estimate LOS for urban street segments (Automobile Mode) simply by using only speed indicators. Another necessary input for HBEFA is the road type. All residential roads are assigned to the road type “residential access road”; the distributor road sections are assigned to the road type “distributor road” and the sections of the main road and the tunnel sections are assigned to the road type “trunk city road”.

A representative fleet composition for Germany including the different vehicle types for the year 2018 is used for both models. In this fleet, 49 % of passenger cars are petrol driven, and 51 % respectively with diesel engines. In the passenger car (PC) fleet, the share of vehicles that already comply with the regulations of the newest emission class Euro 6d for diesel is included (0,2 %). The minority of light commercial vehicles (LCV) are driven by petrol engines (only 4 % of all vehicles of this vehicle type) and all heavy-duty vehicles (HDV) are equipped with diesel engines (**Appendix 4a**). An overview of emission factors for vehicle categories of the defined fleet composition can be found in **Appendix 4b**.

4.3.2 Analysis and Scenario Descriptions

For the analysis, the relative difference (ΔNO_X) between the emission results from HBEFA and the results from PHEM are used which is calculated as follows:

$$\Delta \mathrm{NO}_X = \frac{\mathrm{NO}_X \text{ concentrations from PHEM} - \mathrm{NO}_X \text{ concentrations from HBEFA}}{\mathrm{NO}_X \text{ concentrations from HBEFA}}$$

To check the relationship between this difference (ΔNO_X) and the traffic situation, LOS is calculated. For this, the HCM approach of using “travel speed as a percentage of base free flow speed” which is suggested for the calculation of LOS with an automobile on interrupted urban streets [TRB, 2010, p. 8] is adopted. Instead of percentages, for each road section, the ratio of average speed in relation to the speed limit (v_{act}/v_{max}) is calculated (see **Table 4.2**). The classifications of LOS A and LOS B according to HCM (mean travel speed higher than 67 % of the speed limit) are used to define LOS 1 (the free flow operation) in HBEFA. LOS C and LOS D from HCM (mean travel speed between 40 % and 67 % of the speed limit) are used for LOS 2 (the stable operation) in HBEFA. For the distinction between LOS 3 (less stable operation) and LOS 4 (stop and go), the threshold of 30 % is used.

HCM Threshold: Travel Speed as Percentage of Base Free-Flow Speed	HCM LOS	Calculated Threshold: Ratio	Assigned LOS for HBEFA
> 85 %	A	(> 0,85)	LOS 1
67 – 85 %	B	(0,67 – 0,85)	
50 – 67 %	C	(0,50 – 0,67)	LOS 2
40 – 50 %	D	(0,40 – 0,50)	
30 – 40 %	E	(0,30 – 0,40)	LOS 3
< 30 %	F	(< 0,30)	LOS 4

Table 4.2 LOS for urban street facilities HCM [TRB, 2010] and used ratios

For the analysis of differences between the two modelling approaches in relation to different temporal and spatial aggregation levels, results are analyzed in two scenario groups (**Figure 4.13**):

For temporal aggregation levels, four different time intervals are considered: 15 minutes, 30 minutes, 60 minutes, and 120 minutes (two hours of the morning peak period: 7:00-9:00 AM). To illustrate, to compute emissions for a specific road section with PHEM between 9:00 and 9:15 AM, trajectories from vehicles that drove on that section at that time interval are taken. For the same calculation with HBEFA, traffic volumes (per vehicle type) and average speeds (overall traffic) are exported for the same road section and time interval. Temporal aggregation scenarios are called T15, T30, T60, and T120. To evaluate the differences in emission results (ΔNO_X) in relation to different temporal aggregations, these scenarios are compared to each other (red box in **Figure 4.13**).

To analyze the data aggregation in a spatial context, two scenarios are used: In the first scenario, each road section is considered separately; in the second scenario main and distributor road sections on the same approach are merged into an aggregated longer street segment (e.g. M1NB and M2NB merged into one segment, M1SB and M2SB merged into another). Residential road sections are left the same. The two spatial aggregation scenarios are considered, only for the highly aggregated time intervals (T60 and T120). Spatial aggregation scenarios are marked as S1 and S2. To check the results in relation to spatial aggregation they are compared to each other (orange boxes in **Figure 4.13**).

Temporal Aggregation					
T15 15-minutes intervals (16 intervals)	**T30** 30-minutes intervals (8 intervals)	**T60** 1-hour intervals (4 intervals)	**T120** 2 peak hours (7am-9am) (1 interval)		
S1-T15 (N=1680)	**S1-T30** (N=840)	**S1-T60** (N=420)	**S1-T120** (N=105)	**S1** Per road section (35 road sections, all road types)	**Spatial Aggre-gation**
		S2-T60 (N=96)	**S2-T120** (N=24)	**S2** Per street segment (8 street segments, main & distributor)	

N=Number of Observations (from 3 simulation runs)

Figure 4.13 Overview of analyzed 6 scenarios

From three simulation runs, a sample size of 1.680 observations (calculated emission values) is obtained for scenario S1-T15 (35 road sections x 16 time intervals for 4 hours x 3 runs). Due to temporal aggregation, this number of observations is reduced to 840, 420, and 105 respectively for other scenarios S1-T30, S1-T60, and S1-T120. For the spatial aggregation scenarios S2-T60 and S2-T120, the number of observations is less (96 and 24) due to the further aggregation of road segments.

4.3.3 Results

Firstly, the differences between modelling approaches (ΔNO_X) for different road types are analyzed with the less aggregated scenario S1-T15 (all road sections are considered separately and for 15- minute time intervals). As can be seen in **Figure 4.14**, the mean differences between calculated emissions from the two models (mean of ΔNO_X values for each road type) are around 0 for main and distributor roads. This means that both models gave on average similar results. Results for residential roads, on the other hand, showed higher differences in mean values (higher values from HBEFA). The highest variations in results were seen for distributor road sections with several outliers. One reason for this can be the fact that most of the approaches with traffic signals were on distributor roads, where stop & go traffic situation often occurs.

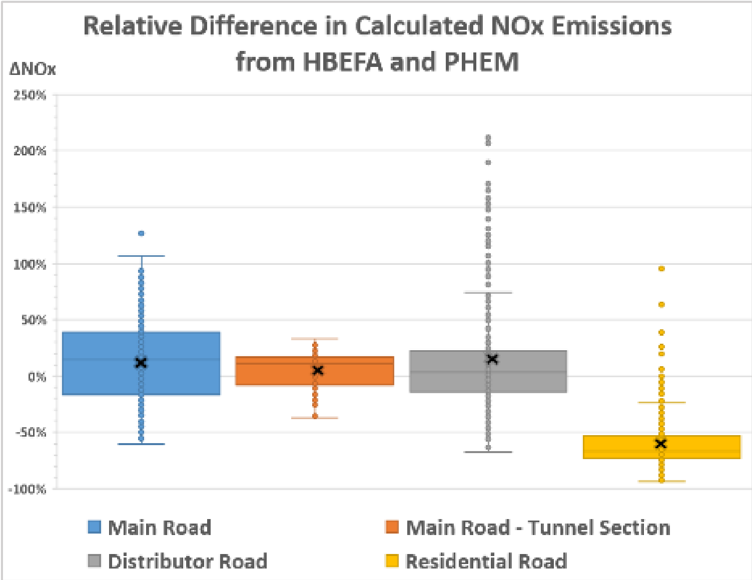

Figure 4.14 Results of ΔNO_X for different road types in Scenario S1-T15

When relative differences (ΔNO_X) are checked according to the different levels of service (**Figure 4.15**), it is seen that higher variances are seen in free-flow conditions (LOS 1) and stop & go conditions (LOS 4). However, it is important to note that the number of observations in these two conditions was more compared to LOS 2 and LOS 3.

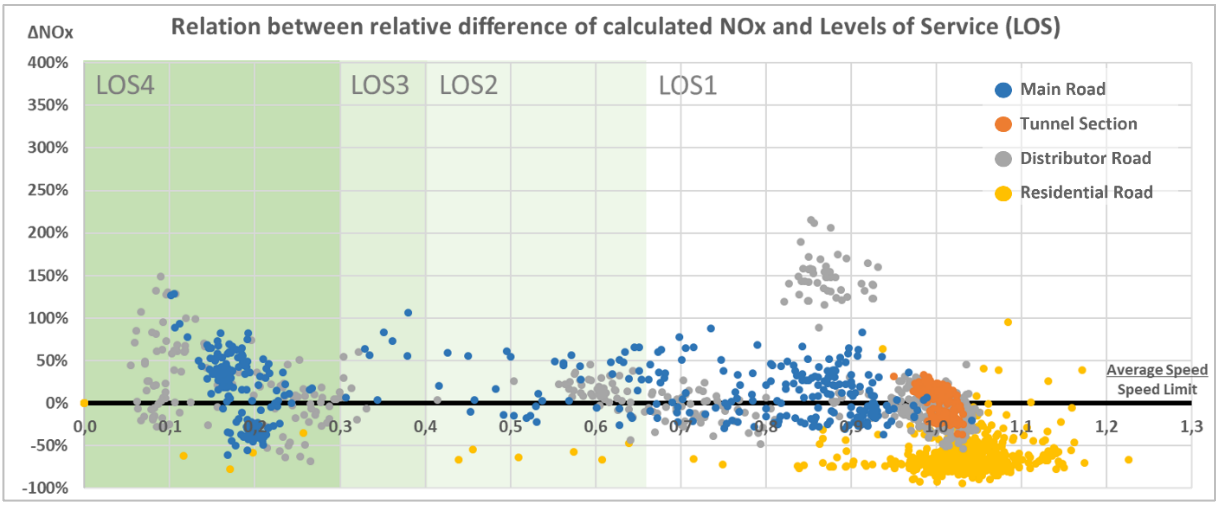

Figure 4.15 Scatter plot for ΔNO_X according to different road types and LOS in scenario S1-T15

Later, the change of relative differences (ΔNO_X) with increasing temporal aggregation levels is analyzed (**Figure 4.16**). Results showed that average differences between the model outputs do not change much with different temporal aggregation levels. However, a higher number of outliers and a larger spread of ΔNO_X is seen with smaller time intervals such as 15 or 30-minute intervals (see scenarios ending with T15 and T30 in **Figure 4.16**). This means that when shorter time intervals are used, the difference between the results from the two models increases for all types of road sections (especially high differences for distributor roads).

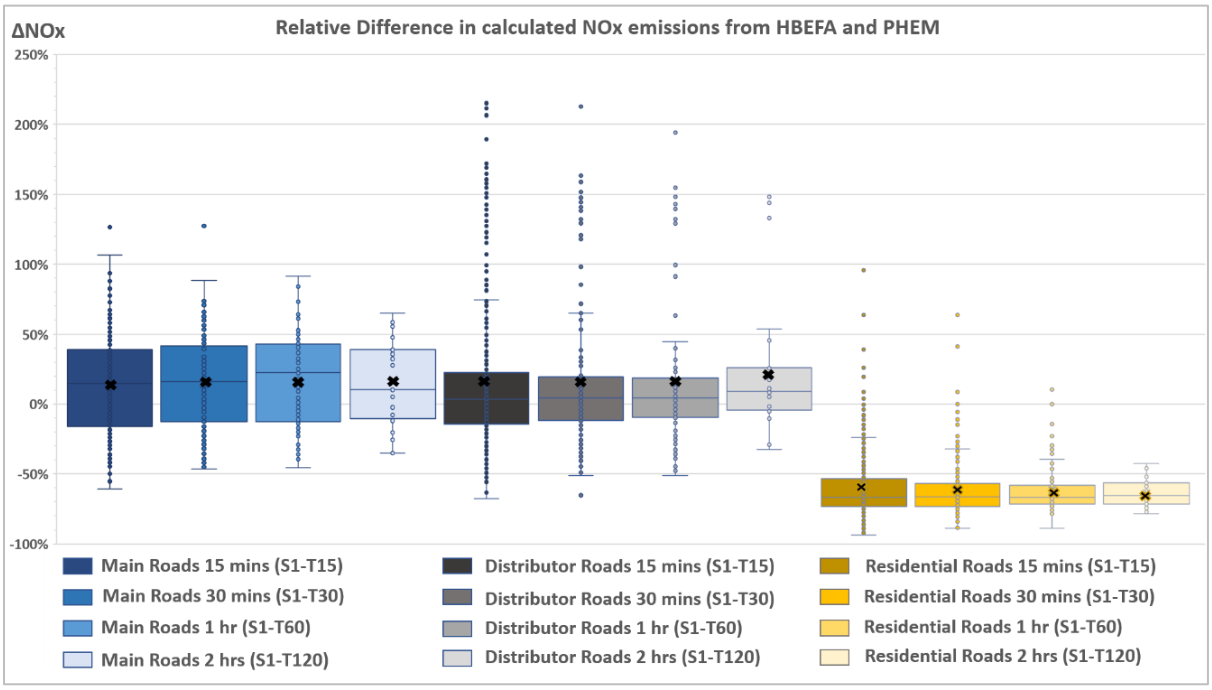

Figure 4.16 ΔNO_X results according to different temporal aggregation levels and road types

When the change of relative differences with spatial aggregation is analyzed (**Figure 4.17**), it is seen again that aggregating road sections to bigger segments resulted in fewer outliers and a lower spread of differences for all road types. To illustrate, outlier ΔNO_X observations from distributor road boxplots (where emission results from the two models are highly different from each other) disappear when road sections are spatially aggregated.

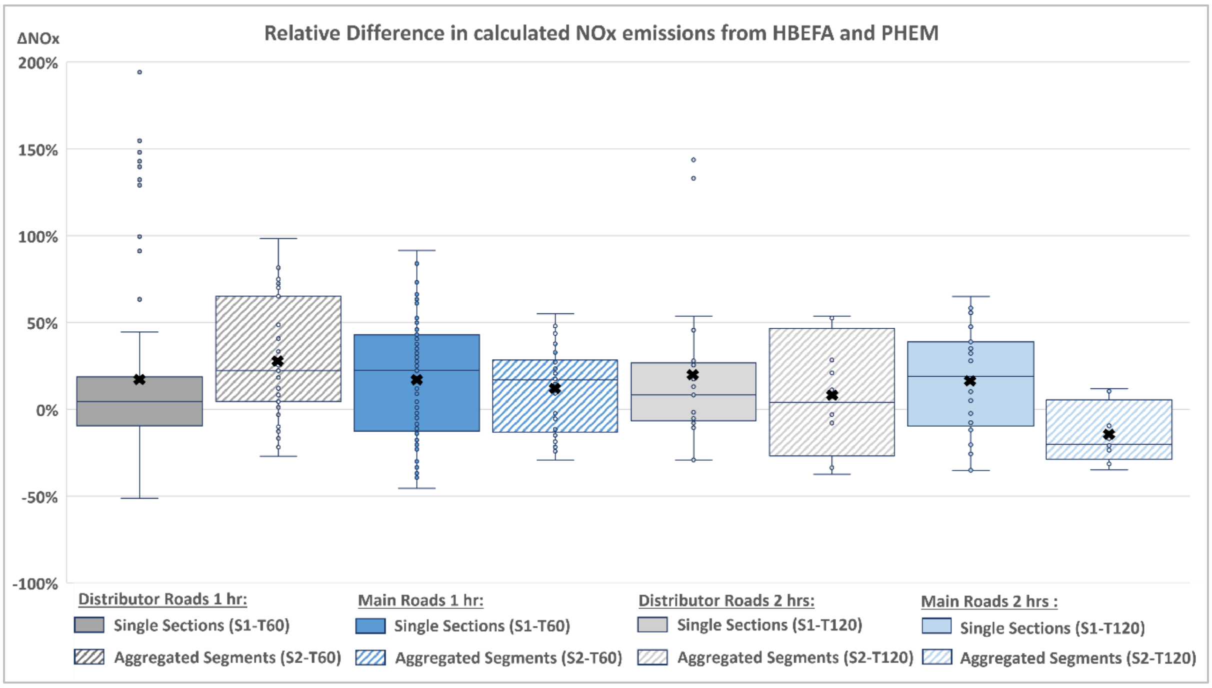

Figure 4.17 ΔNO_X results according to spatial aggregation levels for main and distributor road types

4.3.4 Conclusions

When the differences between the instantaneous (microscopic) and traffic situation-based (macroscopic) emission modelling approaches are compared for NO_X emission calculations, notable differences are seen between the residential roads and the other road types. NO_X values for residential roads calculated by HBEFA are on average higher, compared to the values calculated by PHEM. However, for main and distributor road sections that have higher traffic volumes and traffic signal control, emissions calculated by PHEM were higher. It is also noticeable that the spread of differences and the number of outliers are higher for main and distributor roads compared to residential roads.

The spread of ΔNO_X between different levels of services did not show a specific pattern. Emissions calculated for the residential road sections were higher for all LOS with the macroscopic emission model, compared to the microscopic model. This matches to a degree with the findings of a similar study conducted by ALAM ET AL. [2014] which compares emission calculation by using average speeds and instantaneous speeds using the emission model MOVES. This study finds out that the difference between emission values from the two approaches shows variances for different traffic conditions but for lower network speeds the macroscopic approach overestimates emissions.

This experiment showed that aggregating the time intervals (temporal) and road sections (spatial) result mostly in closer results from the two modelling approaches (i.e. lower spread of the overall differences ΔNO_X). This indicates that for DETM as a dynamic application which needs frequent air quality and traffic assessment with detailed data (e.g. 5 to 30-minute intervals), the type of emission model utilized can have an influence on results for some road sections. It is also seen that the number of ΔNO_X outliers (highest differences between model results) is decreased with higher spatial aggregation levels. This points out that using macroscopic emission models with aggregated data can result in overlooked air pollution peaks under DETM. This conflicts with the goal of DETM applications which is the detection of short-term emission peaks and the reduction of threshold exceedances.

It is also important to keep in mind that when external effects that influence the dispersion of pollutants such as weather conditions and changes in background emission levels are included, the overall effect of these outliers can be even higher on the overall air quality and consequently on the reliability of DETM monitoring and effectivity of DETM measures. While a macroscopic modelling approach is advantageous for a city-wide network screening and the detection of hotspots, they can be supported by microscopic models for detailed air quality assessment for the determined hotspots.

4.4 Summary

In this chapter, a microscopic hotspot-monitoring approach for DETM; from detection to modelling is analyzed. The goal was to evaluate a complete microscopic DETM system for hotspots (based on a use case area in Munich) which will be later used for integration and evaluation of electric vehicles in DETM measures (strategical research need, explained in **Chapter 3.5**).

Firstly, portable air quality monitoring devices with low-cost sensors were tested to see their usability as an additional data source for DETM. The data gathered from the measurement experiment in Munich was quantitatively and qualitatively not enough to be used in further modelling and evaluation stages of this thesis. However, the potential of low-cost measurement devices for comprehensive air quality monitoring as well as for the calibration and validation of the models is acknowledged, by remarking that regular calibration under several conditions and longer measurement periods are needed. Another important outcome of this experiment was the recognition of the usefulness of utilizing a dispersion model in microscopic air quality monitoring. Conducting air quality modelling which considers built environment and meteorological conditions through models, in addition to air quality monitoring devices, is helpful to interpret the results of point measurements, as the literature similarly shows (**Chapter 3.2**)

Later, two different emission calculation approaches were compared, in order to evaluate the advantages and disadvantages of microscopic and macroscopic approaches with a focus on DETM. The analysis indicates that the macroscopic approach has a potential to overlook air pollution concentration peaks for some network sections where different traffic situations can be observed (e.g. road sections with congestion and traffic signal control, etc.) due to using aggregated data and not considering detailed vehicle trajectories. On the other hand, it is acknowledged that the microscopic approach needs detailed data and is computationally demanding. What is found to be useful is a combination of both approaches for DETM, where urban screening is done with a macroscopic approach and supported by a microscopic approach for detailed analysis of hotspots with specific purposes such as dynamic traffic management.

Taking into account all of these results mentioned above from the methodological research, the following decisions are made for the development of a DETM approach (**Chapter 5**) and for the further strategical research on the integration of ZEVs into DETM (**Chapter 6**):

- to use an operational dispersion model, due to the extreme computational requirements of detailed CFD dispersion models (see **Chapter 4.1**).
- to continue the research with a fictitious network, instead of the Munich test-case area; mostly due to the insufficient air quality data from the field (see **Chapter 4.2**). In addition, it is acknowledged that due to air quality being an outcome of a complex set of conditions (transport demand, infrastructure, meteorology, etc.), using a fictitious network model offers to keep some variables fixed and to focus on the main aspects of the research.
- to use microscopic traffic and emission modelling tools, which can represent operational factors in more detail and detect air pollutant concentration peaks that are relevant for hotspots in urban areas (see **Chapter 4.3**).

5. Development of a DETM Approach

As detailly explained in **Chapter 3**, DETM has two main components: monitoring and strategy implementation (see **Figure 3.2**). The monitoring component includes air pollution and traffic detection as well as modelling of these two aspects. Traffic management strategy implementation incorporates steps such as situation and problem assessment as well as selection, implementation, and tracking (i.e. monitoring) of the dynamic traffic management measure(s).

Since this thesis conducts the analysis using a fictitious network and does not involve on-field applications or investigations, the monitoring component of the DETM approach is composed solely of modelling and does not contain detection. Due to the same reason, DETM strategy implementation in this dissertation does not cover implementation and tracking of the dynamic traffic management measures (i.e. does not cover on-field application and monitoring of the selected measures). As a result, the component strategy implementation in this study covers the first two steps which are both based on the modelling: situation and problem assessment (i.e. hotspot detection) as well as identification and evaluation of the measures (**Figure 5.1**). In the following chapters, developed DETM strategy implementation and modelling approaches are explained in detail.

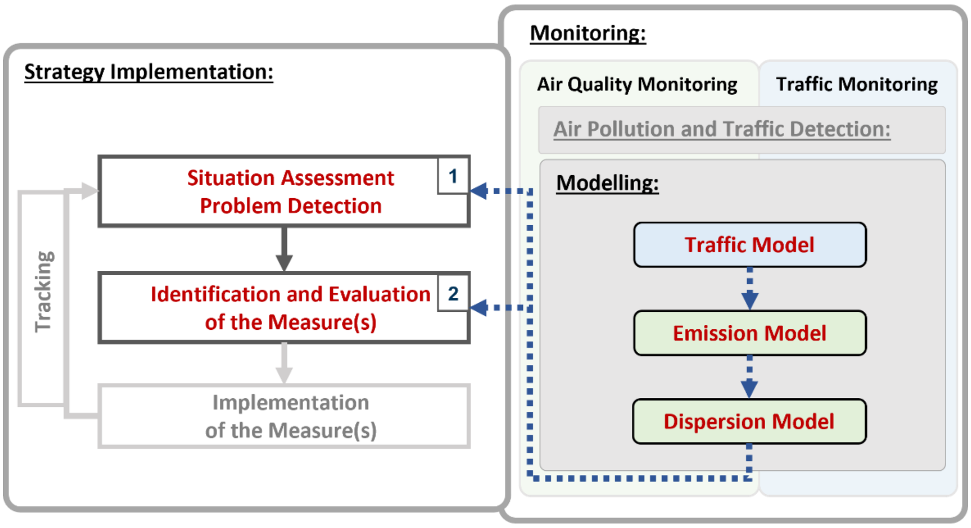

Figure 5.1 Developed DETM approach

5.1 DETM Modelling Approach

For DETM modelling, commonly used and validated traffic, emission, and air pollutant dispersion models are used. For the visualization of final air pollutant concentration values on a map, a GIS application is used. Interfaces between these tools are developed with Python scripts. The outline of the microscopic air quality modelling approach can be found in **Figure 5.2**. Details of each section (i.e. traffic flow, emission, and dispersion modelling) will be explained in the following sub-chapters.

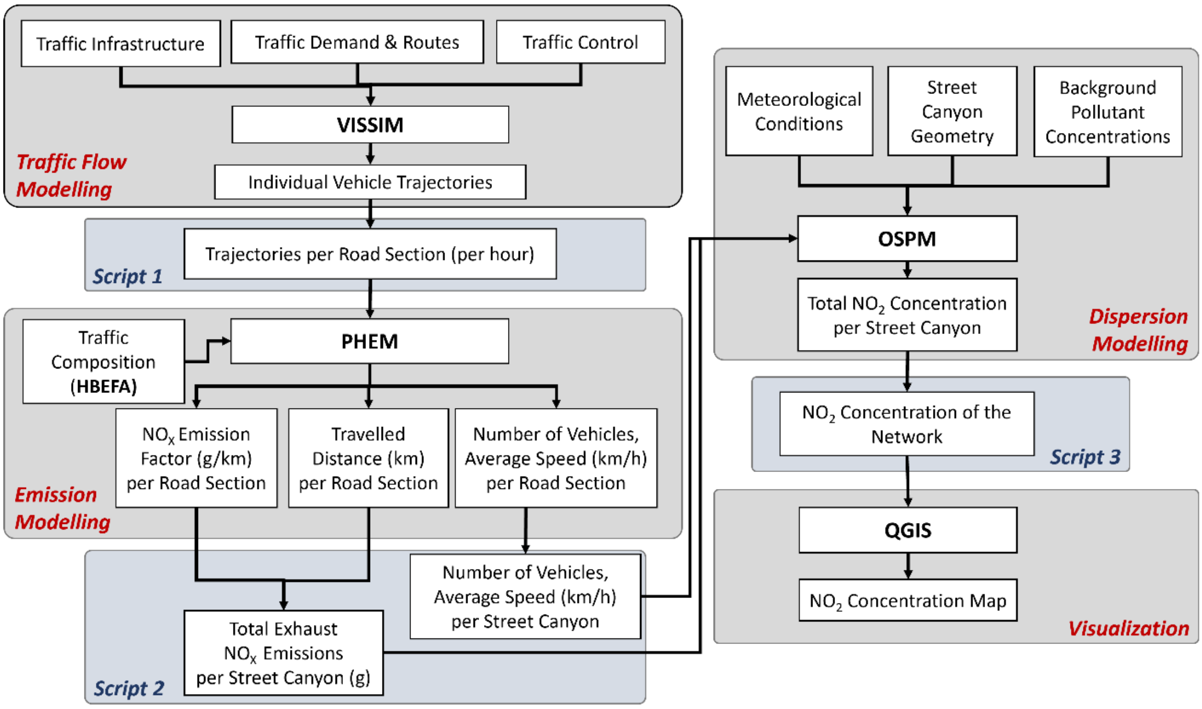

Figure 5.2 DETM modelling approach and developed model-chain

5.1.1 Traffic Flow Modelling

For traffic flow modelling, the microscopic traffic flow simulation tool PTV VISSIM (Version 11) is used. VISSIM is a stochastic, time and behavior-based, multi-purpose traffic simulation modelling tool which simulates individual vehicles and/or pedestrians in detail [FELLENDORF, M. AND VORTISCH, P., 2010; PTV AG, 2018]. In VISSIM vehicle movement is considered based on a traffic flow model which considers driving behavior in terms of lateral (lane-changing-model) and longitudinal (car-following-model) movements [FELLENDORF, M. AND VORTISCH, P., 2010; PTV AG, 2018]. Each vehicle moves in the network in line with a specific driving behavior of its assigned driver and according to that vehicle's technical capacities [PTV AG, 2018]. Inputs for a VISSIM model can be summarized in three main components: traffic infrastructure input (e.g. private and public transport network, parking), traffic input (e.g. characteristics of vehicles, traffic demand, traffic assignment/routing), and traffic control (e.g. priorities, traffic lights, signal programs) [FELLENDORF, M. AND VORTISCH, P., 2010].

Development of the simulation model is conducted in line with the microscopic simulation model guidelines [FGSV, 2006; FHWA, 2004, 2019]. Firstly, a simulation error check is conducted by comparing input and output values, examining point measurements in the network, inspecting travel times as well as viewing animations. As no real use-case area is simulated, there was no field data available for calibration and validation of the simulation parameters. Therefore, in terms of driving behavior, default VISSIM driving parameters for urban roads are used. Only for the merging areas in the network, lane-changing parameters are slightly adjusted to achieve a more cooperative behavior in the simulation. Finally, the plausibility of driving cycles is monitored under error checking. Detailed information on driving behavior parameters and example trajectories can be found in (**Appendix 5a** and **Appendix 5b**).

Due to the stochasticity in the model, it is required to determine a minimum number of simulation runs required for a satisfactory, statistically-valid comparison of the results from different simulation scenarios [FGSV, 2006; FHWA, 2019]. In this study, the necessary number of runs is calculated and applied for each simulated scenario under traffic flow modelling (details in **Chapter 6.2.5**).

5.1.2 Emission Modelling

Exhaust NO_X emissions are modelled by using the instantaneous emission model PHEM (Version 12.0.10) which calculates vehicle emissions by using individual vehicle trajectories and a fleet composition (explained in detail in **Chapter 4.3.1**). Fleet composition information is obtained from HBEFA (Version 3.3) which provides representative fleet compositions for different countries and years for emission calculations. In this study, the average traffic composition for Germany for the year 2020 is used (see **Appendix 5c**).

For PHEM required individual vehicle trajectories (second-by-second) are exported from VISSIM for the whole simulation period. Trajectories include information such as simulation second, vehicle ID and type, VISSIM-Link the vehicle is driving on as well as speed and acceleration of the vehicle. By using the information on VISSIM-Link numbers and simulation seconds, the trajectories are split up into defined road sections and hours by using a script (Script 1, **Figure 5.2**). The definition of the terms VISSIM-Link, road section, and street canyon on an example can be found in **Figure 5.3**.

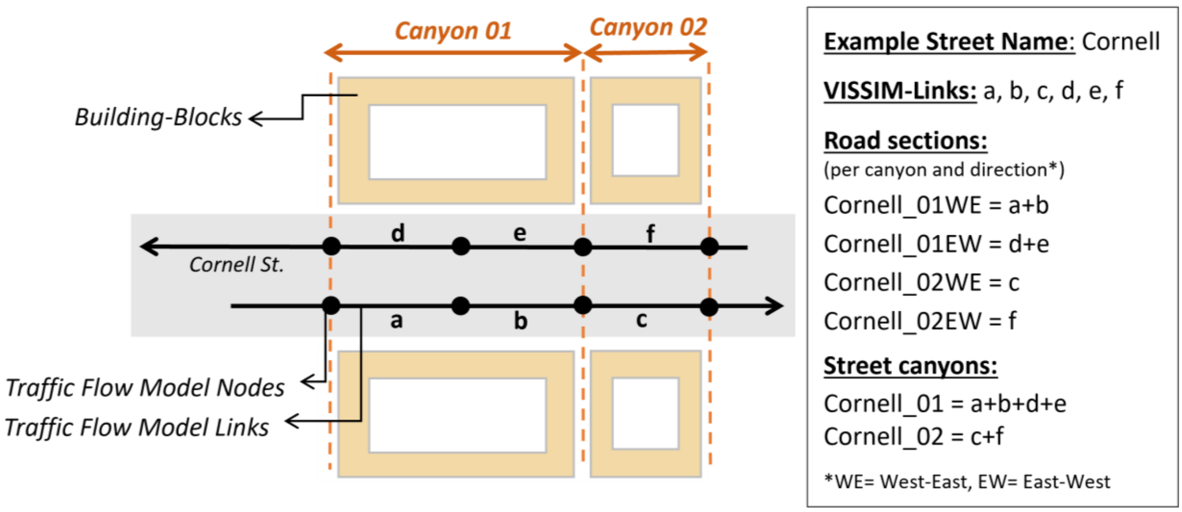

Figure 5.3 Definition of links, road sections, and street canyons

With the above-explained sub-trajectories, hourly NO_X emissions are calculated for each road section (**Figure 5.4**). PHEM is used in advanced mode and only tailpipe emissions (hot) are calculated.

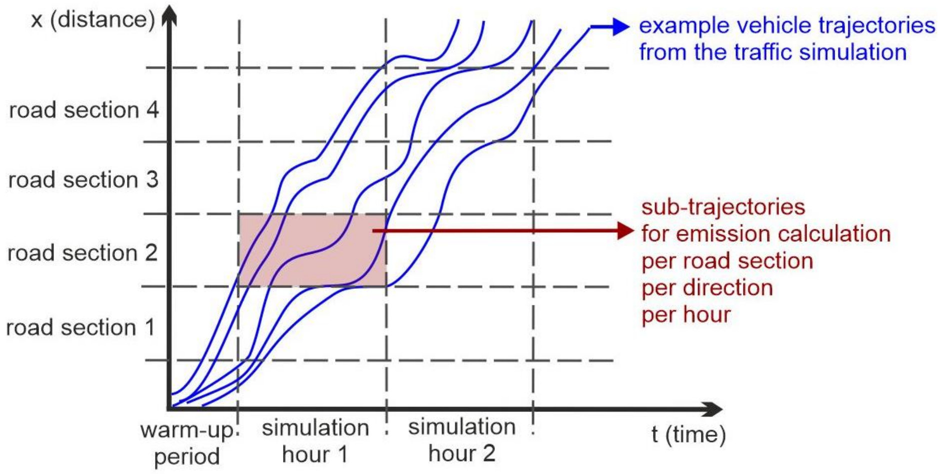

Figure 5.4 Conceptual explanation of emission calculation per road section per hour

Finally, in order to obtain total hourly NO_X emissions for each street canyon, the emission values that were calculated for the two directions of a road section are summed up by using another script (Script 2, **Figure 5.2**).

5.1.3 Dispersion Modelling

Final NO_2 concentrations are calculated by using the dispersion model from the Danish Operational Street Pollution Model (OSPM, Version 5.2.33). OSPM contains an emission model based on average-speed emission model COPERT [Berkowicz, R. et al., 2003], however, for this study only the dispersion model unit of OSPM is utilized. Self-calculated emission values from the instantaneous emission model PHEM are used as input data by using a script for input processing (Script 2, **Figure 5.2**).

OSPM calculates pollutant concentrations resulting from exhaust emissions by combining a plume model which considers the direct contribution of emission sources and a box model to consider the recirculation of the pollutants in the street canyon [Berkowicz, R. et al., 1997, p. 25; Berkowicz, R., 2000]. It uses street canyon geometry, dispersion-relevant traffic data, amount of pollutant emissions, meteorology, and background air pollution concentrations as input data for dispersion modelling (details in **Chapter 3.2.2**). When calculating NO_2 concentrations, the model takes among others nitrogen oxide conversion and turbulence in street canyons (traffic- and wind-induced turbulence) into account [Berkowicz, R., 2000]. Finally, OSPM provides air pollutant concentrations per defined street canyons, considering placed receptors in the model. For modelled street canyons in this dissertation, NO_2 values are gathered from receptors that are placed on the two sides of the street canyon (centered, at 3 m height), and the maximum receptor value is considered. An illustration of OSPM model principles and locations of receptors can be found in **Figure 5.5**.

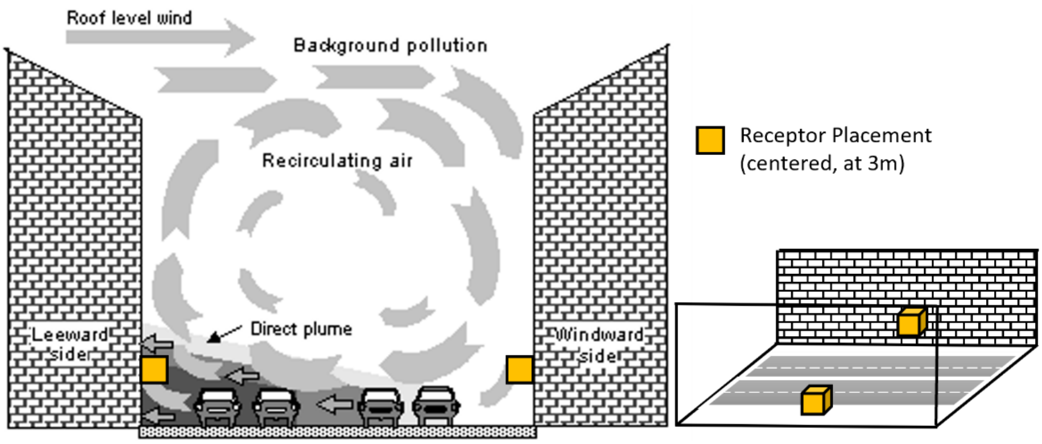

Figure 5.5 Schematic illustration of the model principles in OSPM and receptor placement in this model adapted from [BERKOWICZ, R. ET AL., 1997; Aarhus University, 2020]

The model requires hourly input data and gives hourly average air pollutant concentrations as output [BERKOWICZ, R. ET AL., 2003]. In line with the general air quality modelling process (see **Chapter 3.2.2** and **Figure 3.3**), the following hourly data is used as input for the model (see also **Figure 5.2**):

- calculated NO_X emissions per street canyon,
- dispersion relevant traffic data per street canyon (number of vehicles, average speed),
- street canyon geometry (height, width, length, angle),
- meteorological conditions and background pollution levels (NO_2, NO_X, O_3)

At the end of the dispersion modelling process, output values from OSPM (i.e. air pollutant concentrations per street canyon) are merged into a map by using QGIS (Script 3, **Figure 5.2**).

5.2 DETM Strategy Implementation Approach

The first step of DETM implementation is the situation assessment and detection of the problems (**Figure 5.1**). At this step, the criticality of the air quality situation is checked by using information generated from DETM monitoring (detection and/or modelling). To decide if the air quality situation is critical, a defined threshold value is needed. Currently, there are two threshold values defined for NO_2 concentration based on the standards [EC, 2008] (see **Chapter 2.2.2**, **Table 2.3**):

- One-hour average NO_2 threshold value is 200 µg/m³, with 18 permitted exceedances per year
- One-year average NO_2 threshold value is 40 µg/m³, with no permitted exceedances

It is often observed that hourly average values are less critical and mostly within the defined limits, whereas the limit exceedances in yearly averages still exceed the thresholds. To illustrate, **Figure 5.6** shows the number of stations where threshold exceedances are observed in Germany by year. It shows that one-hour threshold exceedances occur only in a few AQMS. On the other hand, there are several stations where the one-year threshold was exceeded.

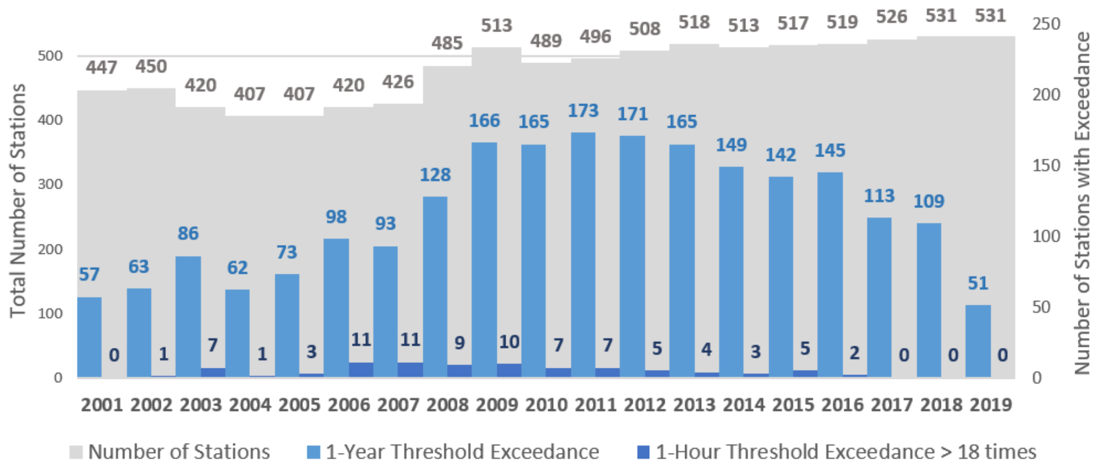

Figure 5.6 Annual NO_2 exceedances from AQMS in Germany
own illustration based on [UBA, 2021]

Therefore, for the DETM strategy, another hourly value (instead of 200 µg/m³) should be adopted to define and detect short-term hourly air pollution peaks. This can be done by using monthly and daily NO_2 concentration trends as well as daily traffic distribution trends in case a pre-defined value is not available (e.g. from empirical data). From DETM examples in Germany, the recent ones use values between 50 and 90 µg/m³; only the Hagen example uses 180 µg/m³ (see **Chapter 3.3**).

Figure 5.7 illustrates the DETM strategy implementation steps followed in this dissertation. Due to not having a real use-case area, the threshold for the proof of concept (**Chapter 6**) is defined according to the pollutant concentrations from the modelling approach and in line with DETM examples from Germany. Later, situation assessment (traffic and air quality situation) and problem detection (i.e. finding air pollution hotspots) steps are followed for the fictitious network (see **Chapter 6.3**). Following this, for detected NO_2 hotspots, ZEV-related DETM measures are identified (see **Chapter 6.4**). Finally, the impacts of these measures are evaluated through the DETM modelling approach (see **Chapter 6.5**).

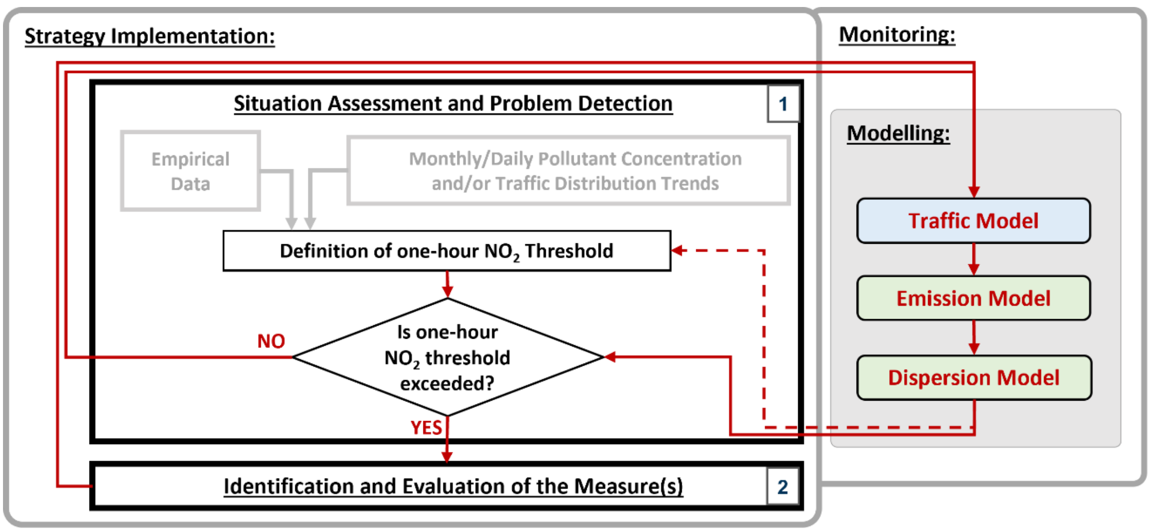

Figure 5.7 DETM strategy implementation approach

6. Integration and Evaluation of ZEVs in DETM[8]

In this Chapter, the integration of ZEVs into DETM and the resulting impacts are evaluated. In line with the results from **Chapter 4**, a proof of concept is conducted on an artificial urban road network by using the developed model-chain (see **Chapter 5.1**). Within the context of DETM strategy implementation, two example DETM measures are modelled: temporary re-routing and temporary traffic flow metering. Each measure is investigated with different ZEV shares of the vehicle fleet and separately with and without ZEV privileges (i.e. exemption of ZEVs from DETM measures).

6.1 Potential Analysis

Before investigating the effects of integrating ZEVs into DETM in detail, the potential reduction in NO_X emissions and NO_2 concentrations by increasing ZEV percentages in an urban road network is analyzed. This is done by using a preliminary artificial network and modelling an example morning peak traffic situation with the microscopic modelling approach explained in the previous chapter. The results of the NO_X emission and NO_2 concentration calculations are analyzed firstly by considering the entire network, later for different road types, and finally for individual road sections.

To analyze the effects of the substitution of conventional vehicles by ZEVs, different degrees of electrification for different vehicle types are considered. These are passenger cars (PC), light commercial vehicles (LCV), and heavy-duty vehicles (HDV). For each vehicle type in the network, ZEV shares of 5 %, 15 %, 30 %, and 70 % are considered in separate scenarios. Details of this preliminary

[8] Sections of this text were originally published in following papers:

CELIKKAYA, N.; BUSCH, F.; PLANK-WIEDENBECK, U. [2019a]: Mikroskopische Simulationsstudie zu Potenzialen von Elektrofahrzeugen. In: Immissionsschutz 24 (3), pp. 110–114. DOI: 10.37307/j.1868-7776.2019.03.04. [CELIKKAYA, N. ET AL., 2019a]

CELIKKAYA, N.; BUSCH, F.; PLANK-WIEDENBECK, U. [2020]: Potenziale von Elektrofahrzeugen zur Verringerung lokaler NO_X-Emissionen und NO_2-Immissionen: Eine mikroskopische Simulationsstudie. In: Straßenverkehrstechnik (ISSN: 0039-2219), vol. 64, no. 2, pp. 79–86. [CELIKKAYA, N. ET AL., 2020]

CELIKKAYA, N.; BUSCH, F.; PLANK-WIEDENBECK, U. [2021]: Modellbasierte Wirkungsanalyse zur Berücksichtigung von emissionsfreien Fahrzeugen in dynamischen Maßnahmen des umweltsensitiven Verkehrsmanagements. In: Straßenverkehrstechnik (ISSN: 0039-2219), vol. 65, no. 11, pp. 815–822. [CELIKKAYA, N. ET AL., 2021].

potential analysis can be found in [CELIKKAYA, N. ET AL., 2019a] and [CELIKKAYA, N. ET AL., 2020]. In this chapter, the main results of this study will be summarized.

6.1.1 Emission Reduction Potential

When the whole network is considered, results show that the highest emission reduction effects of ZEVs are seen in the most congested peak hour. It is also seen that a change in the proportion of zero-emission passenger cars causes the largest absolute reduction in each scenario group since passenger cars account for the largest proportion of the vehicle fleet in the entire network. On the other hand, when the emission reduction per vehicle type is considered, electrification of HDVs results in the highest reduction due to HDVs having higher emission factors.

The comparison of the total emissions according to different road types showed that in comparison to residential roads, emissions were 9 times higher on distributor roads and 13 times higher on main roads in all scenarios. Consequently, the absolute reductions of total emissions were seen highest on main roads and lowest on residential roads.

Intending to understand for which road sections fleet electrification brings a larger emission reduction, a relative reduction potential is evaluated. Since each section has different traffic volumes and road lengths, for this comparison "road-section-based emission factors" (NO_X emission per vehicle per km) are calculated for individual road sections. When these factors are analyzed according to road type, it is seen that main roads and distributor roads had similar relative reductions**,** although they had different absolute emissions. Residential roads showed again the lowest relative reductions. In addition, changes in the proportion of ZE-LCVs and ZE-HDVs had little influence on road-section-based NO_X emission factors of residential roads, unlike for main and distributor roads.

Finally, the spatial distribution of NO_X emission reduction in the road network is investigated in detail, considering individual road sections (independent of the road type). The highest reduction of total emissions (i.e. absolute reduction) is seen on road sections with high traffic volumes and queuing areas or congestion. Similar to absolute emission reduction, high reductions in NO_X emission factors (i.e. relative reduction) are also observed in these sections. In addition, regardless of the road type, the gradient of the road section influenced the relative reduction in NO_X emissions.

Statistical testing of these results supported the findings. It is seen that the absolute emission reduction through electrification of the fleet has a significant correlation with the traffic volumes ($r=0.69$) and the delay times ($r=0.45$) of the road sections. On the other hand, the relative reduction is found to be significantly correlated with the delay time ($r=0.71$) and the longitudinal gradient ($r=0.32$) of road sections.

6.1.2 Air Pollutant Concentration Reduction Potential

The results of the air pollutant reduction potential show similar tendencies as those of the emission reduction potentials. NO_2 concentration reduction potential of ZEVs is particularly visible for the peak hour when the complete network is considered. Furthermore, larger reduction effects can be observed in main roads and distributor roads, while the reduction in residential roads is smaller.

Compared to the reduction of NO_X emissions, the reductions in NO_2 concentrations in residential roads are more visible. This effect can be explained by the built environment; residential roads are modelled with relatively narrow street canyons, compared to the other two road types. NO_2 reduction is particularly apparent on residential roads with comparably high traffic volumes such as residential road sections that are used as alternative routes to main roads in the simulation. On these sections, even similarly high reductions to some main road sections could be observed (**Figure 6.1**)**.** Main roads show slightly less NO_2 reductions compared to the distributor roads in this case (unlike NO_X emissions) since street canyons of main roads are wider and a larger portion of them are located near open/green areas (without any built-structure around).

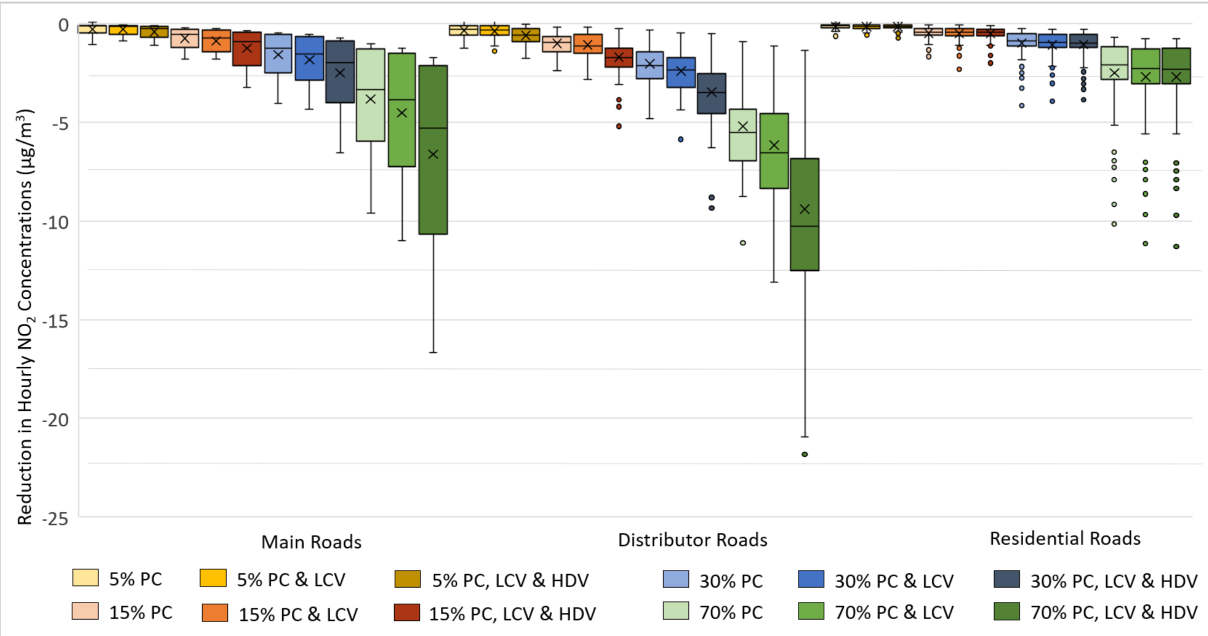

Figure 6.1 Distribution of reductions in hourly NO_2 concentrations for different road types

When the spatial distribution of NO_2 reduction potential in the network is checked (independent from the road type), it is again seen that reductions are higher on the road sections where NO_2 concentrations are higher. When road sections with similar NO_X emission values are compared, the ones that have lower average speed (e.g. traffic signal-queuing areas) showed higher concentration values. This can be explained by the findings of studies [KLEIN, P. K. ET AL., 2000] that vehicle-induced turbulence is an important factor for the dispersion of pollutants and low turbulences can result in higher concentrations.

In this preliminary analysis, a constant background air pollutant concentration and a fixed meteorological situation are used for all road sections and scenarios. At the end of the study, only for one example street canyon, NO_2 concentrations under different meteorological conditions are calculated. The results captured how these external factors can influence the emission and pollutant concentration reduction potentials of ZEVs considerably. For example, under unfavorable air pollution dispersion conditions such as low wind speeds, the reduction through electrification of the fleet is observed to be higher.

6.1.3 Summary

The results of this preliminary simulation study show that, when the entire network is considered, the highest NO_X emission reductions with ZEVs are observed in peak hours (for all scenarios). When the spatial distribution of this reduction potential is considered, the highest absolute emission reductions are observed in main roads (high traffic volumes), whereas the highest relative emission reductions are seen in distributor roads (high traffic volumes and congestion). Residential roads show the lowest absolute and relative emission reductions. In road sections with gradient/slope, higher emission reductions are seen compared to flat or downhill road sections. Furthermore, it could be observed that electrification of the vehicle type with the largest share in the traffic composition within the investigated area (in this case, PC) contributes the most to the absolute emission reduction.

The highest reduction of NO_2 concentrations is also seen in peak hours. Spatially, NO_2 reductions are highest in the street canyons where the highest absolute emission reductions were observed (street canyons with high traffic volumes and/or delay times). Additionally, the influences of street canyon geometry, traffic-induced turbulence, and meteorological conditions are evident in the air pollution reduction potentials. In wide or open street canyons, the reduction potential of NO_2 concentrations was found to be less pronounced (despite high NO_X emission reductions). In contrast, in narrow street canyons, the NO_2 reductions were more visible (despite less remarkable emission reductions).

In general, it could be recognized that electrification of the fleet shows the highest effects on ambient pollution in network areas and time intervals with high emission generation (e.g. at emission hotspots and during peak hours), especially more visible for narrow street canyons. It could further be seen that electrification has a higher potential to reduce final NO_2 concentrations under unfavorable ambient dispersion conditions such as low wind speeds and low vehicle-induced turbulences. These findings confirm the efforts to consider ZEVs in clean air plans for air pollution hotspots, especially under measures that aim to reduce pollutant concentration peaks (e.g. peak hours). For these reasons, in addition to static comprehensive measures, consideration of ZEVs in DETM measures which are activated in case of critical air pollution situations at hotspots to avoid air pollution peaks seems coherent.

6.2 Artificial Use Case Area

The proof of concept is conducted by using an artificial use-case area and modelling ZEV-inclusive DETM measures. The artificial urban network (**Figure 6.2**) is developed in a way that it represents an inner-city road network with surrounding building-blocks: inspired by the test-case area in Munich presented in **Chapter 4**.

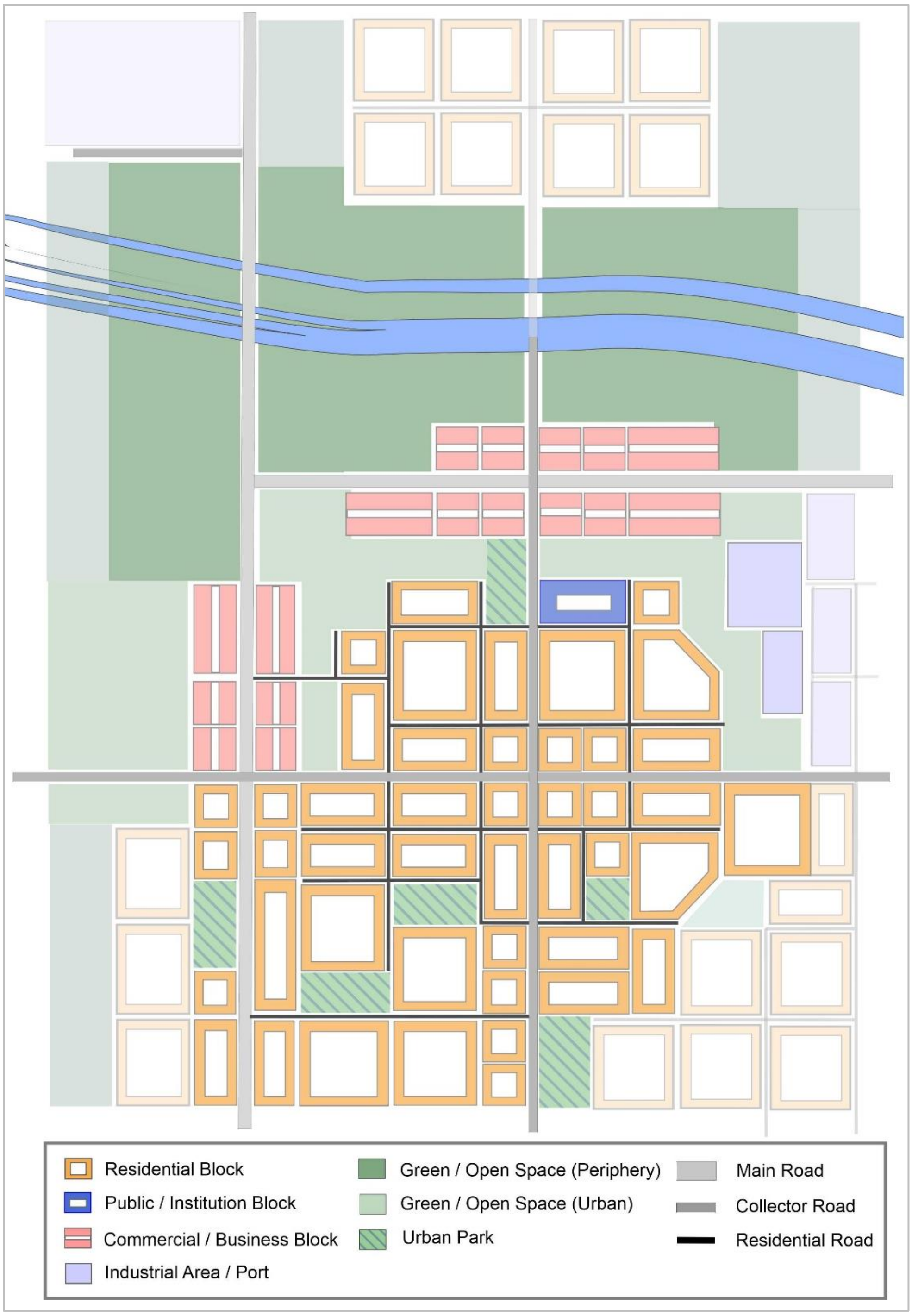

Figure 6.2 Artificial use-case area

6.2.1 Traffic Infrastructure

The artificial road network consists of different hierarchical road types (e.g. main roads, distributor roads, and residential roads) as well as different road-infrastructure elements (e.g. at-grade and grade-separated intersections, intersections with/without signalization, road sections with/without longitudinal inclination).

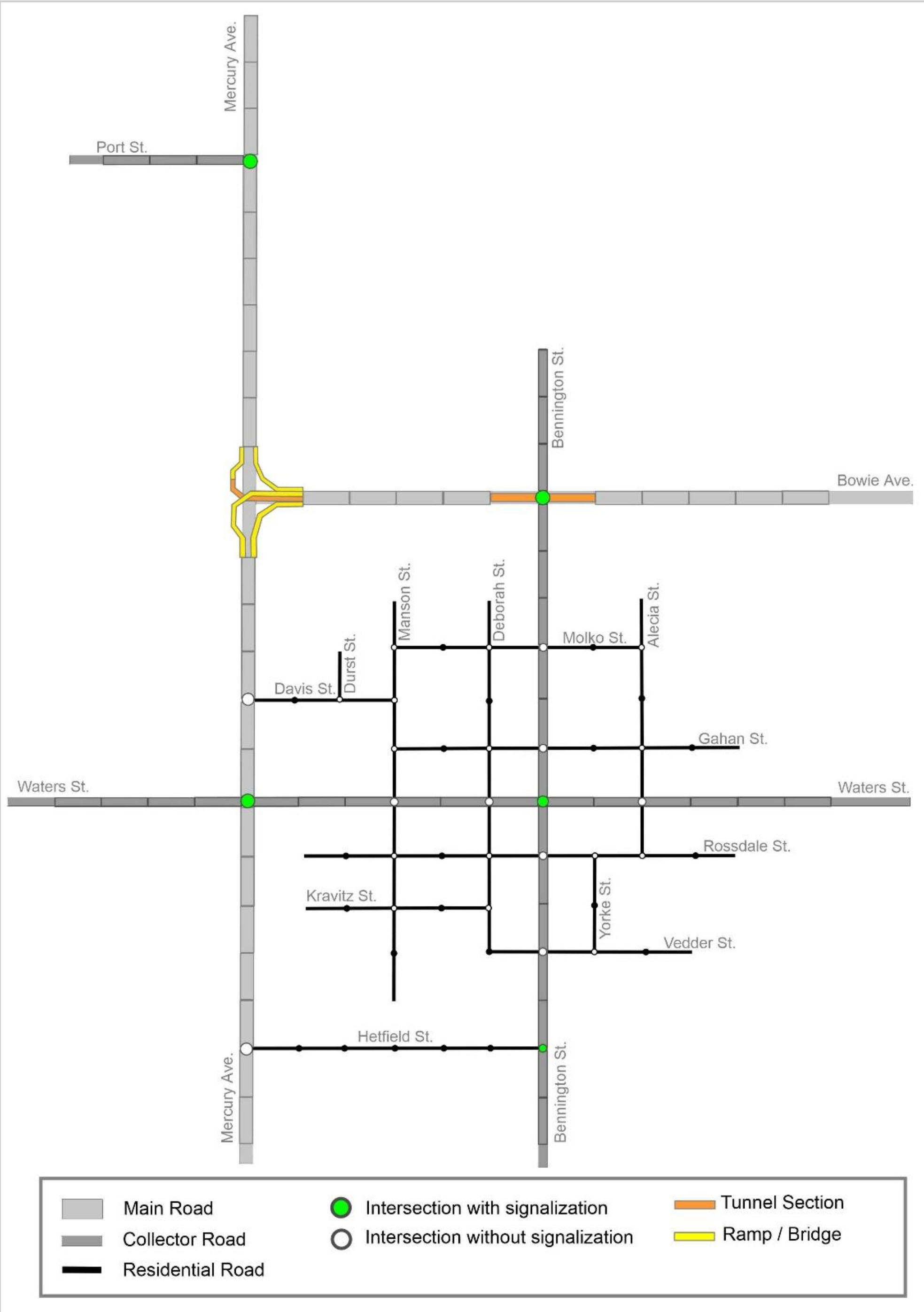

Figure 6.3 Artificial road network

The road network is modelled in approximately 100 m long VISSIM-Links (see **Figure 6.3**) to be able to consider different traffic situations on one single street, later in the emission calculation step (e.g. queuing sections at signalized intersections, merging sections on main roads, road sections with inclination at the entrance and exit of tunnels). As in real road networks, each road type has different characteristics such as the number of lanes, speed limits, and slopes (Table 6.1).

	Description	Total Length (m)	Number of VISSIM Links	Number of Road Sections	Speed Limit (km/h)	Gradient (% of road segments with slope)		
						↘ (-5 %)	↔ (0 %)	↗ (+5 %)
Main Roads	Dual carriageway with 3 lanes per direction	8.866	88	42	60	4%	92%	4%
Distributor Roads	Single carriageway with 2 lanes per direction	7.432	74	54	50	9%	82%	9%
Residential Roads	Single carriageway with 1 lane per direction	12.095	120	92	30	8%	84%	8%
Total		28.393	282	188				

Table 6.1 Detailed description of the road network

6.2.2 Traffic Demand and Assignment

For traffic demand input, the network is divided into 18 traffic zones (**Figure 6.4**). By setting the traffic zones, different types are considered:

- Zones 1, 2, and 3 represent the major origin and destination zones connected with main roads
- Zones 11, 12, 13, 14, and 15 are subsidiary zones linked through distributor roads
- Zones from 101 to 110 represent residential zones

As the next step, Origin-Destination-Matrices are created - for each vehicle type separately (see **Appendix 5d**). Private transport input is composed of passenger cars (PC), light-commercial vehicles (LCV), and heavy-duty vehicles (HDV). At this stage, functions of the zones and the land use (e.g. industrial area, residential area) are considered. For example, high HDV and LCV traffic are assigned to industrial areas and the port, whereas only PC traffic is planned for residential zones (**Appendix 5d**).

In this network, the city center is located/imagined at the southeast edge of the use-case area. Therefore, zones 1 and 3 represent the center, whereas zone 2 can be thought of as a connection to the closest outer-city destination. Main roads can be perceived as parts of a ring road, on the edge of the urban center. In the proof of concept, an example of morning traffic is simulated. Therefore, the main traffic directions are the ones to the city center (e.g. directions: North to South, West to East). In addition to land use, these main traffic directions are considered by the distribution of the traffic demand.

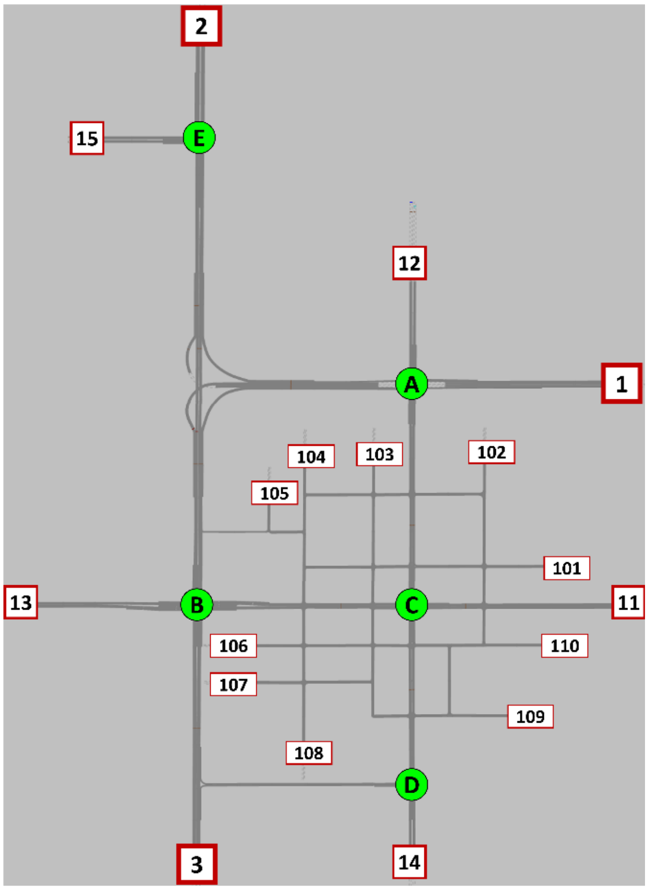

Figure 6.4 Zones (1-110) used for O/D-Matrices and locations of main intersections with signalization (A-E)

The total O/D matrix (all vehicle types) can be seen in **Figure 6.5**. When total traffic demand is considered, high traffic volumes are between the major zones (zone 1, 2, and 3), followed by the traffic volumes to subsidiary zones (zones 11, 12, 13, 14, and 15). The main traffic direction for the morning peak can also be seen in the matrix: higher traffic volumes enter the network from the main zone 2, whereas zones 11 and 14 receive more traffic, compared to other second-degree zones.

O/D Matrix All Vehicles (veh/hr)

FROM \ TO		Zone No	1	2	3	11	12	13	14	15	101	102	103	104	105	106	107	108	109	110
		Name	Main 1	Main 2	Main 3	Dist. 1	Dist. 2	Dist. 3	Dist. 4	Port	Res. 1	Res. 2	Res. 3	Res. 4	Res. 5	Res. 6	Res. 7	Res. 8	Res. 9	Res. 10
Zone No	**Name**	**Sum**	**1762**	**1591**	**1543**	**895**	**341**	**461**	**935**	**141**	**40**	**40**	**40**	**40**	**40**	**40**	**40**	**40**	**40**	**40**
1	Main 1	**1473**		812	332	10	50	50	99	40	8	8	8	8	8	8	8	8	8	8
2	Main 2	**2117**	796		548	237	10	106	208	52	16	16	16	16	16	16	16	16	16	16
3	Main 3	**1382**	362	493		241	50	90	34	32	8	8	8	8	8	8	8	8	8	8
11	Dist. 1	**467**	5	70	146		36	128	58	4	2	2	2	2	2	2	2	2	2	2
12	Dist. 2	**923**	195	5	209	74		28	388	4	2	2	2	2	2	2	2	2	2	2
13	Dist. 3	**740**	146	78	176	188	44		81	7	2	2	2	2	2	2	2	2	2	2
14	Dist. 4	**466**	130	68	5	77	128	36		2	2	2	2	2	2	2	2	2	2	2
15	Port	**91**	28	15	27	8	3	3	7		0	0	0	0	0	0	0	0	0	0
101	Res. 1	**41**	10	5	10	6	2	2	6	0		0	0	0	0	0	0	0	0	0
102	Res. 2	**41**	10	5	10	6	2	2	6	0	0		0	0	0	0	0	0	0	0
103	Res. 3	**41**	10	5	10	6	2	2	6	0	0	0		0	0	0	0	0	0	0
104	Res. 4	**41**	10	5	10	6	2	2	6	0	0	0	0		0	0	0	0	0	0
105	Res. 5	**41**	10	5	10	6	2	2	6	0	0	0	0	0		0	0	0	0	0
106	Res. 6	**41**	10	5	10	6	2	2	6	0	0	0	0	0	0		0	0	0	0
107	Res. 7	**41**	10	5	10	6	2	2	6	0	0	0	0	0	0	0		0	0	0
108	Res. 8	**41**	10	5	10	6	2	2	6	0	0	0	0	0	0	0	0		0	0
109	Res. 9	**41**	10	5	10	6	2	2	6	0	0	0	0	0	0	0	0	0		0
110	Res. 10	**41**	10	5	10	6	2	2	6	0	0	0	0	0	0	0	0	0	0	

Figure 6.5 O/D Matrix (06:30 AM, all vehicle types)

In traffic flow simulation, a period of 5 hours (06:30 AM to 11:30 AM) is modelled as an example of morning traffic. The first 30 minutes are set as a warming-up period for the simulation. Keeping the O/D-relations the same, from 07:00 AM on, the traffic input (for all vehicle inputs from all zones) is continuously increased until 08:00 AM and reduced gradually after (**Figure 6.6**).

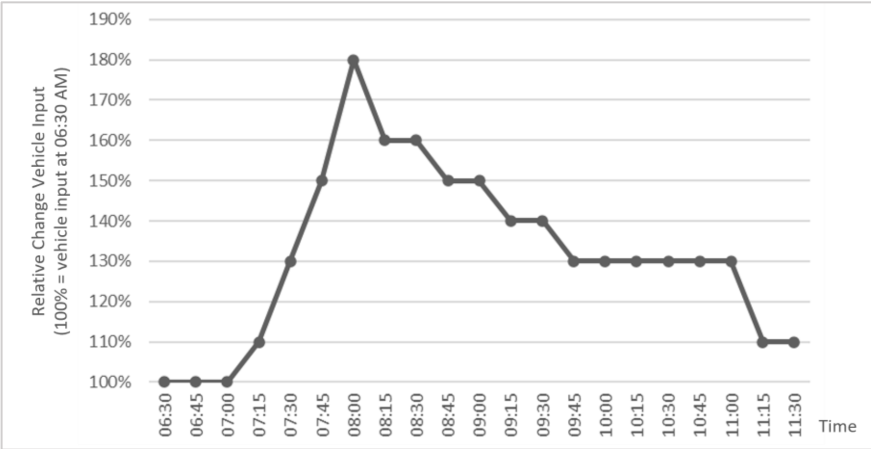

Figure 6.6 Percentage change of vehicle inputs in traffic flow simulation in time

As explained in previous pages, O/D matrices, and vehicle inputs are created manually once and kept fixed. It is important to highlight here that there is no transport demand modelling executed. For traffic assignment in the network, dynamic traffic assignment of VISSIM is used preliminary, to see the optimal traffic assignment and route distribution in the network. Later, these routes are sorted out and minor/not meaningful routes are cleaned out. For actual simulation runs, these final routes are used in static route assignment mode.

In addition to private transport, public transport is taken into account. Three bus lines on distributor roads (between zones 11-13, 12-13, and 12-14) are simulated with their stops. Details on public transport lines and stops can be found in **Appendix 5e**. All bus lines run with a frequency of 10 minutes.

6.2.3 Traffic Control

There are five signalized intersections in the developed artificial network (**Figure 6.4**). They are all simulated with fixed-time traffic control. Intersections on the main roads have a cycle time of 90 seconds (A, B, and E), whereas the intersections on the distributor roads have a cycle time of 70 seconds (C and D). Detailed information on signal programs and level of service analyses can be found in **Appendix 5f**. Furthermore, in **Chapter 6.3** traffic situation in the network and LOS at these intersections during the peak hour is illustrated (**Figure 6.7**).

6.2.4 Additional Input for the Dispersion Model

As explained in **Chapter 5.1**, dispersion-related input data consists of street canyon geometry, meteorological conditions, and background concentrations in addition to the traffic and emission data which is obtained from PHEM. In order to include realistic air pollution dispersion situations, different street canyon geometries are considered in the artificial use-case area (see **Figure 6.2**):

- The network contains not only street canyons with built structures (i.e. buildings on both sides) but also canyons - partly or completely - without built structures (i.e. no buildings on both sides or only on one side) such as canyons near green/open spaces.
- Building-blocks differ between 100 x 100 m, 100 x 200 m, and 200 x 200 m blocks and define the length of street canyons. While smaller blocks are located at central areas (intersections, near public transport stops, etc.), blocks get bigger further from the urban center.
- Well-ventilated wide street canyons surrounded by large green/open areas are in the urban periphery, whereas densely built areas with smaller urban parks are in the central areas.

Detailed information about street canyons can be found in **Table 6.2**. Example street cross-sections that were used for defining canyon widths for each road type are available in **Appendix 5g**.

	Number of Street Canyons	Street Canyon Built Structure			Street Canyon Geometry				
					Length (m)			Width [m]	Height [m]
		2-sided	1-sided	open	100	200	>200		
Main Roads	21	12	2	7	13	10	1	50	15
Distributor Roads	27	16	6	5	19	5	1	30	15
Residential Roads	47	36	10	1	32	14	0	20	15
Total	95	64	18	13	64	29	2		

Table 6.2 Description of the street canyons

Meteorological conditions and background air pollution concentrations are kept stable for the whole simulation period, to ensure comparability of the results and to be able to focus on road traffic-related changes. Input values used in the OSPM model can be seen in **Table 6.3**.

Parameter	**Unit**	**Value**
Outdoor Temperature	C°	20
Wind Speed	m/s	2
Wind Direction (Degrees)	Degrees	45
Light	W/m^2	50
NO_2 Background Concentration	µg/m³	35
NO_X Background Concentration	µg/m³	50
O_3 Background Concentration	µg/m³	50
Fraction NO_2*	%	6
** The fraction (i.e. portion) of directly emitted NO_2 (i.e. primary NO_2) within the total exhaust NO_X emissions*		

Table 6.3 Meteorological conditions and background pollutant concentrations used in OSPM

6.2.5 Execution of the Model-Chain

Since the significance of results from a single simulation run is low due to the randomness in the microscopic traffic flow simulations, multiple runs are necessary. Therefore, the traffic simulation is run multiple times. For each run emissions and air pollution calculations are calculated, as if each run is another observation day on the field in a real study area. By the calculation of the minimum number of traffic simulation runs required, the guidelines [FHWA, 2019] and [FGSV, 2006] are used (**Table 6.4**).

FHWA [2019, p.76]	FGSV [2006, p.38]
$n = \left(\frac{t_{\alpha,\ df} * S}{e\ *\ \bar{x}}\right)^2$	$n = \left(\frac{t_{\alpha,\ df} * S}{e_a}\right)^2$

The number of runs is satisfactory when N > n
where,

N	= executed number of runs (N<30 – small sample)
n	= minimum number of runs required
$t_{(\alpha, df)}$	= t statistic for N-1 degrees of freedom and α% confidence level
df	= degrees of freedom (N-1)
α	= confidence level (percentage, e.g. 0.10 → 10 %)
S	= standard deviation from N number of observations
$\bar{x}$	= mean from N number of observations
e	= desired tolerance error (percentage, e.g. 0.02 → 2 %)
ea	= desired absolute accuracy, i.e. marginal error (e.g. ± 5 km/h)

Table 6.4 Formula for the calculation of the minimum number of simulation runs

Calculation of the minimum number of runs required is done by considering the two decisive simulation outputs which will be used for comparison of alternative scenarios: hourly travel times (considering main and distributor roads) and hourly NO_2 concentrations of each street canyon. In addition, the calculation is done for indicative outputs such as hourly traffic volumes, average speeds, and emissions for each street canyon – with a higher error tolerance.

The results of the calculations can be found in **Table 6.5.** It is concluded that four VISSIM runs are satisfactory to be (decisive outputs):

- 90 % confident that all major routes (17 routes) would have a maximum error of 20 % considering hourly travel times. To illustrate, if the mean travel time of a route is 10 minutes between 8-9 am, each simulation run gives a travel time between 8 and 12 minutes (20 % tolerance error, ± 2 minutes) for this route and for this hour.

- 90 % confident that all street canyons (95 street canyons) would have a maximum error of 5 % considering hourly NO_2 concentration values. To illustrate, if the average pollutant concentration of one street canyon is 50 µg/m³ between 8:00-9:00 AM, each run gives a NO_2 value between 47,5 and 52,5 µg/m³ (5 % tolerance error, ± 2,5 µg/m³) for this street canyon and for this hour.
- 90 % confident that all 188 road sections (including main, distributor, and residential road sections) would have a maximum error of 40 % considering hourly traffic volumes, average speeds, and emissions.

Indicator (Output from)	**Required number of runs (n) calculated for**	**N**	**CL (α)**	**Tolerance error (e)**	**Max. n from all criteria values**	**N>n**
Hourly Travel Times (VISSIM)	17 major routes and 4 hours = 68 criteria values	4	90 %	20 %	2,5	OK
Hourly NO_2 Concentrations (OSPM)	95 street canyons and 4 hours = 380 criteria values	4	90 %	5 %	3,9	OK
Hourly Traffic Volumes (PHEM)	188 road sections and 4 hours = 3008 criteria values	4	90 %	40 %	3,5	OK
Hourly Average Speed (PHEM)	188 road sections and 4 hours = 3008 criteria values	4	90 %	40 %	3,0	OK
Hourly NO_X Emissions (PHEM)	188 road sections and 4 hours = 3008 criteria values	4	90 %	40 %	4,0	OK

Table 6.5 Results of calculation of the minimum number of runs

The tolerance error is set higher for traffic volumes, speeds, and emissions compared to travel times and pollutant concentrations. Thus, each traffic simulation produces a slightly different traffic/ congestion distribution in time and in the network (road sections), whereas average travel times of the main routes and NO_2 concentrations at canyons are similar for each run. This result is satisfactory for the scope of this research. In this way, simulations can represent similar conditions to a real use-case network: with some differences between observation days but with a similar overall situation to have a statistically representative sample day.

Further analysis and evaluation are done by interpreting the distribution of the values from each run by using boxplots (each observation is considered) as well as using the mean values from four simulation runs for each indicator (details in **Chapter 6.5**).

6.3 Base Situation

In this chapter, the base situation in the modelled artificial network is described in terms of traffic, NO_X emission, and NO_2 concentrations.

In the traffic flow simulation, the highest traffic volumes and congestion is seen between 07:30 and 08:30 AM (**Figure 6.7**). Especially main roads are congested in the main traffic direction (on Mercury Ave. from north to south and on Waters St. from west to east). During peak utilization, the level of service (calculated according to the HBS 2015 [FGSV, 2015]) reaches the lowest level F at Intersections B and C. Details about LOS calculations and signal programs for each intersection can be found in **Appendix 5f.**

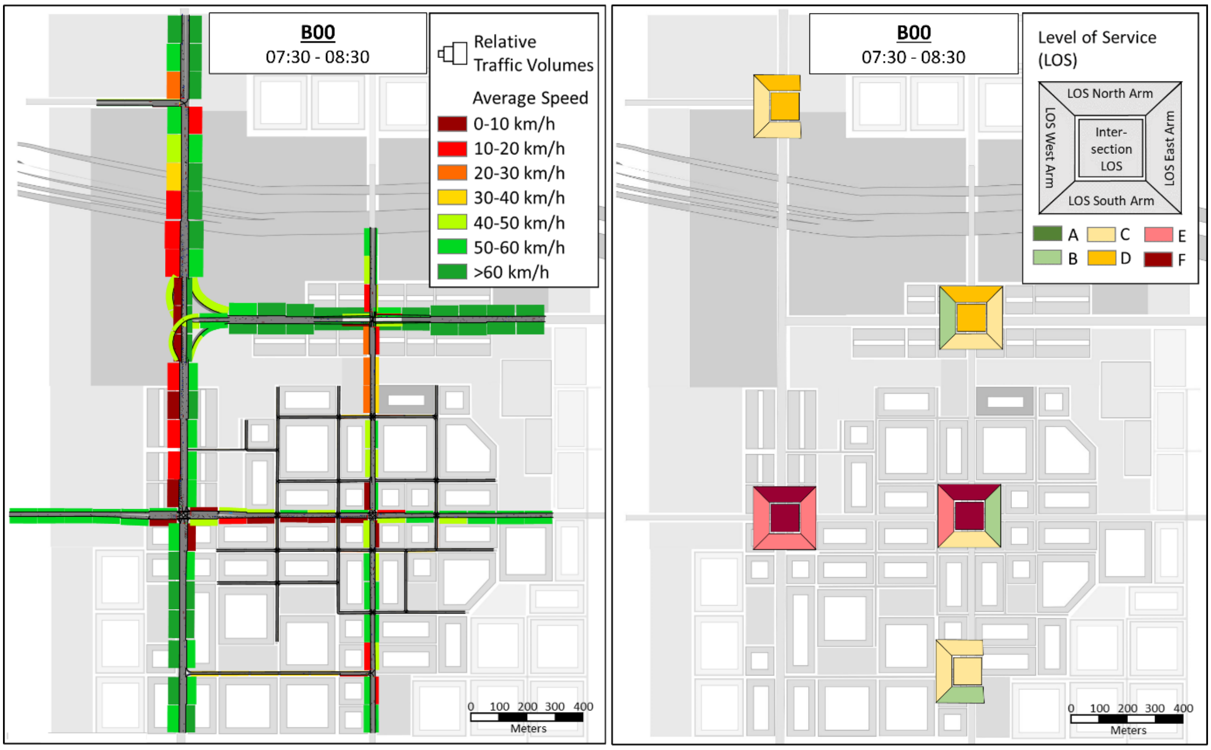

Figure 6.7 Traffic situation (left) and LOS of signalized intersections (right) during the traffic peak hour

The status of the emissions and pollutant concentrations in the base scenario can be found in **Figure 6.8**. Total hourly NO_X emissions in the network are generally higher at street canyons with high traffic volumes (main and distributor roads) and especially on sections with congestion and/or queuing. As expected, residential street canyons show lower hourly average emission values, followed by distributor roads with less traffic volume and/or congestion.

When hourly NO_2 concentrations are considered, it can be seen that values are higher on narrower street canyons where high or moderate emission levels were observed. On the other hand, some of the street canyons near open spaces (i.e. without built structure) show lower concentrations despite high levels of emissions produced, as a result of pollutant dispersion.

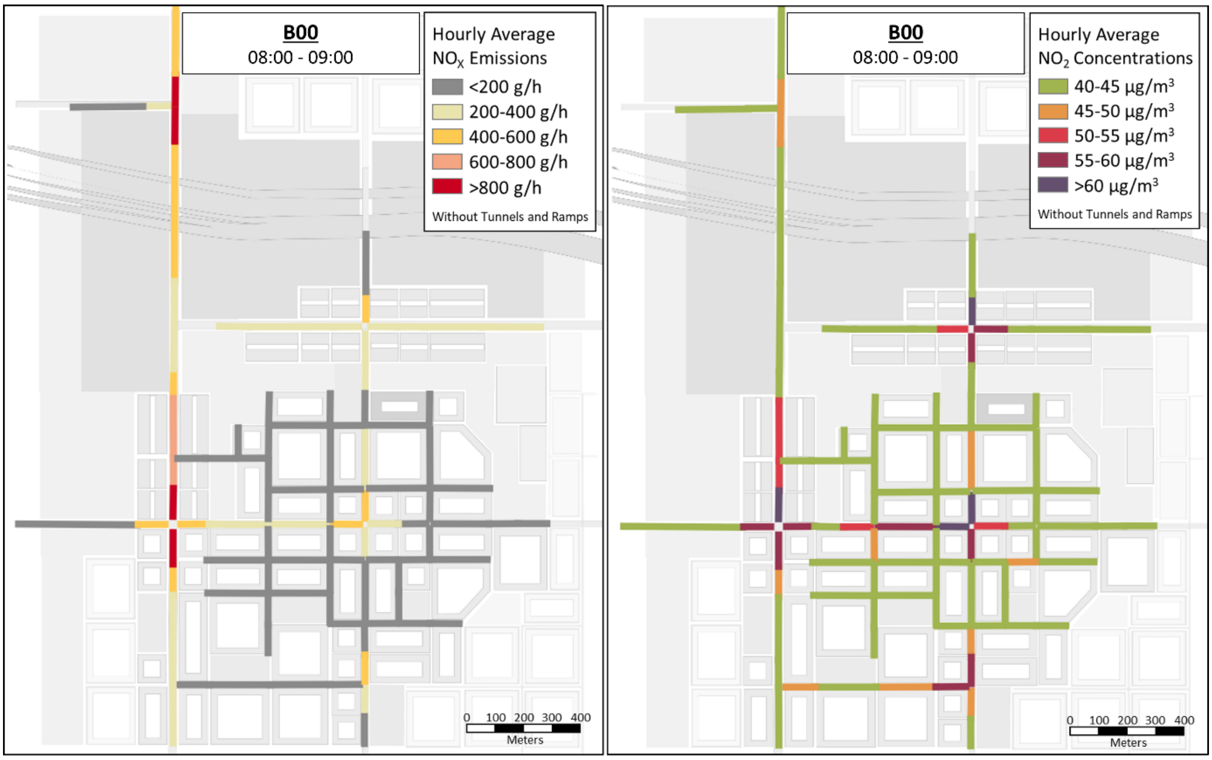

Figure 6.8 NO_X emission (left) and NO_2 concentration (right) situations during the air pollution peak hour

Within the scope of the proof of concept, the threshold for a one-hour average NO_2 concentration is selected as 50 µg/m³ for the strategy implementation on this network (see **Chapter 5.2**). However, due to the high number of stops and emissions as well as low speeds and resulting low turbulence, a reduction of the NO_2 levels in queuing areas (100 m long road sections before the signalized intersections) is quite difficult to achieve, compared to other street canyons in the network (see **Chapter 6.4.1**). Consequently, queuing areas alone are not considered in the definition of a NO_2-Hotspot. Hotspots are defined as a series of street canyons where the defined hourly NO_2 concentration threshold value is exceeded.

The defined hourly limit of NO_2 concentration (50 µg/m³) is exceeded at two locations (which are not stand-alone signal queueing sections) in the road network during peak hours (at 08:00 and 09:00). These network sections which are composed of several street canyons are identified as hotspots (**Figure 6.9**):

- **Hotspot 1** is located on Mercury Ave., on a main road. It is 400 m long and consists of three street canyons. The average traffic volume in the peak hour is 4.250 vehicles with an HDV share of 5 %. The maximum NO_2 hourly mean value is 62 µg/m³.

- **Hotspot 2** is located on Waters St., on a distributor road. It is 400 m long and consists of three street canyons. The average traffic load in the peak hour is 1.800 vehicles with an HDV share of 4 %. The maximum NO_2 hourly mean value is 64 µg/m³.

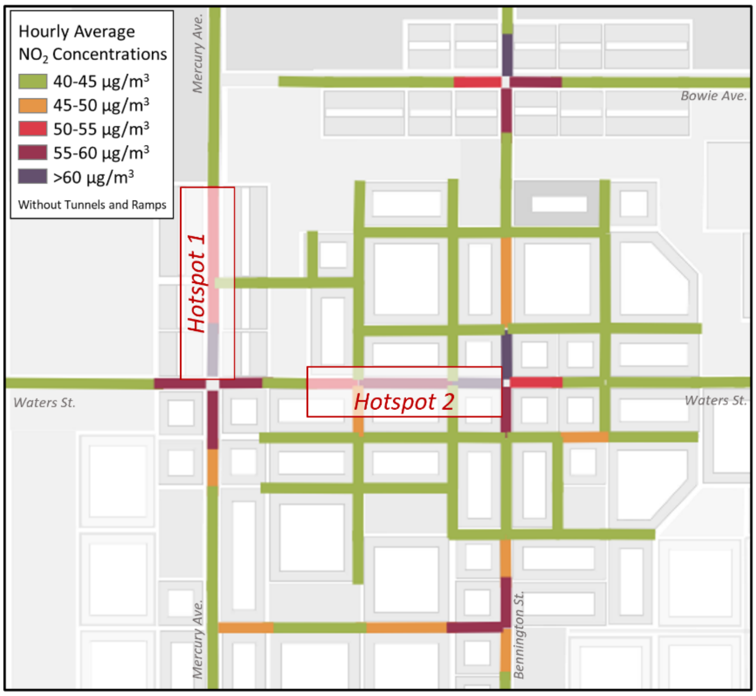

Figure 6.9 Detailed presentation of NO_2 Hotspots

To get an insight into traffic and air quality situations in the course of the simulation period at hotspots, an exceptionally detailed calculation is conducted; only for two example street canyons and only for one simulation run. Relevant values are calculated in detail by using data with 5-minute intervals (for air pollutants, exceptionally for this test, 5-minute input data is used instead of hourly values which is required for the dispersion model). The results of this example can be seen in **Figure 6.10**. The figure shows how traffic, congestion, emissions, and air pollutant concentrations change in time in two canyons from Hotspot 1 and Hotspot 2. It illustrates the trends (rolling average) of the number of vehicles, average speeds, and the number of stops in these two street canyons as well as the resulting NO_X emission and NO_2 concentration values during the simulation period. Since each indicator has a different absolute value and different scales, to be able to compare them to each other, all values are analyzed in relation to the starting values at 07:00 AM (i.e. relative change in indicators starting from 07:00 AM).

It can be seen in **Figure 6.10**. that indicators show different increasing and decreasing trends which are not always synchronous. For example, the number of vehicles in the two street canyons starts to increase around 07:30 AM, whereas emissions start increasing 5 to 10 minutes later. Congestion builds up around 08:00 AM (increasing number of stops and reduced average speed) which is followed by an escalated increase in emissions. Only after these, an increase in NO_2 concentration becomes noticeable. The air pollution peak (emissions and concentrations) is seen around 09:00 AM for the two street canyons. When the trend after the peak hour is considered, it is seen that although the increase in traffic volumes stops, the increase in emissions and concentrations does not necessarily stop immediately. They fluctuate in line with the traffic situation (especially with the number of stops) and start to sink remarkably once the congestion is dissolved.

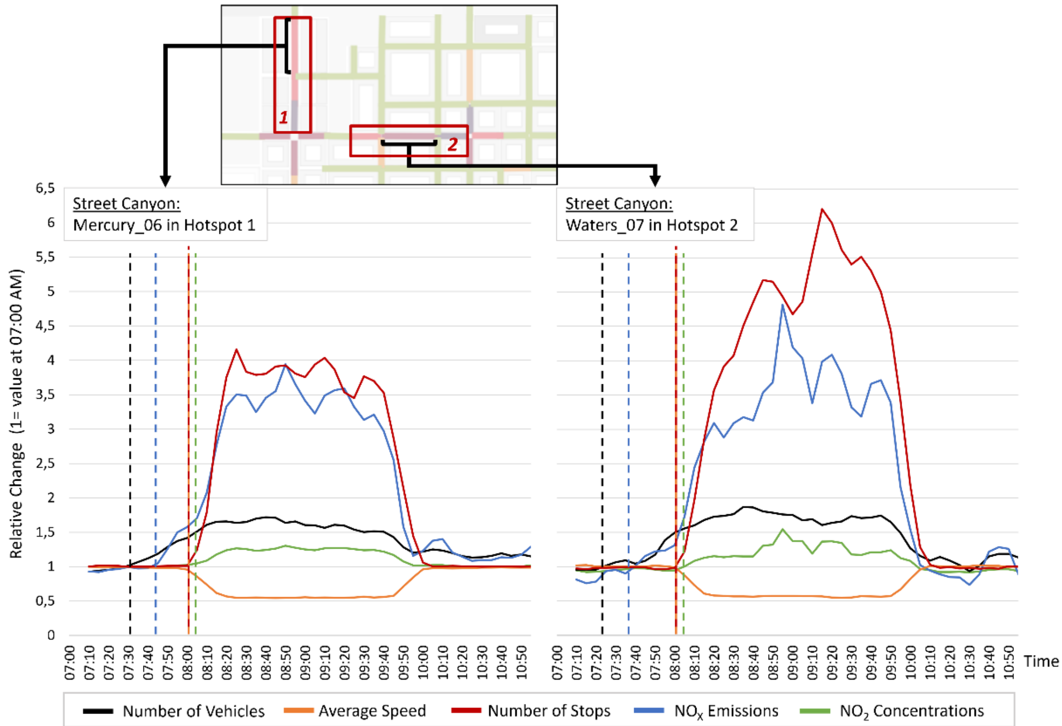

Figure 6.10 NO_2 Hotspot trends

This example detailed analysis supports the knowledge gathered from the state-of-the-art analysis (**Chapter 3**) and the second experimental methodological research (**Chapter 4.3**): For spatially and temporally detailed, dynamic hotspot air quality monitoring, using highly aggregated data (e.g. hourly volumes), aggregated calculation methods (e.g. multiplication with pre-defined emission factors) and macroscopic models which do not consider operational factors fully (e.g. the number of stops, time spent in acceleration) may not be enough to detect short-term air pollution peaks. These results prove the adopted microscopic traffic and emission modelling approach to be proper: in terms of the scale and the scope of the developed DETM approach and particularly for the detailed evaluation of impacts of ZEVs in DETM (proof of concept) in this thesis.

6.4 DETM Measures and Simulation Scenarios

For the proof of concept commonly used example DETM measures are chosen, for which ZEVs can be considered separately. The study examines two different dynamic measures (**Figure 6.11**):

- temporary re-routing
- temporary traffic flow metering at two locations

Details of the measures are explained in the following chapters. It is important to note here that two criteria are considered in the design of the measures: (1) all hotspots must be ruled out (except for the queueing areas) and (2) no new hotspots should be generated. By doing this, it is ensured that the applied measure did not cause any new hotspots both with and without giving privileges to ZEVs.

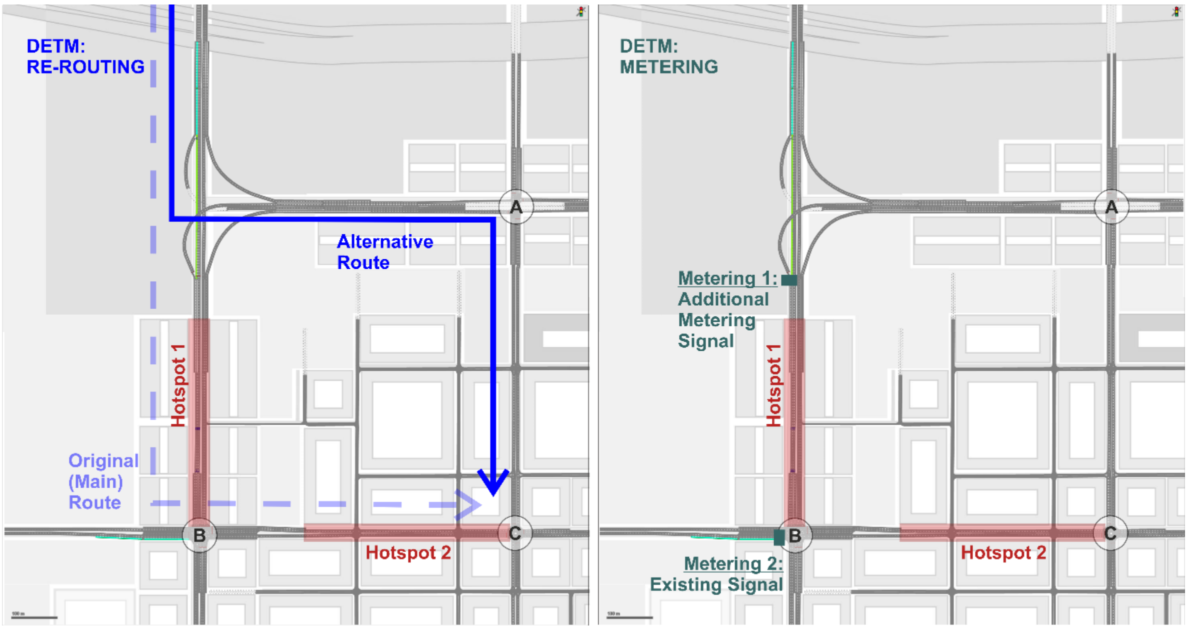

Figure 6.11 Evaluated DETM Measures

6.4.1 Description of Scenarios

Both measures are modelled with and without ZEV privileges (each version with four simulation runs, see **Chapter 6.2.5**). The description and coding of the scenarios can be found in **Table 6.6**. In addition to the base scenario (B00), there are eight scenarios with different ZEV shares in the fleet (B05 to B70) - all without any DETM measures. Furthermore, eleven scenarios with temporary re-routing (R00 to R40-p) and eleven scenarios with temporary traffic flow metering (M00 to M40-p) are simulated.

	Simulated Scenarios				
ZEV share	Base	Re-Routing (R)		Metering (M)	
		Without Privilege	With ZEV Privilege	Without Privilege	With ZEV Privilege
0 %	B00	R00		M00	
5 %	B05	R05	R05-p	M05	M05-p
10 %	B10	R10	R10-p	M10	M10-p
20 %	B20	R20	R20-p	M20	M20-p
30 %	B30	R30	R30-p	M30	M30-p
40 %	B40	R40	R40-p	M40	M40-p
50 %	B50				
60 %	B60				
70 %	B70				

Table 6.6 Description and coding of the scenarios

Firstly, the base situation is simulated with an increasing percentage of ZEVs, to investigate the effects of an increased ZEV share in the fleet and to determine the relevant number of scenarios for DETM measures. **Figure 6.12** illustrates the results of these eight base scenarios for the peak pollutant concentration hour (08:00 - 09:00 AM, mean values from 4 simulation runs).

Figure 6.12 Peak NO_2 concentrations (08:00-09:00 AM) with increasing ZEV shares in base scenarios

It is seen that with a ZEV share of 50 %, hourly limit exceedances start to occur only at street canyons which are the queuing areas in front of signalized intersections (100 m). From a ZEV share of 70 % on, there are no more exceedances of the hourly NO_2 limit value in the network. Defined hotspot areas do not appear in scenarios after 50 % ZEV share. For this reason, only scenarios up to a ZEV share of 40 % are considered for further analysis of DETM measures (see **Table 6.6**).

6.4.2 Temporary Re-Routing

In the first dynamic measure, a part of the traffic which will drive through the hotspot areas is temporarily diverted to an alternative less congested route. With this, it is aimed to relieve the critical area in terms of traffic, NO_X emissions, NO_2 concentrations and to avoid exceedance of the one-hour NO_2 concentration limit (50 µg/m³) at 08:00 AM and 09:00 AM. During the activation period (08:00 - 10:00 AM), all vehicles driving from the north (Origin: zone 2 and 15) to Intersection C (Destination: zone 11, 14 and 101-110), whose route passes through the hotspot areas are diverted to the alternative route (**Figure 6.11, left**). All other vehicle trips passing the hotspots remain unaffected. By modelling of the dynamic re-routing, a compliance rate of 70 % is considered.

In addition to modifying the vehicle routes (static), the fixed-time signal programs at intersections A and C are adjusted to provide an extended green time for the additional traffic on the alternate route (only during the activation period). Thus, it is ensured that no new hotspot was generated. **Figure 6.13** shows the effects of temporary re-routing on peak NO_2 concentrations. The figure shows that the two hotspots do not exist anymore with the application of the measure, even with 0 % ZEV share (R00).

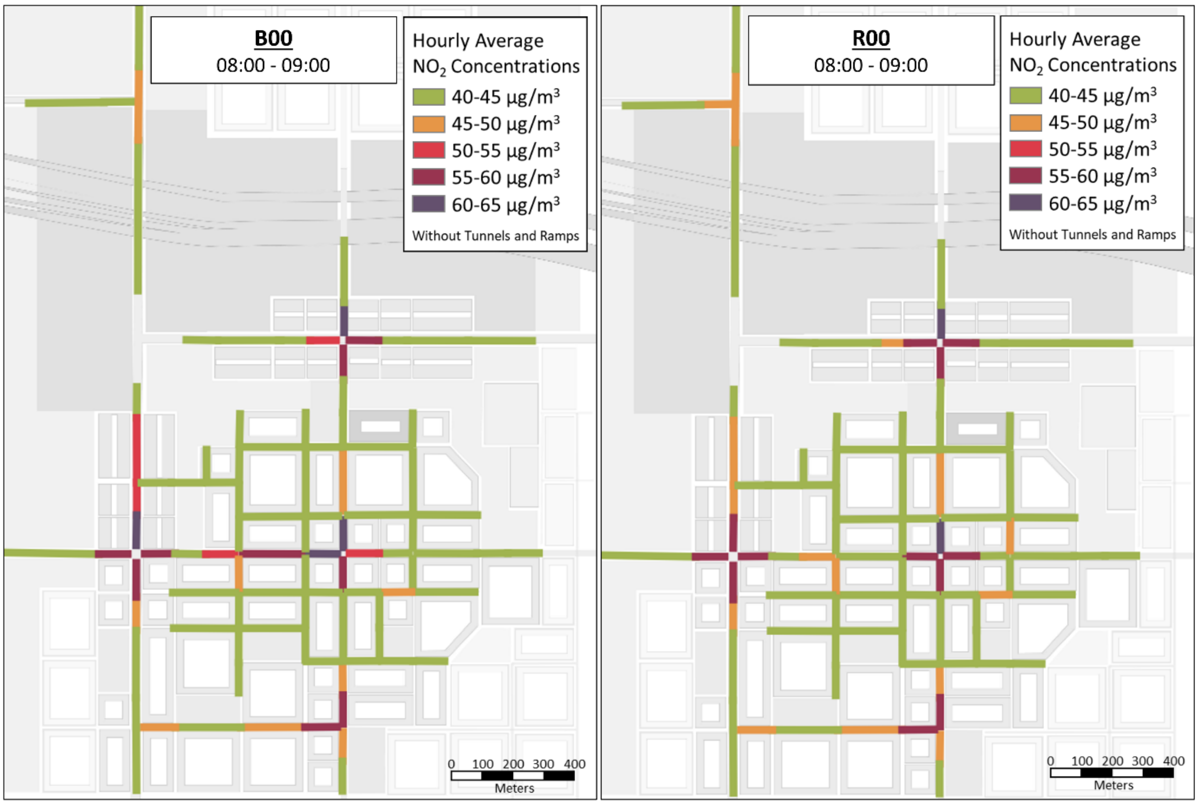

Figure 6.13 Comparison of NO_2 concentrations in base scenario (B00) and initial routing scenario (R00)

For the scenarios with ZEV privilege, an exemption from the dynamic rerouting is considered for all ZEVs which ride on affected routes. Consequently, in the scenarios with privileges, all zero-emission vehicles can continue to follow their original routes (main route), whereas conventional vehicles must use the alternative route (see **Figure 6.11, left**).

6.4.3 Temporary Traffic Flow Metering

The aim of the temporary/dynamic traffic flow metering measure is to reduce the traffic volumes in both hotspot areas and lessen the congestion at intersections B and C which is expected to result in reduced emissions and air pollution in these areas. With this goal, temporary metering is applied and analyzed for the two hotspots with two different approaches (**Figure 6.11, right**):

- In the first version (Metering 1), structural changes such as the installation of a new metering signal and an additional ZEV lane (i.e. temporary right shoulder use for ZEVs) are considered for Hotspot 1. This measure is developed as a practical example approach for outer-city road sections (e.g. ring roads) to meter traffic flow entering an urban network, where the availability of space is not as critical as an inner-city network.
- In the second version (Metering 2), a common metering solution without structural additions is considered. Temporary traffic flow metering for Hotspot 2 is carried out by adapting the green times of the existing signal. This measure is selected as an exemplary DETM measure which is applicable for urban areas, where structural changes are rarely possible.

Metering 1: In the first version, an adaptive metering approach is utilized. A metering signal reduces the vehicle inflow from the north into Hotspot 1, depending on the queue situation which is detected by the queue detectors installed in the northern approach of the intersection B (**Figure 6.14**).

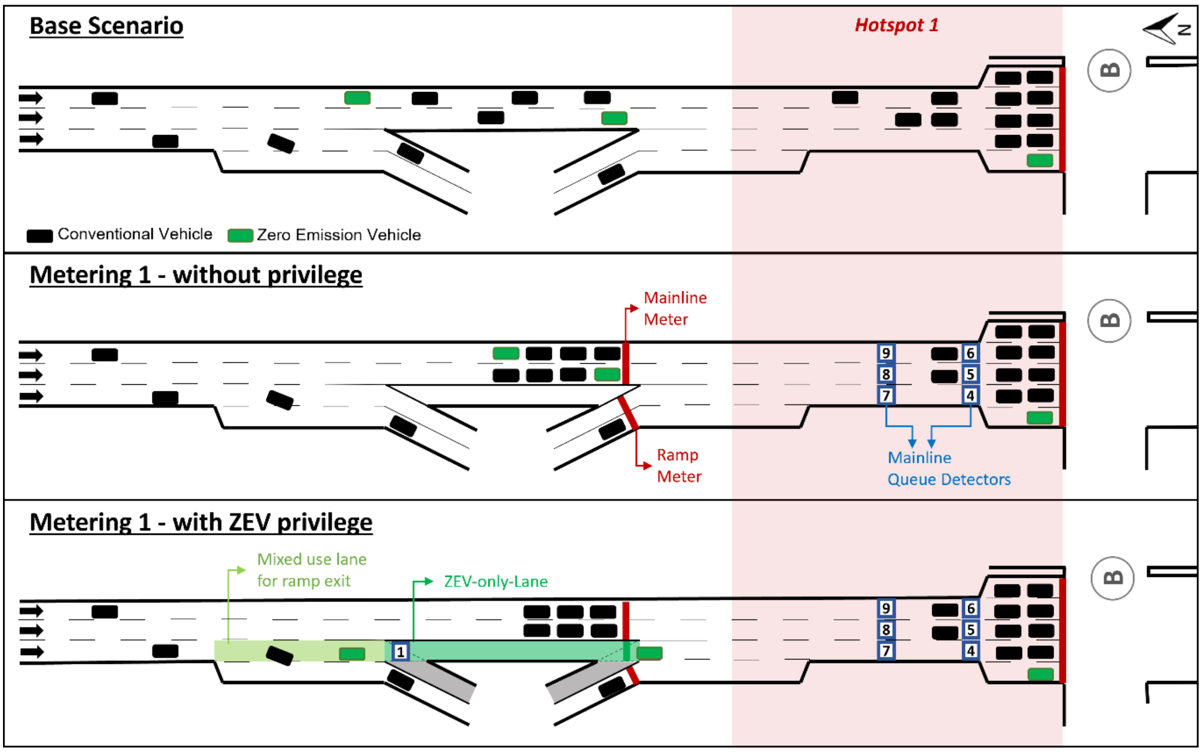

Figure 6.14 Temporary metering measure 1

For the scenarios with ZEV privilege, an additional special lane for ZEVs on the right side of the roadway (comparable to dynamic hard shoulder running) is considered. This ZEV-only-lane (300 m) is only activated during the activation period of DETM (08:00 - 10:00 AM) and has a permanent green light at the mainline metering point. By this method, ZEVs are exempted from the dynamic traffic control measure and can drive through the hotspot area without stopping (**Figure 6.14)**.

For all metering scenarios for Hotspot 1 (with or without privilege), a simple adaptive green time algorithm is implemented in VISSIM by using VISVAP Module. The logic can be summarized as follows (the algorithm can be found in **Appendix 5h**):

- The metering signal program has a cycle time of 90 seconds and is composed of two signal groups (SG): Mainline Meter and Ramp Meter (**Figure 6.14**).
- SG Mainline Meter has a default green time of 40 seconds and a minimum green time of 10 seconds. When queue length in Hotspot 1 is long enough (defined as an occupancy rate of 1/3 at the detectors) to reach the first mainline queue detectors (detectors 4, 5, 6), green time is reduced by 10 seconds (to 30 s) in the next cycle. When the queue reaches the second mainline queue detectors (detectors 7, 8, 9), green time is reduced by additional 10 seconds (to 20 s) in the next cycle.
- SG Ramp Meter has a default green time of 50 seconds and a minimum green time of 5 seconds. When the queue in Hotspot 1 reaches the first mainline queue detectors, green time is reduced by 10 seconds (to 40 s) in the next cycle. When the queue reaches the second mainline queue detectors, green time is reduced by an extra 10 seconds (to 30 s) in the next cycle.

During the first tests of the measure, it is observed that in scenarios with ZEV privilege, the desired emission reduction in the hotspot could not be reached. It is recognized that for time intervals where many ZEVs drive into the hotspot at the same time from the mainline meter (in addition to the conventional vehicles that can drive by during the available green time), congestion and emissions could even increase in Hotspot 1.

As a result, for the scenarios with ZEV privilege, an additional ZEV-Detector is located at the starting point of the ZEV lane (see Detector 1 in **Figure 6.14**). By doing this, the number of vehicles on the ZEV lane is detected and the available green time for the conventional vehicles at SG Mainline Meter is reduced accordingly. In this way, it is ensured that only a defined number of vehicles (independent of the vehicle type) enter Hotspot 1 in each cycle (see **Appendix 5h** for details).

The main algorithm explained above is extended for metering scenarios with ZEV privilege as follows:

- The main metering algorithm is the same. In addition to the former, vehicles on the ZEV lane are counted at Detector 1 (see **Figure 6.14)**. For each ZEV detected, the green time of the mainline meter and the ramp meter (now used only by conventional vehicles) is reduced by 1 second additionally (until the above-stated minimum green times are met).
- It should be noted that, due to the additional ZEV lane, only one lane is available on the affected ramps during the DETM activation time for these scenarios with privileges (see **Figure 6.14)**.

Metering 2: For Hotspot 2, the inflow metering (Metering 2) is carried out by adapting the existing signal program at intersection B. The metering is applied by reducing the green time for vehicles that drive from west to east, into the hotspot area (**Figure 6.15**).

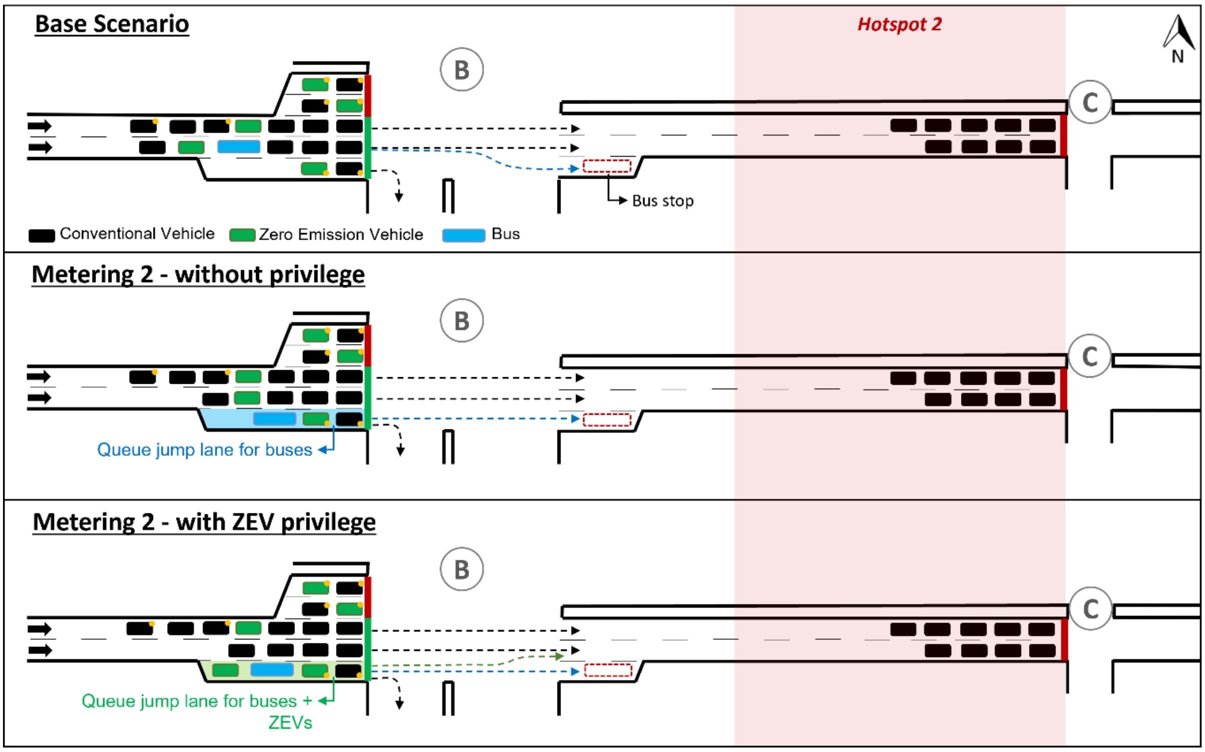

Figure 6.15 Temporary metering measure 2

Since there are existing bus lines on this route (see **Appendix 5e**), an additional bus queue jump lane is applied at the intersection so that bus operation is not slowed down or disadvantaged by the applied DETM measure. The bus queue jump lane offers the possibility for the straight-driving buses to use the right-turn lane as a bypass lane during the activation of the DETM measure.

In the scenarios with ZEV privilege, this queue jump lane can also be used by ZEVs that drive straight from west to east. In this way, ZEVs can bypass the main queue and their waiting times are reduced.

Figure 6.16 shows the effects of temporary/dynamic traffic flow metering at both locations on the peak NO_2 concentrations. As illustrated, it is again ensured that when both measures are activated Hotspot 2 disappears and no new hotspot is generated, even in the case of 0 % ZEV share (M00).

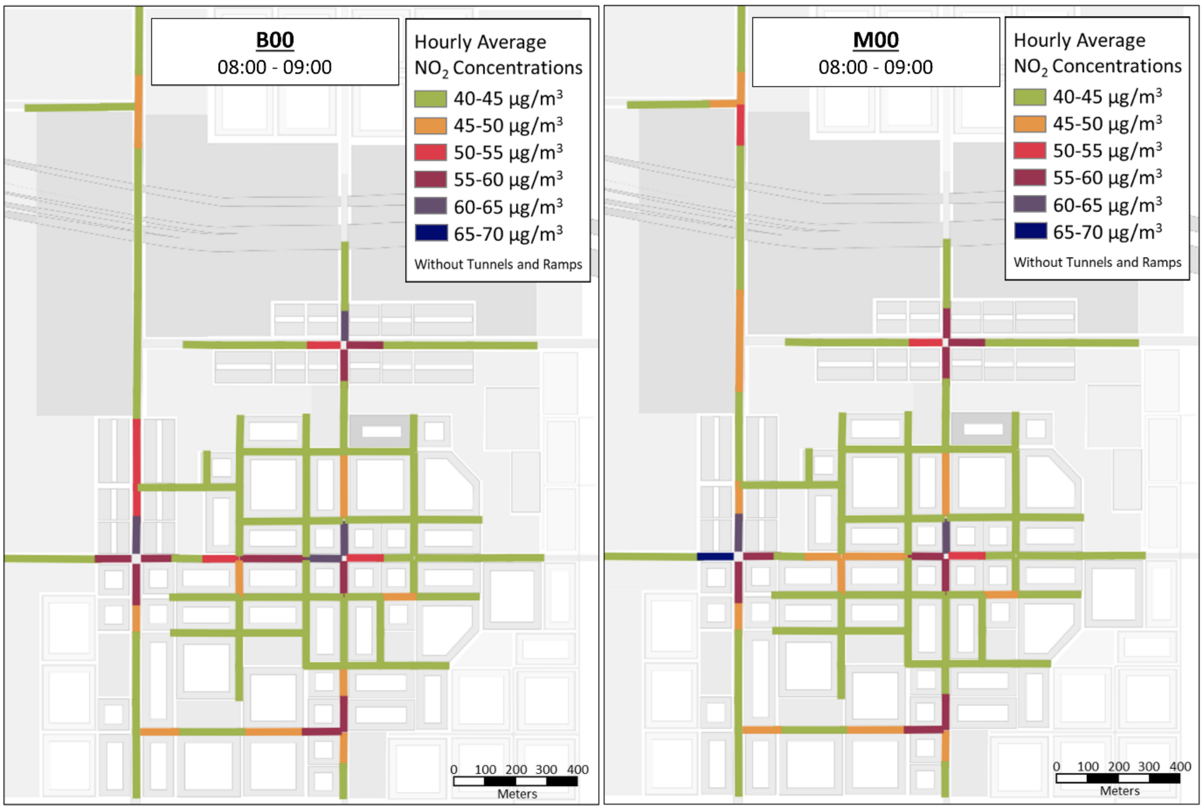

Figure 6.16 Comparison of NO_2 concentrations in base scenario (B00) and initial metering scenario (M00)

6.5 Evaluation Approach

It is important to remind readers here that the analyses performed in this chapter do not address the effects of the DETM measures. In other words, the evaluation does not focus on the comparison between the base scenario and the scenarios with DETM measures. As presented in the previous two chapters, both temporary re-routing and temporary metering measures solve the problem of exceedances of the defined hourly NO_2 threshold value and do not generate new hotspots. Therefore, the analysis focuses on the impacts of consideration and exemption of ZEVs in DETM. This means that the comparison is between the DETM scenarios with privilege and without privilege.

This chapter tries to answer the last four research questions (see **Chapter 1.4**) and examines:

- Whether the DETM measures become more effective with ZEV privilege (**RQ4**)
- Whether the DETM measures become more efficient with ZEV privilege (**RQ5**)
- If ZEVs are subjected to significant advantages in traffic with such measures (**RQ6**)
- What kind of effects do increasing ZEV shares have on these measures with ZEV privilege? (**RQ7**)

To summarize, it is evaluated if the DETM measures considering and privileging ZEVs increase the effectiveness and efficiency of these measures, compared to the conventional DETM measures (where such vehicle types are not regarded separately). Furthermore, it is investigated if such measures increase the attractiveness of ZEVs. All these aspects are analyzed with different ZEV fleet shares.

Effectiveness: Hypothesis 1 states that consideration of ZEVs in DETM measures can increase the effectiveness of these measures by reducing the spatial relocation of traffic and emissions to other areas (see **Chapter 1.2**). In this regard, the impacts of measures on local traffic and air quality situation at hotspots as well as at relocation areas are analyzed. Relocation areas are the network sections where traffic and resulting emissions are directed when the measure is applied: the alternative route, in the case of temporary re-routing; and the queuing areas, in the case of temporary metering. In addition to local impacts, overall network performance is evaluated.

Efficiency: Hypothesis 2 states that consideration of ZEVs in DETM measures can increase the efficiency of these measures by scaling down the temporal relocation of traffic and emissions (see **Chapter 1.2**). This means that with ZEV privilege, measures can solve the congestion and resulting air quality problem in a shorter time. For this, the impacts of the measures on traffic recovery time (by checking the network speed curves) are evaluated.

Attractiveness: Hypothesis 3 states that consideration of ZEVs in DETM measures can increase the attractiveness of these vehicles by bringing advantages in traffic during the activation time (see **Chapter 1.2**). To inspect this, travel times and the number of stops of ZEVs and conventional vehicles are compared by focusing on conventional passenger cars (PC) and zero-emission passenger cars (ZE-PC).

Details on the evaluated indicators for each aspect can be found in **Table 6.7**. The table gives detailed information about each indicator on output data from the model.

Impact on →	**Local Traffic Situation**	**Local Air Quality Situation**	**Network Performance**
Effectiveness Indicators (08 - 10 AM)	**Average travel time** Route-based 5 minutes All vehicles **Average number of stops** Route-based 5 minutes All vehicles **Average stop time** Route-based 5 minutes All vehicles **Maximum queue length** Signal group-based 5 minutes All vehicles	**Total NO_X emissions** Street canyon-based 1 hour All vehicles **Total NO_2 concentrations** Street canyon-based 1 hour All vehicles	**Average delay time** Network-based 5 minutes All vehicles **Average number of stops** Network-based 5 minutes All vehicles **Average stop time** Network-based 5 minutes All vehicles
Efficiency indicator (07 - 11 AM)			**Average speed** Network-based 5 minutes All vehicles
Attractiveness Indicators (08 - 10 AM)	**Average travel time** Route-based 5 minutes PC and ZE-PC **Average number of stops** Route-based 5 minutes PC and ZE-PC		
LEGEND	Output data type	Output data time interval	Considered vehicles

Table 6.7 Evaluation of indicators

It is important to emphasize here that no differentiation is made between the driving behaviors of ZEVs and conventional vehicles (within the same vehicle type) in traffic flow simulation. To illustrate, PCs and zero-emission PCs (ZE-PCs); HDVs and zero-emission HDVs (ZE-HDVs); LCVs and zero-emission LCVs (ZE-LCVs) have the same driving behavior. Consequently, values of traffic indicators do not change between without-privilege scenarios where the same traffic situation is simulated with different ZEV percentages. On the other hand, values of indicators regarding the air quality situation (i.e. emissions and air pollutant concentrations) change for each of these scenarios due to the change in the vehicle fleet on the network.

As a result, traffic-related indicators (local traffic situation and network performance) are compared to the same scenario to keep this comparison simple. R00 is taken as a basis for re-routing measures, whereas M00 is taken as a basis for metering measures. Air quality indicators, however, are compared between the two versions of a measure; between the scenarios with and without privileges for the same ZEV fleet share. **Figure 6.17** illustrates this comparison approach. Blue lines indicate the comparison of traffic-related indicators, whereas green lines indicate the comparison of air quality indicators.

ZEV share	Base	Simulated Scenarios			
		Re-Routing (R)		Metering (M)	
		Without Privilege	With ZEV Privilege	Without Privilege	With ZEV Privilege
0 %	B00	R00		M00	
5 %	B05	R05	R05-p	M05	M05-p
10 %	B10	R10	R10-p	M10	M10-p
20 %	B20	R20	R20-p	M20	M20-p
30 %	B30	R30	R30-p	M30	M30-p
40 %	B40	R40	R40-p	M40	M40-p

Figure 6.17 Illustration of the comparison of scenarios with and without ZEV privilege

To analyze if the changes in indicator values from different scenarios are significant a statistical analysis is conducted. Firstly, it is evaluated if the indicator values are normally distributed. Due to values being not normally distributed, a nonparametric statistical test is applied where the assumption of values being normally distributed is not necessarily met. The Wilcoxon signed-rank test is the applied non-parametric test which is equivalent to the t-test (used for normally distributed data sets).

In this study, values are compared as matched pairs in the Wilcoxon signed-rank test. All indicators from the same observation (i.e. simulation run) under two conditions are compared: with and without ZEV privilege (see **Figure 6.19**). The confidence level used for the statistical analysis is 95 %.

6.6 Results

Results are calculated and presented for both DETM measures in the same way. However, indicators related to different impact areas (see **Table 6.7**) are analyzed in different forms:

- **Local traffic and air quality situation indicators** (required for the assessment of effectiveness and attractiveness) are analyzed separately for hotspots and relocation areas. As explained in **Chapter 6.5** relocation areas are the network sections where traffic and resulting emissions are directed when the measure is applied.

  In the case of re-routing, hotspot areas are defined as road sections on the main route, and relocation areas are defined as street sections on the alternative route. In the case of metering, road sections in hotpots and queuing/tailback areas are considered. An illustration of these areas can be found in **Figure 6.18**.

- **Network performance indicators** (required for the assessment of effectiveness and efficiency) are evaluated by considering the whole network.

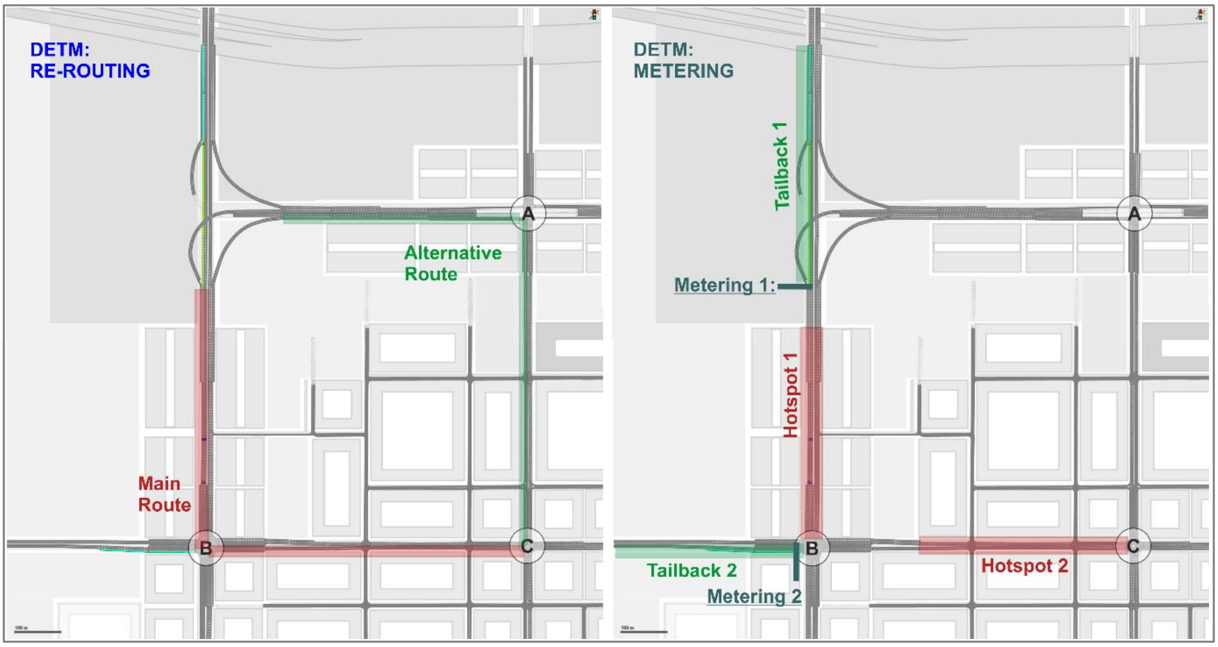

Figure 6.18 Representation of the areas considered for local traffic and air quality analysis

Figure 6.19 illustrates how evaluation outcomes are generated and presented in this dissertation. To begin with, results are presented in evaluation result tables for each indicator and each scenario (**Figure 6.19.a**). In addition to these tables, to see the distribution of the raw values, detailed boxplots are created (**Figure 6.19.b**). These highly detailed tables and boxplots can be found in **Appendix 5i** for the re-routing measure and **Appendix 5j** for the metering measure.

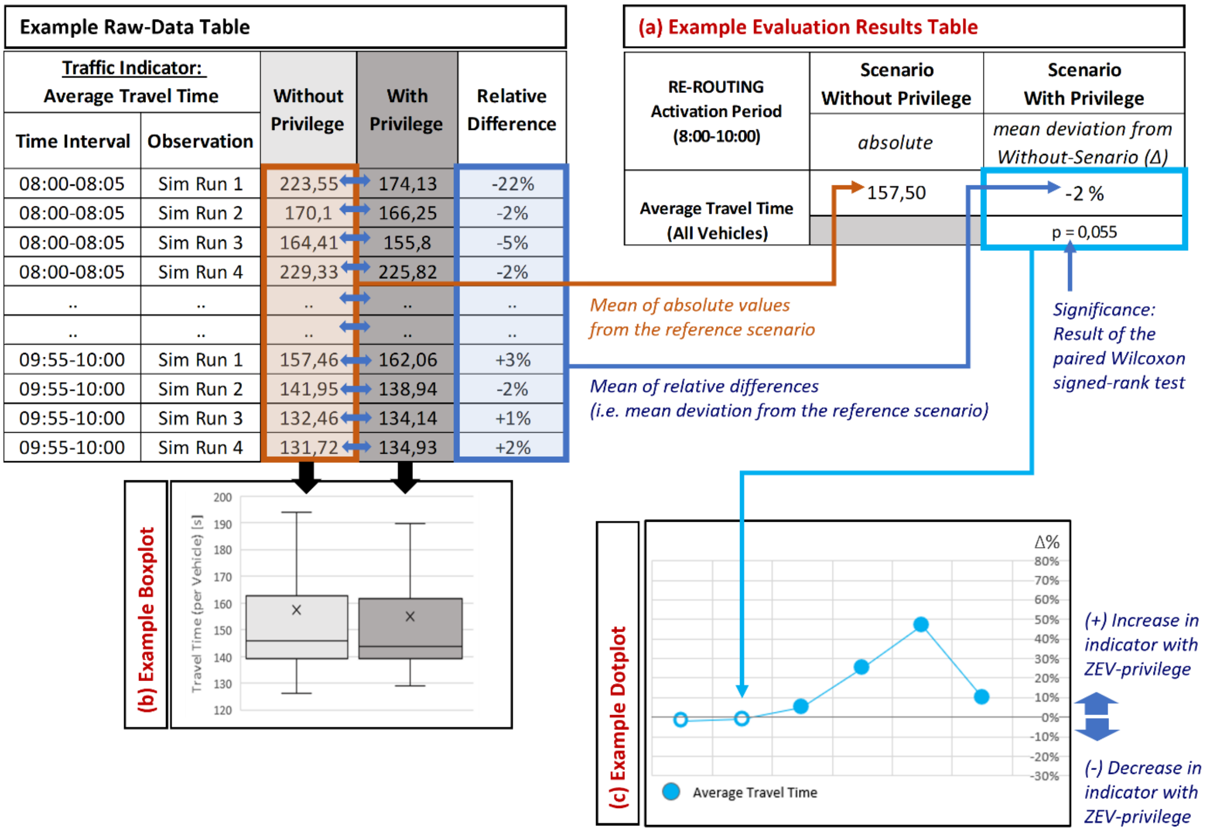

Figure 6.19 Illustration of the evaluation method, example raw data and evaluation result tables

In the main text, results from all indicators related to effectiveness and attractiveness are presented as dotplots (see **Figure 6.19.c**). These plots show the mean of relative differences (Δ) for each scenario, as percentages. Values that did not pass the significance test are illustrated with empty dots, whereas significant values are shown with full dots. These indicators are evaluated for the measure activation period from 08:00 -10:00 AM (see **Table 6.7**).

There is only one efficiency indicator: average speed in the network. In the main text, results from this indicator are evaluated by checking the change in the average network speed (i.e. network speed curves), due to dealing with traffic recovery time. Efficiency analysis covers the whole simulation period from 07:00 -11:00 AM (see **Table 6.7**).

6.6.1 Temporary Re-Routing

Effectiveness – Local Traffic and Air Quality Situation

The results of local traffic indicator values show that all indicators improve for the alternative route during the activation period, with a ZEV privilege (**Figure 6.20**). This is because ZEVs are allowed to stay on the main route with the privilege which results in a reduction in overall traffic volumes on the alternative route.

With increasing ZEV percentages, more and more vehicles drive by on the main route and fewer vehicles on the alternative route. Consequently, the amount of improvement in local traffic indicators of the alternative route increases with rising ZEV shares. For example, the average number of stops on the alternative route is reduced up to 40 % already with a 5 % ZEV share and reached 70 % with higher ZEV shares (starting from 20% ZEV share).

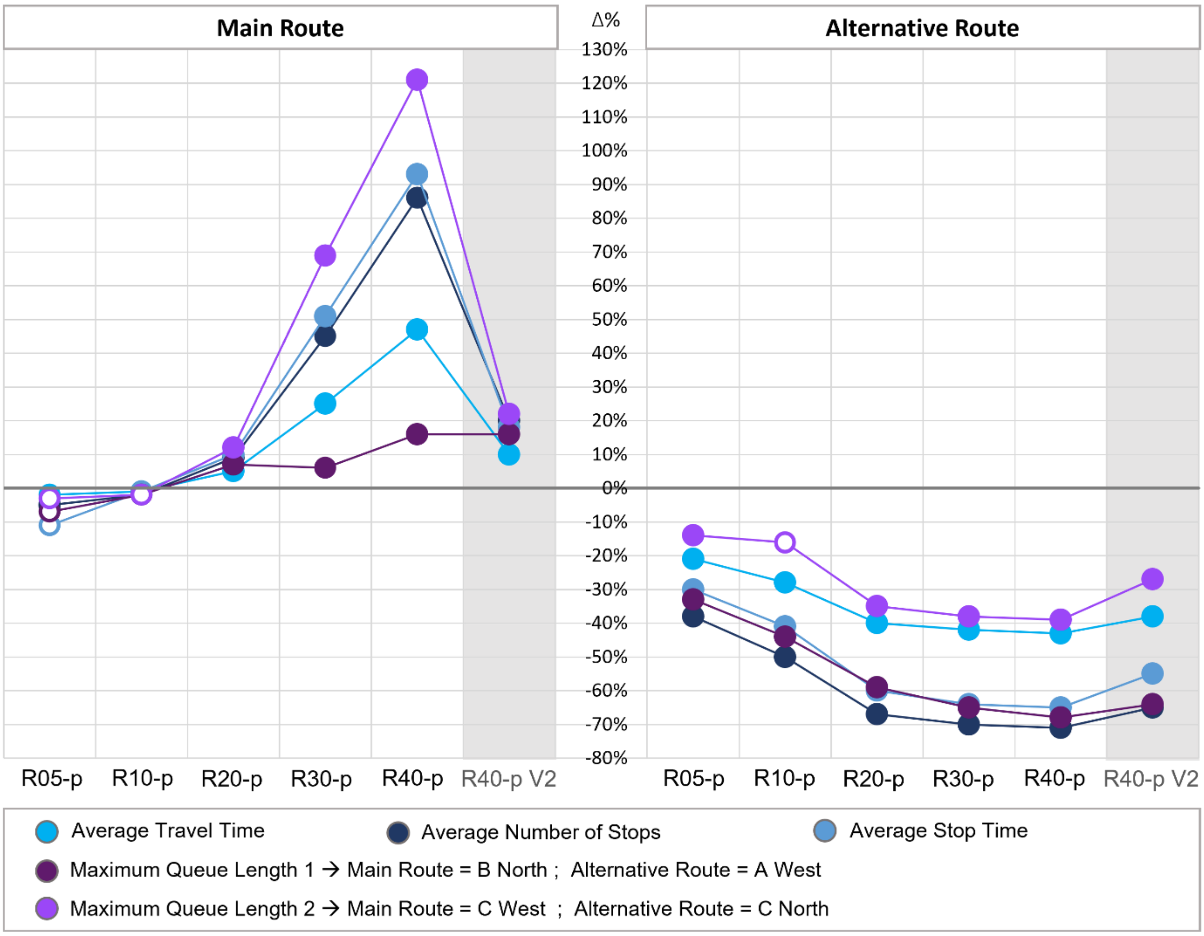

Figure 6.20 Local traffic situation indicators for re-routing scenarios

On the other hand, traffic volumes on the main route gradually increase with higher ZEV shares when there is a ZEV privilege. While this privilege does not affect traffic indicators of the main route much at low ZEV shares (5 % and 10 %), with a 20 % ZEV share, all indicators slightly worsen for the main route in comparison to the DETM measure without ZEV privilege. It is important to highlight here that although the main route becomes busier with the privilege compared to the no-privilege case, all traffic and air quality indicators are still significantly improved (reduction between 50 - 80 %) in comparison to the base scenario (see **Appendix 5i -1, -2 and -3**).

A higher increase in all indicators is observed after ZEV percentages of 30 % and 40 % on the main route. This is a result of fixed-time signal programs that are used in traffic flow simulation. As explained in **Chapter 6.4.2**, signal programs are adapted in line with the new re-routing strategy, so that no congestion is created on the alternative route. However, it is important to keep in mind that the signal control in the simulation is not adaptive. Consequently, when more and more ZEVs are allowed to use the main route, these adjusted green times (which are optimized for the increased traffic volumes on the alternative route) become insufficient for the main route, at some point. With an additional scenario, a new signal program that matches the demands on both routes is tested for 40 % ZEV share (Scenario R40-p second version: **R40-p V2**). The results for all indicators are improved with this scenario and they become similar to the results of R20-p (see **Figure 6.20**). This means that the observed "congestion-comeback-effect" on the main route with high ZEV shares (30 - 40 %) can be reduced when traffic control at main intersections on the network were adaptive.

With ZEV privilege, traffic volumes and resulting congestion on the alternative route are reduced. Consequently, NO_X emissions and NO_2 concentrations are reduced on the alternative route as well (**Figure 6.21**). With increasing ZEV share, this reduction gets higher (up to a 10 - 13 % reduction in total emissions, around a 1 - 2 % reduction in total concentrations).

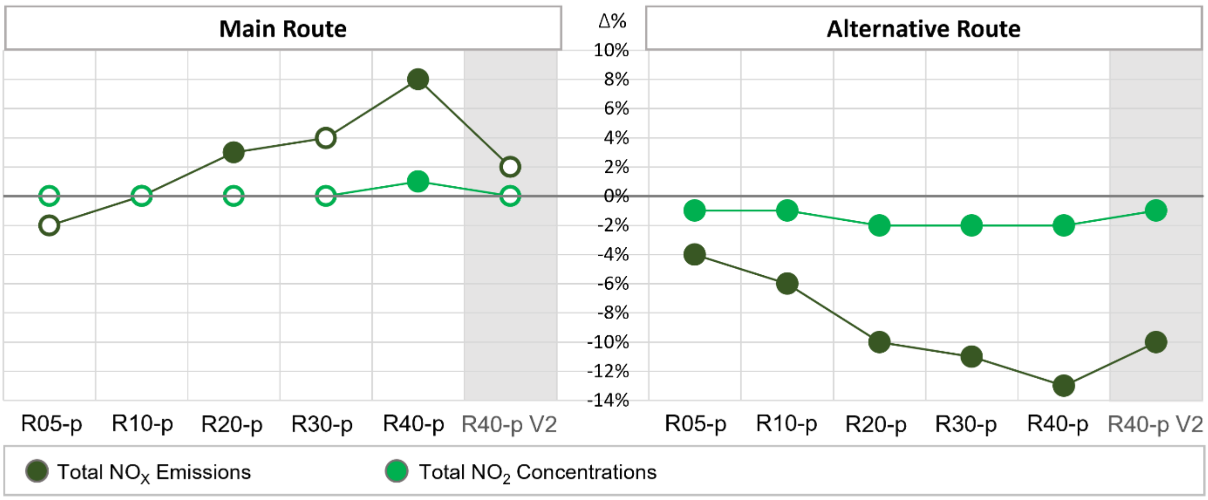

Figure 6.21 Local air quality indicators for re-routing scenarios

Similar to the local traffic situation analysis, there is a light increase in NO_X emissions on the main route with privileges. When ZEVs are exempted from the re-routing measure, they contribute to traffic volumes and congestion on the main route. Although they are exhaust emission-free (i.e. zero-emission at tailpipe), their contribution to the congestion results in a slight increase in total emissions that are produced by other conventional vehicles. However, this does not result in a significant increase in NO_2 concentrations on the main route (sum of concentrations of all street canyons on the route) and does not cause a "hotspot-comeback-effect". In this artificial network, this is also due to the structure of the street canyons on the main route which are mostly wide and/or well-ventilated (i.e. without/partly with built structure).

It is important to mention again that this increase is seen only when results are compared to the no-privilege case. Compared to the initial situation (Base Scenarios) without DETM, air quality on the main route is still significantly improved (see **Appendix 5i -4 and -5**). In addition, it should be noted here that significance is low for air quality indicators in general (compared to traffic-related indicators), due to the smaller sample size of observations. While local traffic situation and network performance indicators are evaluated in 5-minute intervals, air quality indicators are hourly values (see **Table 6.7**).

Effectiveness – Network Performance

Analysis of the network performance shows that there are overall improvements in the network during the activation period with ZEV privilege, compared to the re-routing measure without any privilege (**Figure 6.22**). Even with a ZEV share of 5 %, significant reductions can be observed. Especially, the average number of stops at the whole network is reduced (up to 15 % in scenario R20-p). The highest improvements are seen at 20 % ZEV share. These improvements are even higher, when indicators are compared to the base scenario (B00) - for all indicators and scenarios (reductions of 30 % - 50 %) (see **Appendix 5i -6 and -7**).

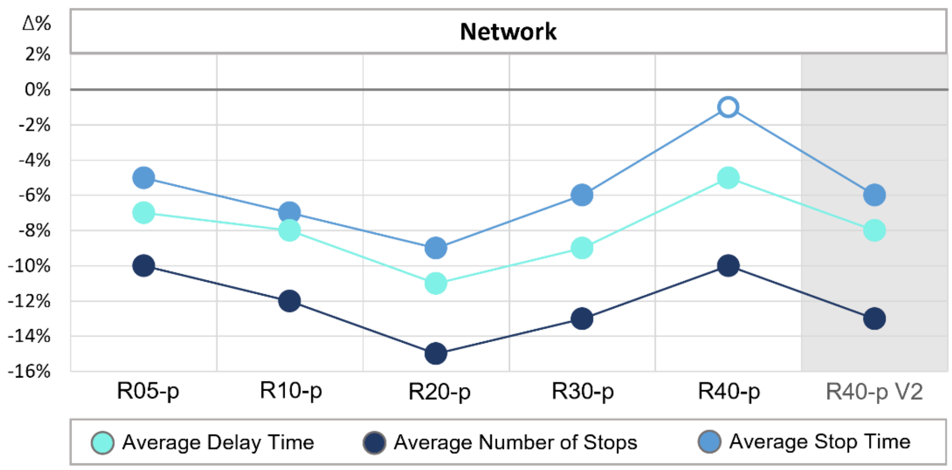

Figure 6.22 Network performance indicators for re-routing scenarios

Efficiency

The change in average network speed in time can be seen in **Figure 6.23**. The figure illustrates when the speed drop occurs and dissolves in the network, comparing different scenarios. Compared to the base scenario (B00), congestion ends earlier in the re-routing scenario without ZEV privilege (R00). In all scenarios with additional ZEV privilege (R05p - R40v2-p), the network speed drop lasts even shorter.

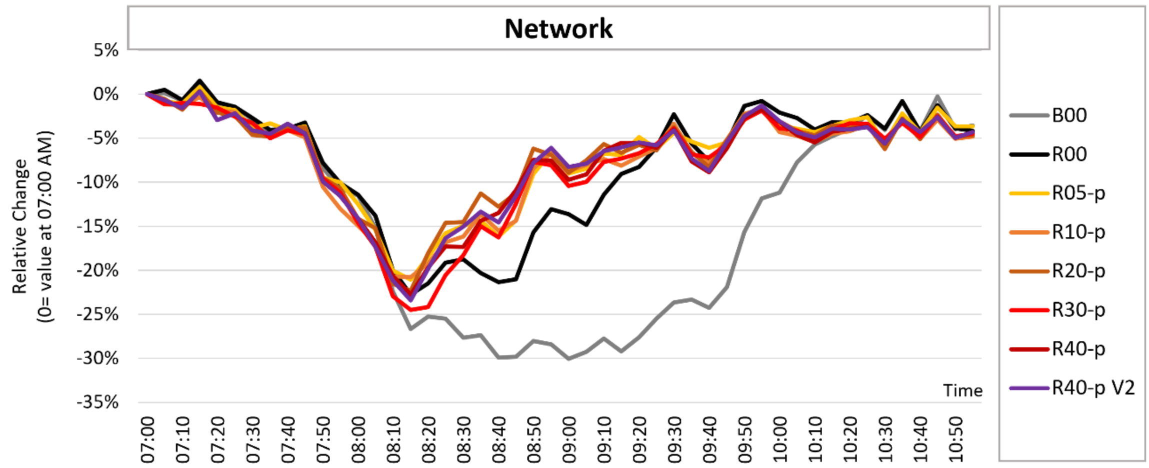

Figure 6.23 Network speed curves for re-routing scenarios

This result shows that consideration and exemption of ZEVs in the dynamic re-routing measure contribute to the efficiency/resilience of the network. It also indicates that the activation period for such DETM measures can be shortened by providing privileges to exhaust-emission-free vehicles. This outcome is also supported by the network performance results (**Figure 6.22**), which show that all indicators are improved with ZEV privilege, in all scenarios.

Attractiveness

Results of attractiveness indicators show that with privilege, not only zero-emission passenger cars (ZE-PCs) but also conventional passenger cars (PCs) get significant reductions in travel times and number of stops during the DETM activation time (compared to the no-privilege case). **Figure 6.24** shows that all indicators for both vehicle types are under the zero value, which shows a decrease.

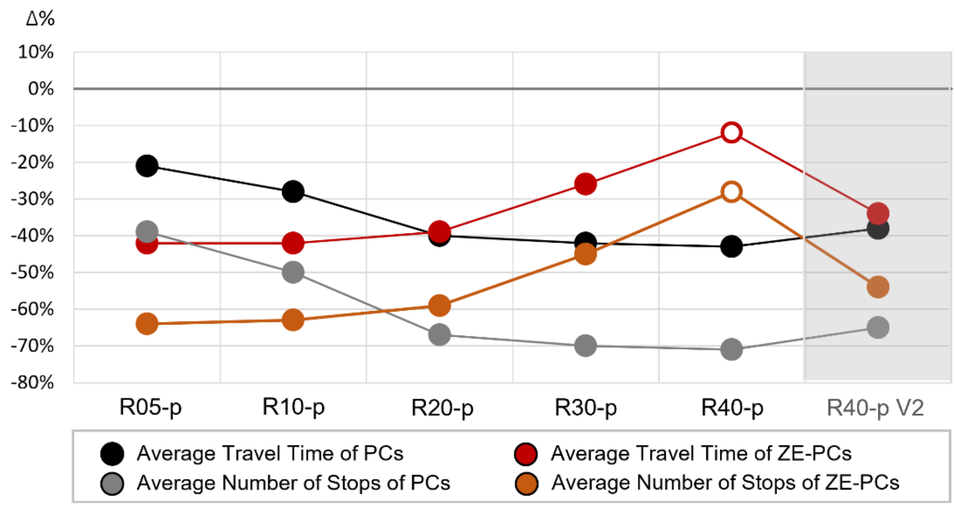

Figure 6.24 Attractiveness indicators for re-routing scenarios

Even with a 5 % ZEV share, the average travel time of PCs is reduced by 20 %, whereas the average travel time of ZE-PCs is reduced by 40 - 45 %. This reduction effect is even higher for the number of stops for both vehicle types. Since ZEVs are allowed to use the main route with the ZEV privilege (exemption from dynamic re-routing measure), traffic volumes are distributed to two routes which result in advantages for all vehicles.

As mentioned earlier, with increasing ZEV share, more and more vehicles are allowed to stay on the main route, due to the exemption. Correspondingly, fewer vehicles are driving on the alternative route. As a result, conventional passenger cars which were diverted to the alternative route have less travel time and number of stops with higher ZEV percentages, compared to the no-privilege scenarios. The advantages of conventional PCs increase gradually with increasing ZEV shares.

On the other hand, the advantages of zero-emission vehicles driving on the main route decrease gradually, with higher ZEV percentages. Consequently, ZEVs lose their significant travel time advantages compared to conventional vehicles after 20 % ZEV share. However, as mentioned, compared to the re-routing measure without privilege, all vehicles still have less travel time and number of stops in all scenarios (i.e. all attractiveness indicators have negative Δ%). Detailed boxplots and evaluation tables can be found in **Appendix 5i -8 and -9**.

6.6.2 Temporary Traffic Flow Metering

Effectiveness – Local Traffic and Air Quality Situation

The results of local traffic indicator values related to Hotspot 1 (located on a main road) can be seen in **Figure 6.25.** The figure shows that with ZEV privilege, all indicators are slightly improved in Hotspot 1, compared to without-privilege scenarios. In Tailback Area 1, average travel and stop times are slightly increased in most of the scenarios (except for the 5 % and 40 % ZEV share). On the other hand, the average number of stops and maximum queue length at the main meter is significantly reduced in all scenarios. This means that this adaptive metering strategy at Hotpot 1 (i.e. for each ZEV that can drive in, conventional vehicles should wait longer) causes a reduction in the queue length and number of stops at the tailback area but results in slightly longer stops, which results in slightly higher travel times on average.

This increased stop time is especially visible at a ZEV share of 20 %. At low ZEV shares (5 % and 10 %) ZEVs do not affect (i.e. reduce) the green times of conventional vehicles remarkably. On the other hand, with high ZEV shares (30 % and 40 %) the number of conventional vehicles in the metering area gets less, and the minimum green time at the metering signal is reached which means that conventional vehicles cannot wait longer when more ZEVs drive into the hotspot. The results show that at 20 % ZEV share, there are enough ZEVs to make conventional vehicles wait longer at the metering signal but their share in the fleet is not high enough to reduce the number of conventional vehicles in the queue (i.e. conventional vehicles still compose 80 % of the vehicle composition).

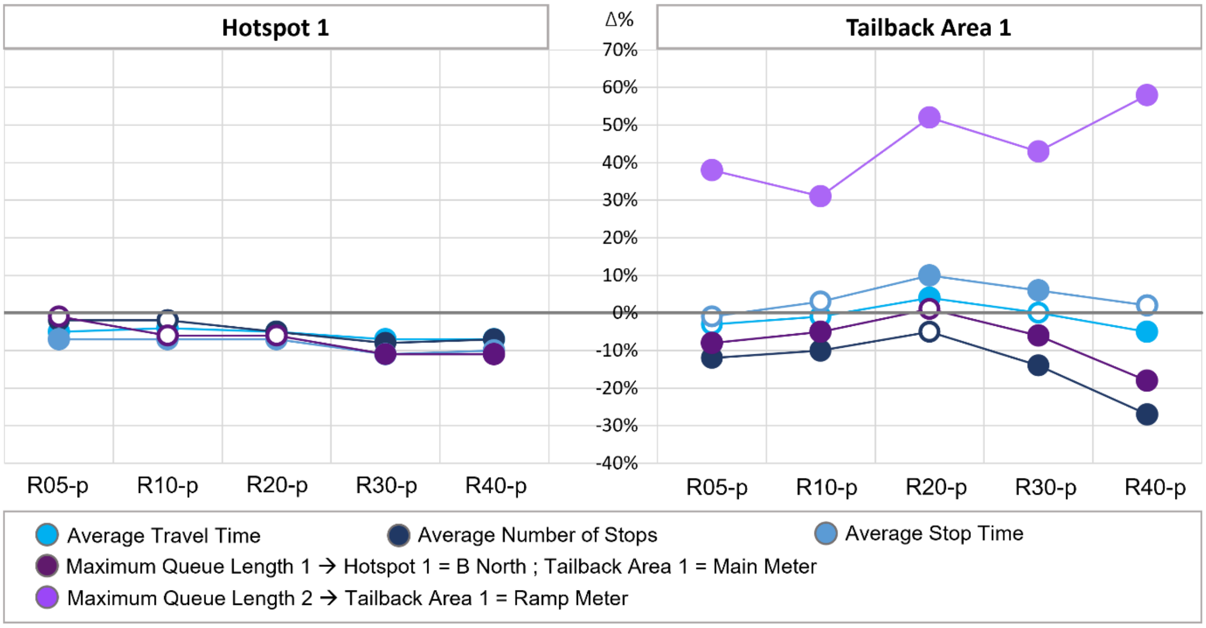

Figure 6.25 Local traffic situation indicators for metering scenarios Hotspot 1

The maximum queue length of signals in the hotspot and tailback area slightly decreases with ZEV privilege. As an exemption, the maximum queue length at the ramp meter increases significantly. This is due to the design of the ZEV privilege and additional ZEV lane which caused a lane reduction at the ramp (see **Chapter 6.4.3** and **Figure 6.14**).

With this adaptive ZEV privilege approach applied at Hotspot 1, air quality indicators of the hotspot area do not change significantly, whereas total NO_X emissions at the tailback area increase (**Figure 6.26**). Although the average number of stops (all vehicles) at the tailback area is reduced (see **Figure 6.25**), conventional vehicles stop slightly more often in this area as a result of the metering measure (see **Figure 6.31**). Consequently, an emission increase is observed for Tailback Area 1.

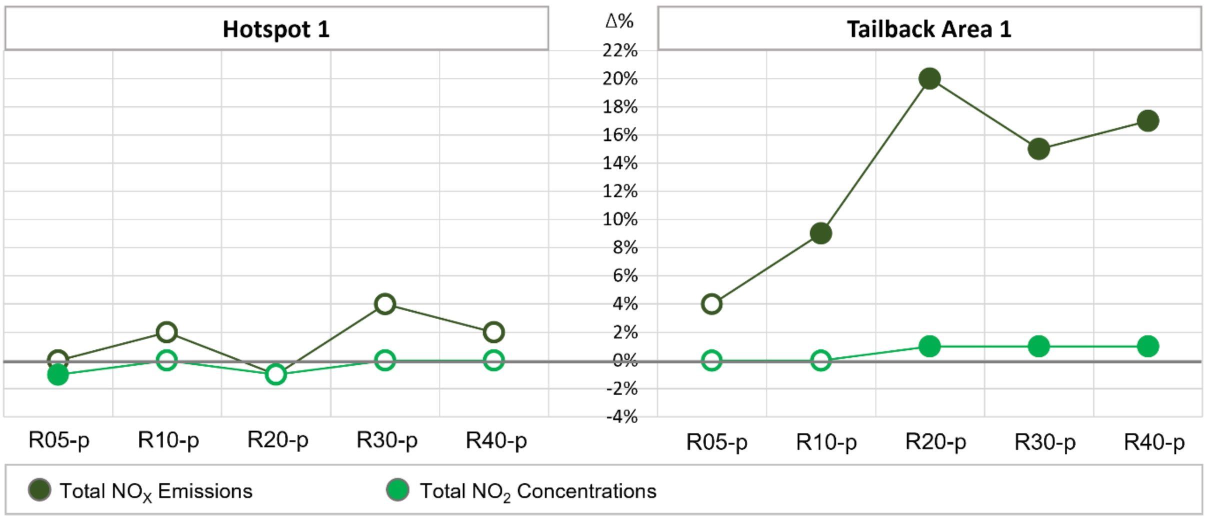

Figure 6.26 Local air quality indicators for metering scenarios Hotspot 1

However, this increase in total NO_X emissions does not affect the average NO_2 concentrations at the tailback area significantly. This can again be explained by the street canyon structure of this area: it is a wide street canyon without a built structure around it. Similarly, in DETM applications, metering locations are ideally selected from uncritical, wide and well-ventilated street canyons outside of the city center since a slight increase in emissions in those areas is expected. This is a possible compromise as long as the traffic management measure helps to solve the air quality problems at the hotspot and does not result in critically high concentrations in tailback areas (i.e. no new hotspots).

The results of local traffic situation indicators related to Hotspot 2 (located on a distributor road) can be seen in **Figure 6.27**. The figure shows that with a non-adaptive metering version, negative effects can be observed at the hotspot resulting from the privilege (compared to the no-privilege case) in the case of high ZEV shares. In this version, conventional vehicles do not wait longer at the metering signal for each privileged ZEV. ZEVs drive into the hotspot, in addition to the number of conventional vehicles that can drive into the hotspot area at reduced green times. As a result, traffic volumes increase at Hotspot 2 with ZEV privilege and even more with increasing ZEV shares. Consequently, an increase in the average number of stops, stop time, travel time, as well as maximum queue length in Hotspot 2 can be observed with 30 % and 40 % ZEV shares.

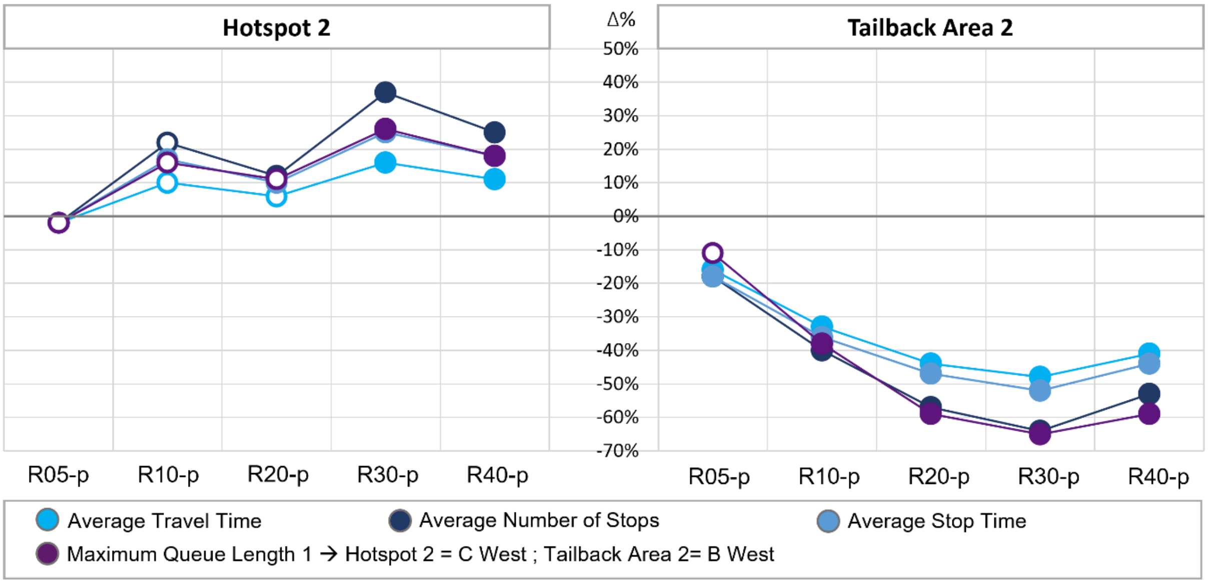

Figure 6.27 Local traffic situation indicators for metering scenarios Hotspot 2

On the other hand, this approach results in high improvements in traffic indicators in Tailback Area 2 (**Figure 6.27**). This is important because Tailback Area 2 is located on a distributor road, in an urban area, and is a street canyon with built structures, unlike Tailback Area 1. Therefore, an increase in traffic and air pollution can not be tolerated (as was the case for the city boundary) and could cause new hotspots. It is also important to highlight that improvements at the tailback area are higher, (up to 70 %) compared to the negative effects at Hotspot 2 (up to 40 %). Please note again that compared to the base scenario (B00), not only Hotspot 1, but also Hotspot 2 still has significant improvements with ZEV privileges, and no new hotspot is generated (see **Appendix 5j -1, -2, -3 and -4**).

Although with high ZEV shares, the traffic increases at Hotspot 2, effects on NO_X emissions and NO_2 concentrations are not extremely high and partly not significant (**Figure 6.28**), especially at low ZEV shares. At Tailback Area 2, emissions and concentrations are reduced but there is no significant change in air quality. Detailed boxplots and tables can be found in **Appendix 5j -5, -6, -7 and -8**).

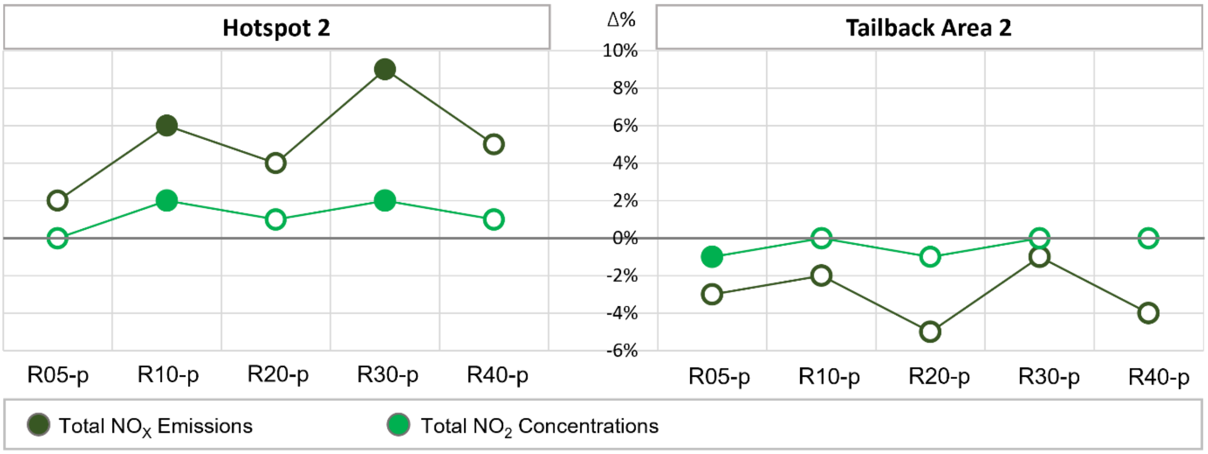

Figure 6.28 Local air quality indicators for metering scenarios Hotspot 2

Effectiveness – Network Performance

In scenarios where temporary metering measures are activated (1 and 2 together) with ZEV privilege, all network performance indicators improve (compared to metering without ZEV privilege). As seen in **Figure 6.29**, all indicators have a negative Δ%. This shows that giving privileges to ZEVs results in a decrease in average delay time, number of stops, and stop time for the whole network. This reduction is visible and significant already at 5 % ZEV share (with 5 - 7 %) and rises with increasing ZEV share. At 40 % ZEV share, the average number of stops during the activation period can be decreased up to 27 %.

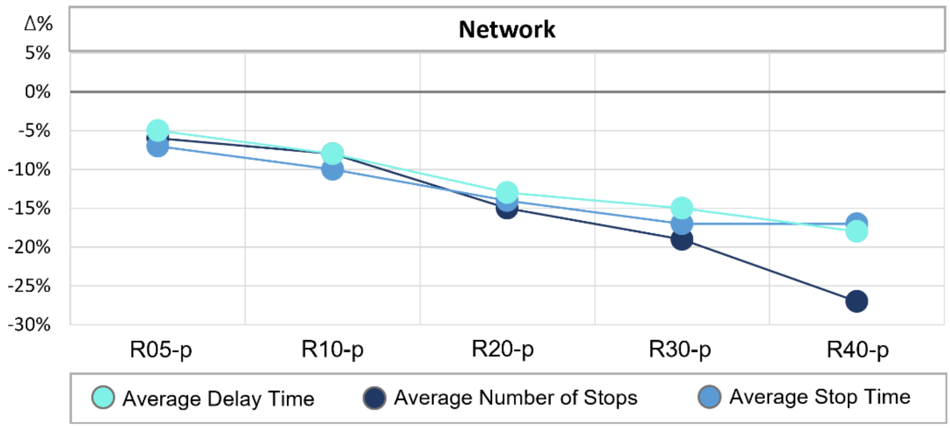

Figure 6.29 Network performance indicators for metering scenarios

As expected, compared to the base scenario (B00), the application of temporary metering measures results in an increase in average stop time, delay time, and number of stops in the network. However, with ZEV privileges this effect is lessened. After a 20 % ZEV share, the reduction in the number of stops per vehicle is so much reduced with ZEV privilege that it becomes even less than the base scenario (B00) - where no metering measure was applied (see **Appendix 5j -9 and -10**).

Efficiency

Figure 6.30 shows the change in average network speed in time for all metering scenarios. As expected, the temporary metering measure (M00) results in a lower average network speed during the activation time (08:00 -10:00 AM) compared to the base scenario (B00). When ZEV privilege is implemented in addition to the metering strategy, the speed drop is reduced after 20 % ZEV share. This result supports the outcomes of the network performance analysis.

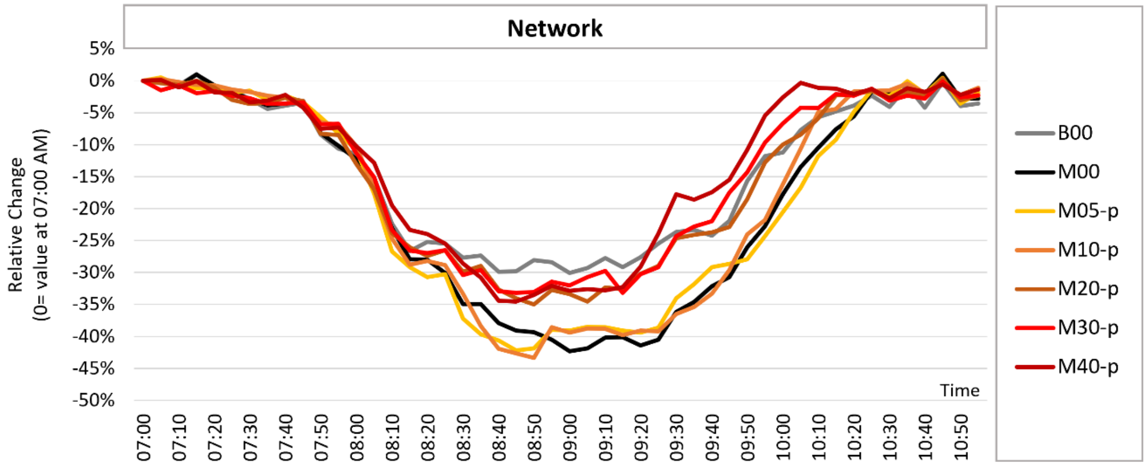

Figure 6.30 Network speed curves for metering scenarios

At low ZEV shares (5 % and 10 %) there is no remarkable change in the average network speed, compared to the metering scenario without privilege (M00). Although the base scenario shows the highest average network speed, it should be kept in mind that this does not mean that the base situation was better. In the base scenario traffic volumes, congestion, speed drop, and emissions were observed at hotspots, whereas in metering scenarios (both with and without privilege) the traffic and resulting congestion and emissions are kept at tailback areas.

Attractiveness

When Hotspot 1 is considered, with the proposed adaptive metering approach and a ZEV privilege, not only ZE-PCs but also conventional PCs stop slightly less often and have shorter travel times in the hotspot (**Figure 6.31**). In Tailback Area 1, ZE-PCs have significantly less travel time (around 60 %) with privilege. Due to this adaptive approach where PCs have to wait for each privileged ZE-PC, conventional passenger cars stop slightly more often and stop longer at the metering signal (resulting in higher average travel times for PCs). This effect is especially visible after 20 % ZEV share.

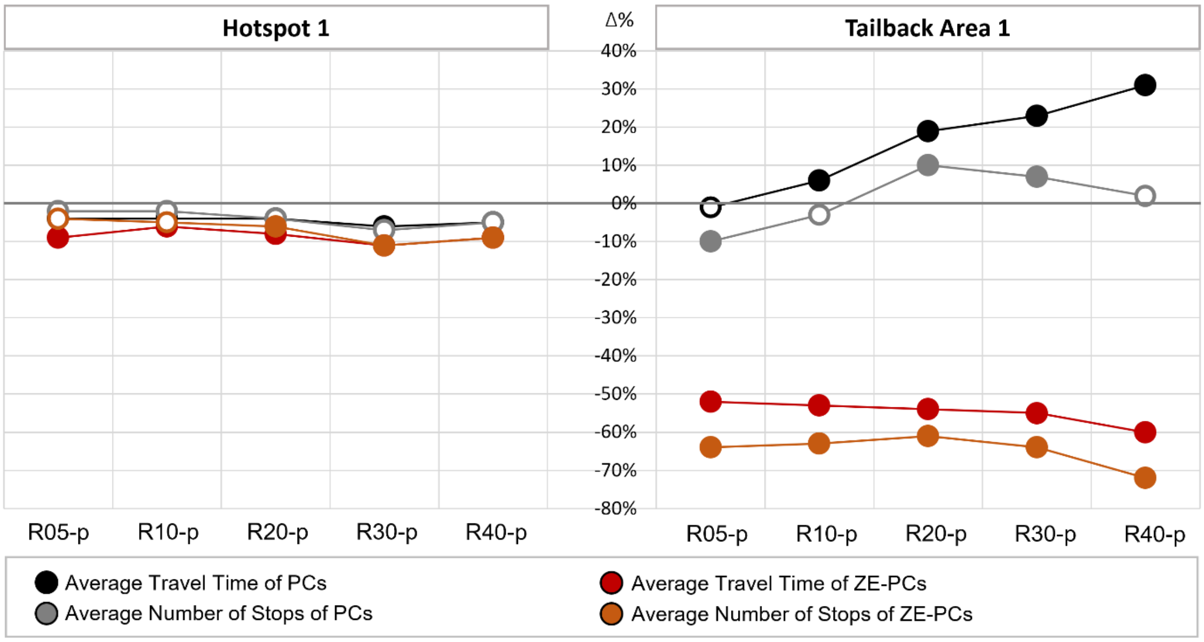

Figure 6.31 Attractiveness indicators for metering scenarios Hotspot 1

When the same traffic indicators are compared for Hotspot 2, the results do not show remarkable differences between the two passenger vehicle types (**Figure 6.32**). This is mostly due to the non-adaptive metering approach, where conventional vehicles are not directly affected by the privileges given to zero-emission vehicles. For both passenger vehicle types, average travel times and the number of stops increase at Hotspot 2 and decrease at Tailback Area 2 with ZEV privilege.

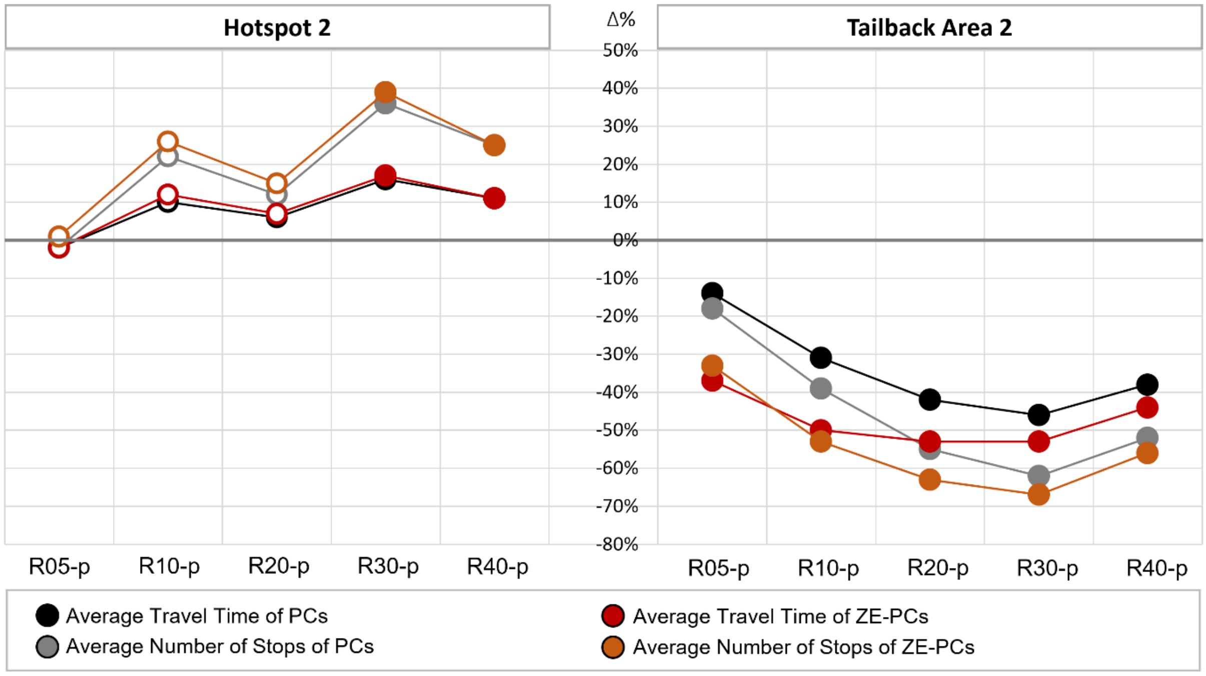

Figure 6.32 Attractiveness indicators for metering scenarios Hotspot 2

The advantages of ZE-PCs over PCs at Tailback Area 2 are more visible at low ZEV shares. For example, at 5 % ZEV share, ZE-PCs have almost 40 % less travel time with privilege, while it is around 10 % for conventional PCs. The same trend is also visible for the average number of stops per vehicle type. As ZEV share increases, improvements in average travel time and number of stops by the ZEV privilege become similar for both vehicle types. Detailed boxplots and tables can be found in **Appendix 5j -11, -12, -13, -14 and -15**).

6.7 Summary

The results of **Chapter 6** show that consideration and integration of zero-emission vehicles in dynamic environmental traffic management is meaningful. Firstly, the potential analysis (**Chapter 6.1**) depicts that ZEVs can contribute to NO_X-emission and NO_2-concentration reduction mainly in network areas where high traffic volumes and congestion are seen. High reduction potential through these vehicles is especially observed during peak hours and under unfavorable dispersion conditions. This matches with the goals of the DETM which aims to reduce short-term critical air pollution situations at hotspots resulting from road traffic. The results of the proof of concept by using a microscopic DETM modelling approach on an artificial/fictitious urban road network support this idea.

The first example DETM measure analyzed under the proof of concept is temporary re-routing during critical air pollution concentration levels. In this measure, conventional vehicles are diverted to an alternative route, whereas ZEVs are allowed to stay on their original route and drive through hotspots. The model results concerning local traffic and air quality situations show that exempting ZEVs from the re-routing measure reduces the relocation of traffic and emissions on the alternative route significantly. Giving privileges to ZEVs lead to efficient use of both routes. It is also seen that above a certain ZEV share (in this study 30 %), such a privilege can cause the main route to get busier if the signal control is not adaptive. On the other hand, simulations conducted during the scenario development phase show that after 40 % ZEV share, most of the NO_2 hotspots in the network disappear, anyway. Another important outcome from the proof of concept is that giving privileges to ZEVs during temporary re-routing not only contributes to the increased attractiveness of ZEVs through reduced travel time and number of stops; but also improves the same indicators for conventional vehicles. This result is also supported by the network analysis. ZEV privilege improves the overall network performance and the traffic recovery time (i.e. network efficiency) in all scenarios.

The second DETM measure modelled under the proof of concept is temporary traffic flow metering. This measure is examined in two versions. The first one is a dynamic privilege and metering approach with an additional metering signal and a temporary ZEV lane, which can be an example application for main roads entering urban areas. In this version, for each privileged ZEV that is exempted from metering, conventional vehicles must wait longer at the metering signal. The second version is a typical traffic metering approach for urban central areas. It is applied through the adjustment of green times at existing signalized intersections for the period of critical air pollution levels.

When local effects are considered, the results show that the first metering version results in improvements in the hotspot in terms of traffic and air quality, whereas it causes conventional vehicles to stop often and longer at the tailback area. This results in slightly higher emissions at the tailback area but no significant increase in air pollution concentrations since the tailback area is located at uncritical street canyons. In this version, ZEVs get significantly high advantages in terms of less travel time and the number of stops, whereas conventional vehicles face disadvantages.

In the second temporary metering version, the local traffic and air quality situation at the hotspot is worsened through ZEV privileges in case of high ZEV shares (above 30 %). On the other hand, in this version, high improvements are seen for the tailback area due to the significant reductions in queue lengths, number of stops, and stop times. Resulting from the reduced congestion in the tailback area, both ZEVs and conventional vehicles benefit from the effects of the ZEV privilege (i.e. shorter travel times and fewer number of stops). While the benefits of ZEVs are higher compared to conventional vehicles at low ZEV shares, above 30 % advantages of ZEVs and conventional vehicles get closer.

In short, the adaptive metering/privileging approach is advantageous to control traffic volumes, congestion, and resulting emissions at hotspots during the activation time and to provide significant attractiveness to ZEVs (at all ZEV shares). The non-adaptive approach is beneficial for all vehicle types but is more meaningful for low ZEV percentages; after a certain ZEV share, it can increase traffic volumes and emissions at hotspots. The network analysis of the traffic flow metering measure (both versions activated at the same time) shows that the network performance gets significantly better with ZEV privilege. Considering the network efficiency, remarkable effects of privilege (e.g. shorter network recovery time) are seen at medium-high ZEV shares (with 20 %) compared to the no-privilege case.

To summarize, the outcomes from the two example DETM measures show a trade-off effect when local effects of ZEV privilege at the hotspots and relocation areas are compared. While local traffic and air quality indicators are improved for the hotspot, indicators for the tailback area or for the alternative route can get worse, or vice-versa. At low ZEV shares in the vehicle fleet, a win-win effect can be observed, where one part is improved and no significant setback is observed for the other part. At high ZEV percentages, this trade-off can cause increased traffic, emissions, and air pollution in some areas, especially if traffic control (e.g. signals or metering system) is not adaptive to changing traffic volumes.

However, for both DETM measure examples, giving privileges to ZEVs improved the overall network performance, at all ZEV shares. When the effectiveness of DETM measures on the network is considered, improvements through privileges are visible starting from low ZEV shares (5 %) and optimal at mid-level ZEV shares (20 %) for re-routing. For metering, these improvements are also visible at low shares but increase gradually with higher ZEV shares. Under efficiency analysis, it is seen that re-routing with ZEV privilege has advantages in all scenarios, whereas these advantages are visible for metering measures at mid-level ZEV shares (from 20 % on).

7. Discussion and Conclusion

7.1 Main Findings and Contributions

Promoting cleaner vehicles is one of the policy instruments that aim to reduce road transport related emissions. The focus on the potential of these vehicles mostly lies in reducing CO_2 emissions currently and less in diminishing local air pollution. The literature review (**Chapter 2**) showed that NO_2 is the critical traffic-related air pollutant in urban areas in Europe and the contribution of electric vehicles (EVs) to air pollution control can vary. Local emission reduction potentials of hybrid vehicles range greatly depending on the type of vehicle and the share of electric driving on an urban network. As a result, this dissertation focused on zero-emission-vehicles (i.e. pure electric, all-electric, only-electric, or fully-electric vehicles) under cleaner vehicles and NO_2 as the critical air pollutant. These outcomes answered *Research Question 1* and defined the scope of the thesis.

Another instrument to reduce the negative effects of road transport on emissions and air pollution is traffic management. Traffic management concentrating on the environmental effects of transport is called environmental traffic management (ETM). The literature review (**Chapter 2**) and the state-of-the-art analysis (**Chapter 3**) showed that the potential of ETM measures focusing only on shifting and controlling road traffic (temporarily or permanently) is often limited, due to the risk of re-locating traffic and emissions on other areas of the network. Dynamic environmental traffic management (DETM) offers a more efficient network use (compared to static traffic management) while reducing air pollution. However, examples show that DETM applications also result in short-term relocation of traffic and air pollution and therefore are limited in air pollution control. Consequently, it is important to consider traffic management as a whole and to consider avoiding traffic, to include traffic demand management by reducing motorized traffic, promoting non-motorized transport, public transport, etc.

The main argument of this research is that zero-emission vehicles (ZEVs) which we see more and more in vehicle fleets, can reduce the limitations of DETM applications. Mutually, the recognition of ZEVs in DETM as cleaner vehicles can promote these vehicles in the long term. However, it is seen from the literature review that ZEVs are rarely considered and/or given privileges in traffic management measures today. The main contribution of this dissertation is the investigation of DETM-ZEV integration. It answers a strategic question: how ZEVs can be considered in DETM measures and what kind of impacts can they have, especially considering the traffic/emission re-location problem by DETM applications.

To answer these, firstly a methodology had to be set. The state-of-the-art analysis (**Chapter 3**) showed that there were numerous methods to analyze traffic-related air pollution and the selected method played an important role in the application and evaluation of traffic management measures. Studies highlighted, among others, the importance of the availability of comprehensive and detailed data for monitoring and modelling of traffic and air quality. Consequently, as a methodological research need, different data collection and modelling approaches within the scope of DETM were explored. With two experiments (**Chapter 4**), a microscopic air pollution hotspot-monitoring approach is analyzed.

The results of the first experiment showed that portable air quality monitoring devices with low-cost sensors had some potential as an additional data source for DETM, as long as the data accuracy is ensured (**Chapter 4.2**). In addition, the importance of dispersion modelling in examining point data from field experiments is acknowledged. It is concluded that air quality monitoring, focusing on DETM, can function better when comprehensive detection and modelling methodologies are utilized together. The results of the second experiment confirmed that microscopic emission modelling (which considers the operational factors affecting vehicle emissions in detail) can support DETM in detecting short-term emission peaks at hotspot areas better (**Chapter 4.3**). However, it is acknowledged that a complete microscopic modelling approach (traffic, emission, and dispersion) was computationally more demanding compared to macroscopic approaches. Consequently, this thesis concludes that microscopic models can be used for dynamic hotspot analysis in DETM, in addition to the macroscopic approach which is used for regional and local screening (answering *Research Question 2*).

Once the methodological questions were answered, in line with the literature review and experiment results, a DETM approach is developed to evaluate the integration of ZEVs into DETM measures (**Chapter 5**). This microscopic DETM approach uses a model-chain (composed of existing validated modelling tools: VISSIM, PHEM, and OSPM) for traffic and air quality monitoring and adopts common DETM-application steps (i.e. strategy implementation steps such as screening, hotspot detection, measure identification and activation, impact evaluation) on a self-developed artificial urban network.

Before a proof of concept on DETM-ZEV integration (**Chapter 6**), firstly potentials of ZEVs in air quality improvement in urban areas are investigated (without considering any traffic management measure) by using the developed model-chain on a primary simple network (**Chapter 6.1**). This is done by changing the vehicle composition in the model and analyzing the reductions in NO_X emissions and NO_2 concentrations, spatially and temporally. The outcome of the potential analysis indicates that having ZEVs in vehicle composition can improve air quality, especially during peak times and particularly at network sections with high traffic volumes along with congestion. In addition, model results illustrate that ZEVs can contribute to air quality improvement, especially at disadvantageous/sensitive street canyons (e.g. narrow street canyons with slopes) and in case of unfavorable environmental conditions for air pollution (e.g. low wind speeds). These results (answering *Research Question 3*) affirm that ZEVs can contribute to DETM whose primary goal is to reduce peak air pollution concentrations at hotspots.

Finally, the proof of concept is conducted by using the developed DETM system on a comprehensive artificial network to evaluate the integration of ZEVs in DETM. This is done by modelling two common examples of DETM measures: dynamic re-routing and dynamic traffic flow metering. Model results show that ZEV privileges can increase the effectiveness of DETM measures by reducing the re-location of traffic and emissions (particularly easily at low ZEV shares and especially in re-routing scenarios) as well as by increasing the overall network performance (answering *Research Question 4*). It can also increase the efficiency of these measures by improving the recovery time after an observed congestion at hotspots (answering *Research Question 5*). By re-routing measure, this increase in efficiency through ZEV privilege is visible in all scenarios (i.e. by all ZEV percentages), whereas by metering it is visible after 20% ZEV share. In addition, results show that ZEV privileges bring significant advantages to ZEVs in traffic which can contribute to an increase in their attractiveness in the long term (answering *Research Question 6*). Moreover, in most cases, giving exemptions to ZEVs from DETM measures is found to be advantageous also for conventional vehicles; due to the overall improvement in the network. The research results showed that considering ZEV privileges in DETM is especially beneficial for ZEVs at low to mid-level fleet shares (up to 30%). At higher levels (from 50% on), ZEV privileges are not optimal. First of all, the air quality problem becomes less critical with such high ZEV shares. Furthermore, these privileges may cause problems where no adaptive traffic control is utilized. Finally, due to their high share, ZEVs cannot be considered as special vehicles any longer and static/permanent privileges for ZEVs may become more considerable (answering *Research Question 7*).

To sum up, the main contribution of this dissertation is the evaluation of the possible impacts of cleaner vehicles on road traffic-related local air pollution and in particular, the analysis of the potentials of ZEVs in NO_2 concentration control in urban areas through dynamic environmental traffic management (DETM). Although the number of newly registered ZEVs had already started to increase, the turnover of the complete vehicle fleet will take time. Despite several ambitious goals (e.g. the goal of EC to reach 30 million ZEVs by 2030), it may take, depending on the application of the clean transport goals, several decades to reach a high share of ZEVs on the roads (see **Chapter 2.3.2**) and to observe high air pollution reductions. Results of this dissertation recommend integrating ZEVs in DETM, where possible, already at low ZEV percentages to start using their potential in increasing the effectiveness and efficiency of DETM measures. In addition, results indicate that consideration and exemption of ZEVs in DETM can be used as an additional incentive to increase the attractiveness of cleaner vehicles. Especially at low ZEV shares in the fleet, ZEVs would have remarkable advantages compared to conventional vehicles in traffic and the possibility of causing negative local impacts (on traffic and emissions) through such privileges would be lower.

7.2 Limitations and Outlook

This thesis investigated the integration of zero-emission vehicles in dynamic traffic management as a strategical question and demonstrated example possibilities through a conceptual study based on an artificial use-case area. Further studies can look into the implementation of this concept in the field in detail, including operational aspects such as technical feasibility or legislative framework. Strategical and operational implementation of such DETM measures with ZEV privileges (as in all DETM measures) depends on legislation, available tools, and local conditions at the hotspot as well as the considered urban area. It would be interesting to see the transferability of these results to different real applications in different urban areas.

Furthermore, this research can be extended with other DETM measures that ZEVs can be integrated into. At this point, further measures (both static and dynamic) can be investigated in terms of integration of zero-emission vehicles, focusing on air pollution control. How ZEVs can be integrated into different monetary incentives such as congestion charging, or into parking measures, or mobility management is worth examining (focusing on air pollution).

The evaluation of the impacts of ZEV privileges under DETM is conducted by using a modelling approach and on an artificial network in this thesis. As mentioned under the outcomes of the experimental methodological research (**Chapter 4.2.4**), this methodology provides advantages in terms of evaluating road traffic-related effects on air pollution independent from environmental conditions. In reality, air quality is a very complex issue, and it is not easy to monitor and evaluate influencing factors separately. It would be remarkably exciting to investigate the air pollution reduction potentials of ZEVs within the framework of field tests. Due to the limitations in time and resources (as well as detection techniques not being the core of this study), new air pollution monitoring tools and in particular potentials of portable low-cost devices could only be analyzed briefly. For a better understanding, longer measurements and comprehensive tests with different sensors could be run in further studies focusing on road traffic management. Similarly, traffic detection methods can be evaluated in detail, to see how ZEVs can be detected in mixed traffic. Furthermore, the potential of ZEVs in reducing other air pollutants, which are critical in other continents would provide supplementary information to this thesis. This document focused on traffic related air pollution in Europe (in terms of DETM examples, Germany) and on NO_2; the geographical scope can be extended.

Some aspects of traffic flow modelling were kept static in the modelling approach, in order to be able to evaluate the impacts of DETM measures exclusively. For example, dynamic routing or adaptive traffic control (except for one metering example) was not utilized. Further modelling studies in this area can model traffic and ZEV-related measures in a more dynamic manner. It would also be valuable to add the transport demand modelling aspect to see how origin and destination, or route choice of travelers, change in line with such measures. For example, would drivers of conventional vehicles change their routes depending on the activation of a metering measure or queue length? In addition, it is important to ask further questions about the impacts of giving privileges to ZEVs in DETM on the aspects of mode-choice, attractiveness, and acceptance. This can be done through surveys to understand how traffic participants would perceive and react (drivers of both ZEVs and conventional vehicles) as well as under which conditions estimated behavioral changes can be observed.

Last but not least, I acknowledge that the impacts of ZEVs and the possible outcomes of such privileges are not limited to vehicle use and local emissions in urban areas. Therefore, further studies are needed for a complete analysis of ZEVs, covering other aspects such as vehicle, battery, or energy production. In this way, it can be evaluated if these local potentials of electric vehicles in air pollution reduction are also supported by their global impacts on the environment as well.

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List of Abbreviations

AAQD	**A**mbient **A**ir **Q**uality **D**irective
ADMS	**A**tmospheric **D**ispersion **M**odelling **S**ystem
AERMOD	American Meteorological Society (**A**MS) and the United States Environmental Protection Agency (**E**PA) **R**egulatory **Mod**el
AQMS	**A**ir **Q**uality **M**easurement/**M**onitoring **S**tation
AQP	**A**ir **Q**uality **P**lan
BASt	**B**undes**A**nstalt für **St**raßenwesen (Eng.: German Federal Road Research Institute)
BEV	**B**attery **E**lectric **V**ehicle
CALINE	**CA**lifornia **LINE** Source Dispersion Model
CALPUFF	**CAL**ifornia **PUFF** Model
CFD	**C**omputational **F**luid **D**ynamics
CH_4	Methane
CMEM	**C**omprehensive **M**odal **E**mission **M**odel
CO	Carbon Monoxide
COPERT	**CO**mputer **P**rogram to calculate **E**missions for **R**oad **T**ransport
CO_2	Carbon Dioxide
CPB	**C**anyon-**P**lume-**B**ox Model
DETM	**D**ynamic **E**nvironmental **T**raffic **M**anagement
DTM	**D**ynamic **T**raffic **M**anagement
DUVM	**D**ynamisches **U**mweltsensitives **V**erkehrsmanagement (Eng.: Dynamic Environmental Traffic Management)
DWD	**D**eutscher **W**etter**D**ienst (Eng.: Germany's National Meteorological Service)

EC	**E**uropean **C**ommission
EEA	**E**uropean **E**nvironment **A**gency
EmoG	**E**lektro**mo**bilitäts**g**esetz (Eng.: Electric Mobility Act)
ETM	**E**nvironmental **T**raffic **M**anagement
ESS	**E**nergy **S**torage **S**ystems
EV	**E**lectric **V**ehicle
FCD	**F**loating **C**ar **D**ata
FCEV	**F**uel **C**ell **E**lectric **V**ehicle
FGSV	**F**orschungs**G**esellschaft für **S**traßen- und **V**erkehrswesen (Eng.: German Road and Transportation Research Association)
FHWA	**F**ederal **H**igh**W**ay **A**dministration
GHG	**G**reen**h**ouse **G**as
GPS	**G**lobal **P**ositioning **S**ystem
GRAL	**GRA**z **L**agrangian Model
HBEFA	**H**and**B**ook of **E**mission **FA**ctors for road transport
HBS	**H**andbuch für die **B**emessung von **S**traßenverkehrsanlagen (Eng.: German Highway Capacity Manual)
HC	Hydrocarbon
HCM	**H**ighway **C**apacity **M**anual
HDV	**H**eavy-**D**uty **V**ehicle
HEV	**H**ybrid **E**lectric **V**ehicle
ICE	**I**nternal **C**ombustion **E**ngine
LCV	**L**ight **C**ommercial **V**ehicle
LfU	Bayerisches **L**andesamt **f**ür **U**mwelt (Eng.: Bavarian Environment Agency)

LOS **L**evel **O**f **S**ervice

MATSim **M**ulti-**A**gent **T**ransport **Sim**ulation

MOVES **MO**tor **V**ehicle **E**mission **S**imulator

MISKAM **MI**kro**S**kaliges **K**lima- und **A**usbreitungs**M**odell
(Eng.: Microscale Climate and Dispersion Model)

NAEI **N**ational **A**tmospheric **E**missions **I**nventory (UK)

N_2O Nitrous Oxide

NO_2 Nitrogen Dioxide

NO_X Nitrogen Oxide

O_3 Ozone

O/D-Matrix **O**rigin-**D**estination-Matrix

OPC **O**ptical **P**articulate **C**ounters

OSPM **O**perational **S**treet **P**ollution **M**odel

Pb Lead

PC **P**assenger **C**ar

PHEM **P**assenger Car and **H**eavy-Duty **E**mission **M**odel

PHEV **P**lug-in **H**ybrid **E**lectric **V**ehicle

PM **P**articulate **M**atter

RDE **R**eal **D**riving **E**missions

REEV **R**ange-**E**xtended **E**lectric **V**ehicle

RQ **R**esearch **Q**uestion

RMSPE **R**oot **M**ean **S**quare **P**ercentage **E**rror

SG **S**ignal **G**roup

SO_2 Sulphur Dioxide

SO_X Sulphur Oxide

SUMO	**S**imulation of **U**rban **MO**bility
TMC	**T**raffic **M**anagement **C**enter
TRAP	**T**raffic-**R**elated **A**ir **P**ollution
TRB	**T**ransportation **R**esearch **B**oard
TREM	**TR**ansport **E**mission **M**odel
TTW	**T**ank-**T**o-**W**heel
UBA	**U**mwelt**B**undes**A**mt (Eng.: German Environment Agency)
UN	**U**nited **N**ations
UNECE	**U**nited **N**ations **E**conomic **C**ommission for **E**urope
URBAIR	**URB**an **AIR** Quality system
UTM	**U**rban **T**raffic **M**anagement
UVM	**U**mweltsensitives **V**erkehrsmanagement (Eng.: Environmental Traffic Management)
VERSIT+	**VER**keers **SIT**uatie Model
VISSIM	**V**erkehr **I**n **S**tädten - **SI**mulations**M**odell
VISVAP	**V**erkehr **I**n **S**tädten – **V**erkehrs**A**bhängige **P**rogrammierung
VIT	**V**ehicle **I**nduced **T**urbulence
VOC	**V**olatile **O**rganic **C**ompounds
WHO	**W**orld **H**ealth **O**rganization
ZE-HDV	**Z**ero-**E**mission **H**eavy-**D**uty **V**ehicle
ZE-LCV	**Z**ero-**E**mission **L**ight **C**ommercial **V**ehicle
ZE-PC	**Z**ero-**E**mission **P**assenger **C**ar
ZEV	**Z**ero-**E**mission **V**ehicle at tailpipe or exhaust-emission-free electric vehicles

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Appendix

Appendix 4a

Fleet composition for Germany for the year 2018 from HBEFA

Passenger cars (PC)			Light commercial vehicles (LCV)			Heavy-duty vehicles (HDV)		
Engine type	Emission class	Share [%]	Engine type	Emission class	Share [%]	Engine type	Emission class	Share [%]
Petrol	Euro 0	0,7	Petrol	Euro 0	0,2			
	Euro 1	0,6		Euro 1	0,0			
	Euro 2	0,7		Euro 2	0,3			
	Euro 3	1,7		Euro 3	0,3			
	Euro 4	16,1		Euro 4	0,8			
	Euro 5	16,0		Euro 5	1,0			
	Euro 6	13,0		Euro 6	1,3			
Diesel			Diesel	Euro 0	0,8	Diesel	Euro 0	0,7
	Euro 1	0,3		Euro 1	1,7		Euro I	0,3
	Euro 2	0,6		Euro 2	4,5		Euro II	1,6
	Euro 3	2,3		Euro 3	10,2		Euro III	5,0
	Euro 4	7,4		Euro 4	15,2		Euro IV	3,6
	Euro 5	19,2		Euro 5	32,8		Euro V	27,1
	Euro 6	21,3		Euro 6	31,0		Euro VI	61,8
	Euro 6d (RDE)	0,2						

Appendix 4b

Emission factors per vehicle categories of the defined fleet composition (Germany 2018) from HBEFA

Traffic Situation			Average Speed [km/h]	Emission Factor [g/km]					
				NO_X			PM		
				PC	LCV	HDV	PC	LCV	HDV
Residential Access Road (30 km/h)	free flow condition	LOS 1	> 20	0,04094	0,00813	3,05602	0,00540	0,02802	0,03549
	stable traffic	LOS 2	> 12-20	0,03865	0,00675	3,19912	0,00485	0,02686	0,03625
	less stable traffic	LOS 3	> 9-12	0,04201	0,00757	3,77779	0,00533	0,03000	0,03996
	stop & go	LOS 4	≤ 9	0,05753	0,00885	5,34404	0,00760	0,03879	0,05467
Distributor Road (50 km/h)	free flow condition	LOS 1	> 33	0,02954	0,00563	1,76354	0,00364	0,02148	0,02271
	stable traffic	LOS 2	> 20-33	0,03252	0,00624	2,21779	0,00403	0,02149	0,02785
	less stable traffic	LOS 3	> 15-20	0,03670	0,00711	2,32812	0,00445	0,02340	0,02863
	stop & go	LOS 4	≤ 15	0,05753	0,00885	5,34404	0,00760	0,03879	0,05467
Trunk City Road (50 km/h)	free flow condition	LOS 1	> 33	0,02725	0,00507	1,43892	0,00347	0,02179	0,02115
	stable traffic	LOS 2	> 20-33	0,03027	0,00504	1,72556	0,00397	0,02046	0,02498
	less stable traffic	LOS 3	> 15-20	0,03261	0,00612	2,20386	0,00408	0,02289	0,02828
	stop & go	LOS 4	≤ 15	0,05753	0,00885	5,34404	0,00760	0,03879	0,05467

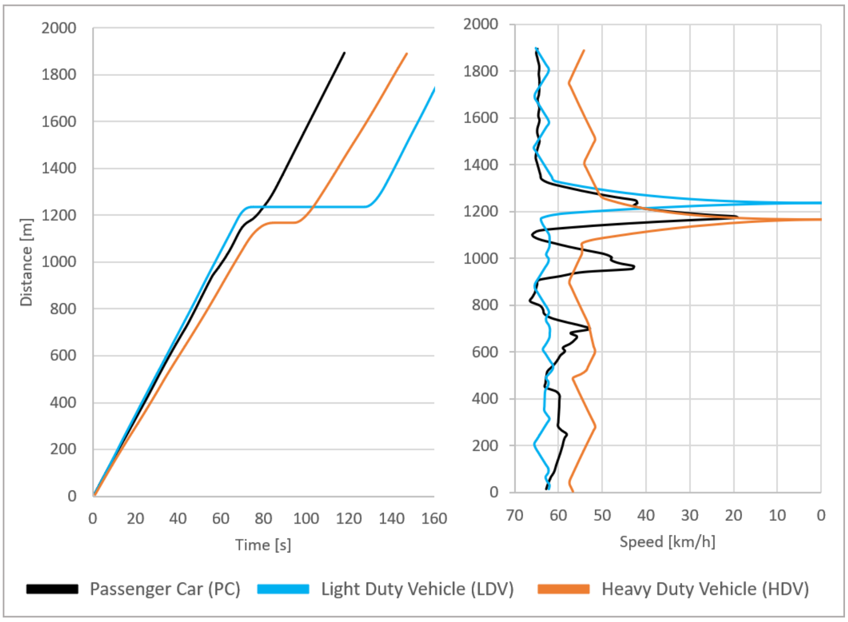
Appendix 5a

Utilized driving behaviour parameters in microscopic traffic simulation VISSIM

			Urban (motorized)	Urban Merging (motorized)
Following	Look ahead distance	Minimum	20,00 m	20,00 m
		Maximum	250,00 m	250,00 m
		Number of interaction objects	4	4
		Number of interaction vehicles	99	99
	Look back distance	Minimum	15,00 m	15,00 m
		Maximum	150,00 m	150,00 m
	Temporary lack of attention	Duration	0 s	0 s
		Probability	0,00 %	0,00 %
	Standstill distance for static obstacles		O (no)	O (no)
	Enforce absolute braking distance		O (no)	O (no)
	Use implicit stochastics		X (yes)	X (yes)
Car Following	Car following model		Wiedemann 74	
	Model parameters	Average standstill distance	2,00 m	2,00 m
		Additive part of safety distance	2,00	2,00
		Multiplic. part of safety distance	3,00	3,00
	Following behavior depending on the vehicle class of the leading vehicle:		none	none
Lane Change	General behavior	free lane selection		
	Necessary lane change (route)	Maximum deceleration (own)	-4,00 m/s^2	-4,50 m/s^2
		-1m/s^2 per distance (own)	100,00 m	100,00 m
		Accepted deceleration (own)	-1,00 m/s^2	-1,50 m/s^2
		Maximum deceleration (trailing vehicle)	-3,00 m/s^2	-3,50 m/s^2
		-1m/s^2 per distance (trailing vehicle)	100,00 m	100,00 m
		Accepted deceleration (trailing vehicle)	-1,00 m/s^2	-1,50 m/s^2
		Waiting time before diffusion	100,00 s	120,00 s
		Min. headway (front/rear)	0,50 m	0,50 m
		To slower lane if collision time is above	O (no)	O (no)
		Safety distance reduction factor	0,60	0,40
		Maximum deceleration for cooperative braking	-3,00 m/s^2	-6,00 m/s^2
		Overtake reduced speed areas	O (no)	O (no)
		Advanced merging	X (yes)	X (yes)
		Vehicle routing decision look ahead	X (yes)	X (yes)
		Cooperative lane change	O (no)	X (yes)
		Maximum speed difference		10,80 km/h
		Maximum collision time		10,00 s
		Rear correction of lateral position	O (no)	O (no)

Appendix 5b

Example vehicles trajectories of different vehicle types from the microscopic traffic simulation VISSIM



Appendix 5c

Fleet composition for Germany for the year 2020 from HBEFA

Passenger cars (PC)			Light commercial vehicles (LCV)			Heavy-duty vehicles (HDV)		
Engine type	**Emission class**	**Share [%]**	**Engine type**	**Emission class**	**Share [%]**	**Engine type**	**Emission class**	**Share [%]**
Petrol	Euro 0	0,7	**Petrol**	Euro 0	0,1			
	Euro 1	0,7		Euro 1	0,0			
	Euro 2	0,5		Euro 2	0,1			
	Euro 3	1,0		Euro 3	0,2			
	Euro 4	11,6		Euro 4	0,6			
	Euro 5	14,1		Euro 5	0,7			
	Euro 6	12,9		Euro 6	1,2			
	Euro 6c (RDE)	6,7		Euro 6c (RDE)	0,6			
Diesel			**Diesel**	Euro 0	0,7	**Diesel**	Euro 0	0,6
	Euro 1	0,2		Euro 1	1,0		Euro I	0,2
	Euro 2	0,4		Euro 2	3,0		Euro II	0,9
	Euro 3	1,5		Euro 3	7,4		Euro III	3,1
	Euro 4	4,9		Euro 4	11,5		Euro IV	2,5
	Euro 5	14,8		Euro 5	23,2		Euro V	17,9
	Euro 6	21,9		Euro 6	38,4		Euro VI	74,8
	Euro 6d1 (RDE)	6,7		Euro 6c (RDE)	11,3			
	Euro 6d2 (RDE)	1,7						

Appendix 5d

Origin-Destination-Matrices for vehicle types PC, LCV, HDV and all vehicles

O/D Matrix Passenger Cars (PCs) (veh/hr)

FROM	TO	Zone No	1	2	3	11	12	13	14	15	101	102	103	104	105	106	107	108	109	110
		Name	Main 1	Main 2	Main 3	Dist. 1	Dist. 2	Dist. 3	Dist. 4	Port	Res. 1	Res. 2	Res. 3	Res. 4	Res. 5	Res. 6	Res. 7	Res. 8	Res. 9	Res. 10
Zone No	Name	Sum	**1566**	**1431**	**1342**	**738**	**286**	**406**	**826**	**32**	**40**	**40**	**40**	**40**	**40**	**40**	**40**	**40**	**40**	**40**
1	Main 1	**1280**		752	280	0	40	40	80	8	8	8	8	8	8	8	8	8	8	8
2	Main 2	**1840**	720		480	184	0	96	184	16	16	16	16	16	16	16	16	16	16	16
3	Main 3	**1200**	320	432		216	40	80	24	8	8	8	8	8	8	8	8	8	8	8
11	Dist. 1	**404**	0	64	128		32	112	48	0	2	2	2	2	2	2	2	2	2	2
12	Dist. 2	**804**	176	0	184	48		24	352	0	2	2	2	2	2	2	2	2	2	2
13	Dist. 3	**644**	128	64	160	160	40		72	0	2	2	2	2	2	2	2	2	2	2
14	Dist. 4	**404**	112	64	0	64	112	32		0	2	2	2	2	2	2	2	2	2	2
15	Port	**41**	10	5	10	6	2	2	6		0	0	0	0	0	0	0	0	0	0
101	Res. 1	**41**	10	5	10	6	2	2	6	0		0	0	0	0	0	0	0	0	0
102	Res. 2	**41**	10	5	10	6	2	2	6	0	0		0	0	0	0	0	0	0	0
103	Res. 3	**41**	10	5	10	6	2	2	6	0	0	0		0	0	0	0	0	0	0
104	Res. 4	**41**	10	5	10	6	2	2	6	0	0	0	0		0	0	0	0	0	0
105	Res. 5	**41**	10	5	10	6	2	2	6	0	0	0	0	0		0	0	0	0	0
106	Res. 6	**41**	10	5	10	6	2	2	6	0	0	0	0	0	0		0	0	0	0
107	Res. 7	**41**	10	5	10	6	2	2	6	0	0	0	0	0	0	0		0	0	0
108	Res. 8	**41**	10	5	10	6	2	2	6	0	0	0	0	0	0	0	0		0	0
109	Res. 9	**41**	10	5	10	6	2	2	6	0	0	0	0	0	0	0	0	0		0
110	Res. 10	**41**	10	5	10	6	2	2	6	0	0	0	0	0	0	0	0	0	0	

O/D Matrix Light Commercial Vehicles (LCVs) (veh/hr)

FROM	TO	Zone No	1	2	3	11	12	13	14	15	101	102	103	104	105	106	107	108	109	110
		Name	Main 1	Main 2	Main 3	Dist. 1	Dist. 2	Dist. 3	Dist. 4	Port	Res. 1	Res. 2	Res. 3	Res. 4	Res. 5	Res. 6	Res. 7	Res. 8	Res. 9	Res. 10
Zone No	Name	Sum	**126**	**100**	**134**	**133**	**38**	**38**	**81**	**12**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
1	Main 1	**128**		44	40	8	8	8	16	4	0	0	0	0	0	0	0	0	0	0
2	Main 2	**184**	52		48	48	8	8	16	4	0	0	0	0	0	0	0	0	0	0
3	Main 3	**120**	32	40		20	8	8	8	4	0	0	0	0	0	0	0	0	0	0
11	Dist. 1	**41**	3	2	16		2	10	8	0	0	0	0	0	0	0	0	0	0	0
12	Dist. 2	**80**	11	2	15	24		2	26	0	0	0	0	0	0	0	0	0	0	0
13	Dist. 3	**63**	13	8	11	22	2		7	0	0	0	0	0	0	0	0	0	0	0
14	Dist. 4	**41**	13	2	3	11	10	2		0	0	0	0	0	0	0	0	0	0	0
15	Port	**5**	2	2	1	0	0	0	0		0	0	0	0	0	0	0	0	0	0
101	Res. 1	**0**	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0
102	Res. 2	**0**	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0
103	Res. 3	**0**	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0
104	Res. 4	**0**	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0
105	Res. 5	**0**	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0
106	Res. 6	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0
107	Res. 7	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0
108	Res. 8	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0
109	Res. 9	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
110	Res. 10	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

O/D Matrix Heavy-Duty Vehicles (HDVs) (veh/hr)

FROM	TO	Zone No	1	2	3	11	12	13	14	15	101	102	103	104	105	106	107	108	109	110
		Name	Main 1	Main 2	Main 3	Dist. 1	Dist. 2	Dist. 3	Dist. 4	Port	Res. 1	Res. 2	Res. 3	Res. 4	Res. 5	Res. 6	Res. 7	Res. 8	Res. 9	Res. 10
Zone No	Name	Sum	**70**	**60**	**67**	**24**	**17**	**17**	**28**	**97**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
1	Main 1	**65**		16	12	2	2	2	3	28	0	0	0	0	0	0	0	0	0	0
2	Main 2	**93**	24		20	5	2	2	8	32	0	0	0	0	0	0	0	0	0	0
3	Main 3	**62**	10	21		5	2	2	2	20	0	0	0	0	0	0	0	0	0	0
11	Dist. 1	**22**	2	4	2		2	6	2	4	0	0	0	0	0	0	0	0	0	0
12	Dist. 2	**39**	8	3	10	2		2	10	4	0	0	0	0	0	0	0	0	0	0
13	Dist. 3	**33**	5	6	5	6	2		2	7	0	0	0	0	0	0	0	0	0	0
14	Dist. 4	**21**	5	2	2	2	6	2		2	0	0	0	0	0	0	0	0	0	0
15	Port	**45**	16	8	16	2	1	1	1		0	0	0	0	0	0	0	0	0	0
101	Res. 1	**0**	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0
102	Res. 2	**0**	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0
103	Res. 3	**0**	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0
104	Res. 4	**0**	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0
105	Res. 5	**0**	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0
106	Res. 6	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0
107	Res. 7	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0
108	Res. 8	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0
109	Res. 9	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
110	Res. 10	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

O/D Matrix All Vehicles (veh/hr)

FROM	TO	Zone No	1	2	3	11	12	13	14	15	101	102	103	104	105	106	107	108	109	110
		Name	Main 1	Main 2	Main 3	Dist. 1	Dist. 2	Dist. 3	Dist. 4	Port	Res. 1	Res. 2	Res. 3	Res. 4	Res. 5	Res. 6	Res. 7	Res. 8	Res. 9	Res. 10
Zone No	Name	Sum	**1762**	**1591**	**1543**	**895**	**341**	**461**	**935**	**141**	**40**	**40**	**40**	**40**	**40**	**40**	**40**	**40**	**40**	**40**
1	Main 1	**1473**		812	332	10	50	50	99	40	8	8	8	8	8	8	8	8	8	8
2	Main 2	**2117**	796		548	237	10	106	208	52	16	16	16	16	16	16	16	16	16	16
3	Main 3	**1382**	362	493		241	50	90	34	32	8	8	8	8	8	8	8	8	8	8
11	Dist. 1	**467**	5	70	146		36	128	58	4	2	2	2	2	2	2	2	2	2	2
12	Dist. 2	**923**	195	5	209	74		28	388	4	2	2	2	2	2	2	2	2	2	2
13	Dist. 3	**740**	146	78	176	188	44		81	7	2	2	2	2	2	2	2	2	2	2
14	Dist. 4	**466**	130	68	5	77	128	36		2	2	2	2	2	2	2	2	2	2	2
15	Port	**91**	28	15	27	8	3	3	7		0	0	0	0	0	0	0	0	0	0
101	Res. 1	**41**	10	5	10	6	2	2	6	0		0	0	0	0	0	0	0	0	0
102	Res. 2	**41**	10	5	10	6	2	2	6	0	0		0	0	0	0	0	0	0	0
103	Res. 3	**41**	10	5	10	6	2	2	6	0	0	0		0	0	0	0	0	0	0
104	Res. 4	**41**	10	5	10	6	2	2	6	0	0	0	0		0	0	0	0	0	0
105	Res. 5	**41**	10	5	10	6	2	2	6	0	0	0	0	0		0	0	0	0	0
106	Res. 6	**41**	10	5	10	6	2	2	6	0	0	0	0	0	0		0	0	0	0
107	Res. 7	**41**	10	5	10	6	2	2	6	0	0	0	0	0	0	0		0	0	0
108	Res. 8	**41**	10	5	10	6	2	2	6	0	0	0	0	0	0	0	0		0	0
109	Res. 9	**41**	10	5	10	6	2	2	6	0	0	0	0	0	0	0	0	0		0
110	Res. 10	**41**	10	5	10	6	2	2	6	0	0	0	0	0	0	0	0	0	0	

Appendix 5e

Bus lines and bus stops modelled in the microscopic traffic simulation VISSIM

Appendix 5f

Detailed information on the signalized intersections and their Level of Service at peak hour

Intersection A

cycle time:	90 s
intergreen time:	4 s
peak hour:	7:30 - 8:30 AM

north (LOS approach: D)

LOS lane	D	D	B
traffic volume [veh/h]	575	585	307
green time [s]	28	28	23
signal group	A4	A4	A6
	↙↓	↓	↘

west (LOS approach: B)

LOS lane	traffic volume [veh/h]	green time [s]	signal group	
B	130	23	A9	↗
B	408	28	A7	↘

east (LOS approach: C)

	signal group	green time [s]	traffic volume [veh/h]	LOS lane
↖	A1	28	74	B
↙	A3	23	378	C

south (LOS approach: C)

	↖	↑	↑↗
signal group	A12	A10	A10
green time [s]	23	28	28
traffic volume [veh/h]	148	309	563
LOS lane	B	B	C

Intersection B

cycle time: 90 s
intergreen time: 4 s
peak hour: 7:30 - 8:30 AM

north					
LOS approach	F				
LOS lane	D	F	E	F	F
traffic volume [veh/h]	597	645	637	296	303
green time [s]	28	28	28	12	12
signal group	B4	B4	B4	B6	B6
	↙↓	↓	↓	↘	↘

west: LOS approach	LOS lane	traffic volume [veh/h]	green time [s]	signal group	
E	E	225	11	B9	↗
	D	222	11	B9	↗
	C	228	15	B8	→
	C	224	15	B8	→
	D	293	15	B7	↘

east	signal group	green time [s]	traffic volume [veh/h]	LOS lane	LOS approach
↖	B1	15	105	B	E
←	B1	15	130	C	
←	B1	15	124	C	
↙	B3	11	242	E	
↙	B3	11	243	E	

south					
	↖	↖	↑	↑	↑↗
signal group	B12	B12	B10	B10	B10
green time [s]	12	12	28	28	28
traffic volume [veh/h]	91	103	619	569	582
LOS lane	C	C	E	D	D
LOS approach	E				

Intersection C

cycle time: 70 s
intergreen time: 4 s
peak hour: 7:30 - 8:30 AM

North (LOS approach: F)

LOS lane	F	F	E
traffic volume [veh/h]	486	501	263
green time [s]	16	16	9
signal group	16	16	9
	↙↓	↓	↘

West (LOS approach: E)

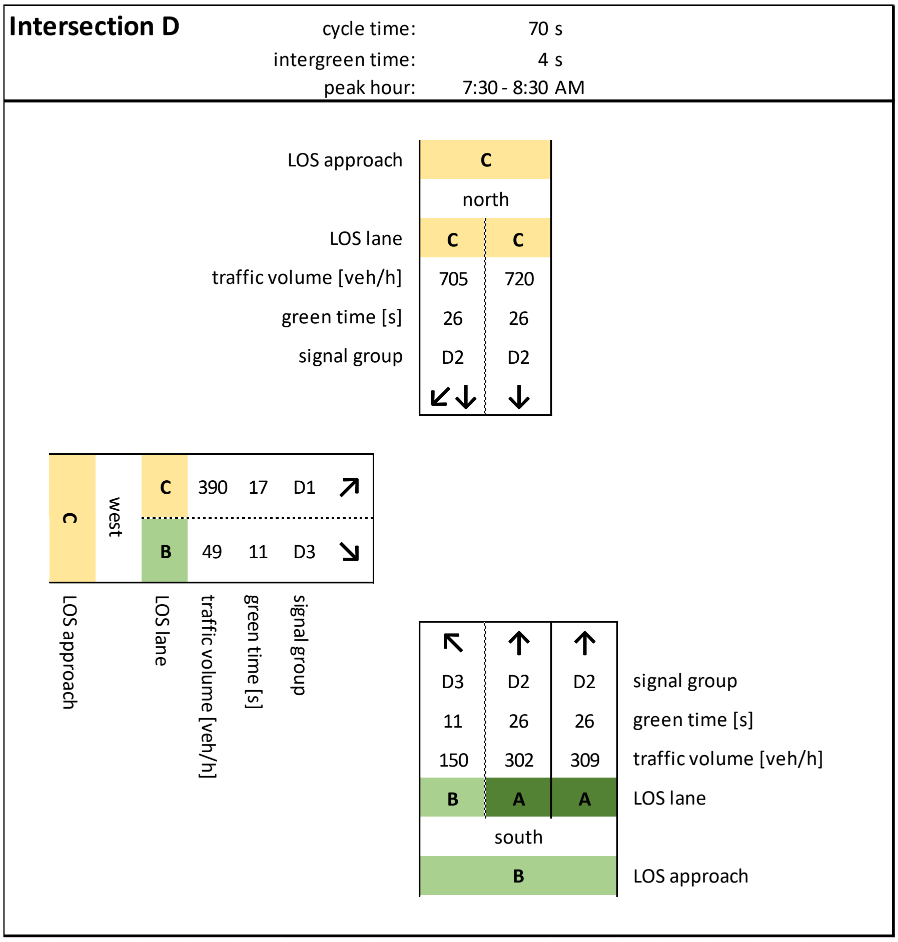
LOS lane	traffic volume [veh/h]	green time [s]	signal group	
C	158	7	C3	↗
E	484	16	C1	→
E	482	16	C1	→↘

East (LOS approach: B)

	signal group	green time [s]	traffic volume [veh/h]	LOS lane
↖←	C1	16	285	B
←	C1	16	305	B
↙	C3	7	94	B

South (LOS approach: C)

	↖	↑	↑↗
signal group	C4	C2	C2
green time [s]	9	16	16
traffic volume [veh/h]	101	387	426
LOS lane	B	C	D


Intersection D
cycle time: 70 s
intergreen time: 4 s
peak hour: 7:30 - 8:30 AM
LOS approach C
north
LOS lane C C
traffic volume [veh/h] 705 720
green time [s] 26 26
signal group D2 D2
C
west
C 390 17 D1
B 49 11 D3
LOS approach
LOS lane
traffic volume [veh/h]
green time [s]
signal group
signal group D3 D2 D2
green time [s] 11 26 26
traffic volume [veh/h] 150 302 309
LOS lane B A A
south
LOS approach B

Intersection E

cycle time:	90 s
intergreen time:	4 s
peak hour:	7:30 - 8:30 AM

north

LOS approach	D			
LOS lane	A	B	D	B
traffic volume [veh/h]	76	1043	1204	1086
green time [s]	55	55	55	55
signal group	E2	E2	E2	E2
	↙	↓	↓	↓

west

LOS approach	LOS lane	traffic volume [veh/h]	green time [s]	signal group	
C	C	4	8	E1	↗
	C	20	8	E1	↗
	C	84	11	E4	↘
	C	33	11	E4	↘

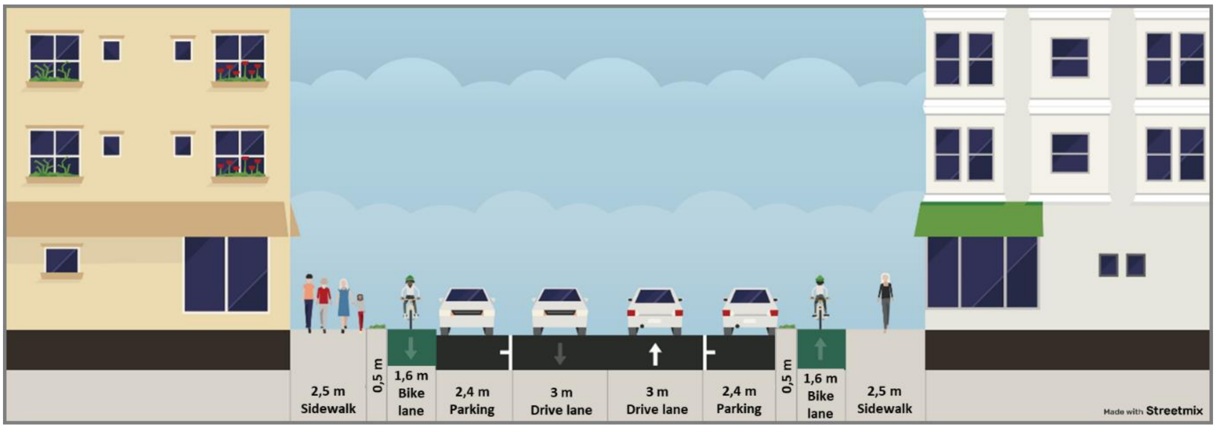
south

	↖	↑	↑	↑
signal group	E4	E2	E2	E2
green time [s]	11	55	55	55
traffic volume [veh/h]	142	771	828	966
LOS lane	C	A	A	A
LOS approach	C			

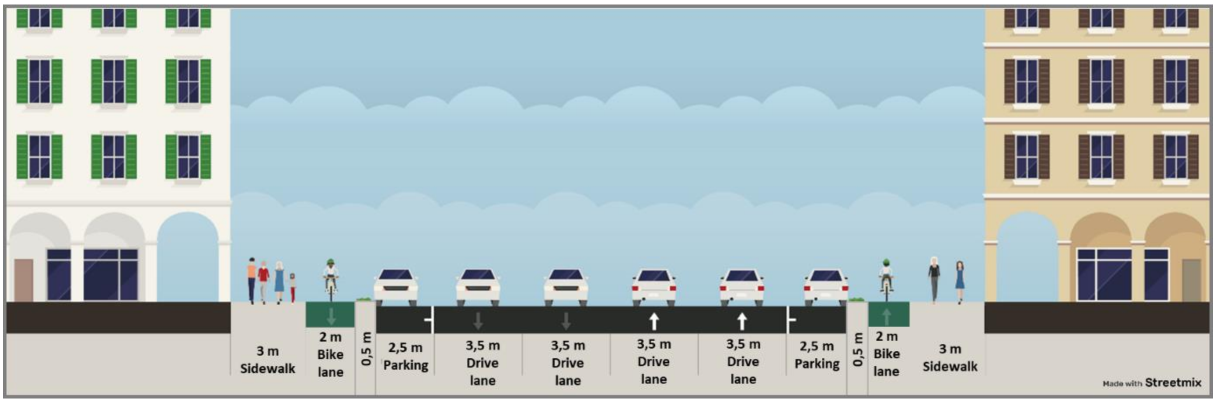
Appendix 5g

Example street cross-sections for different street canyons types in line with defined road types

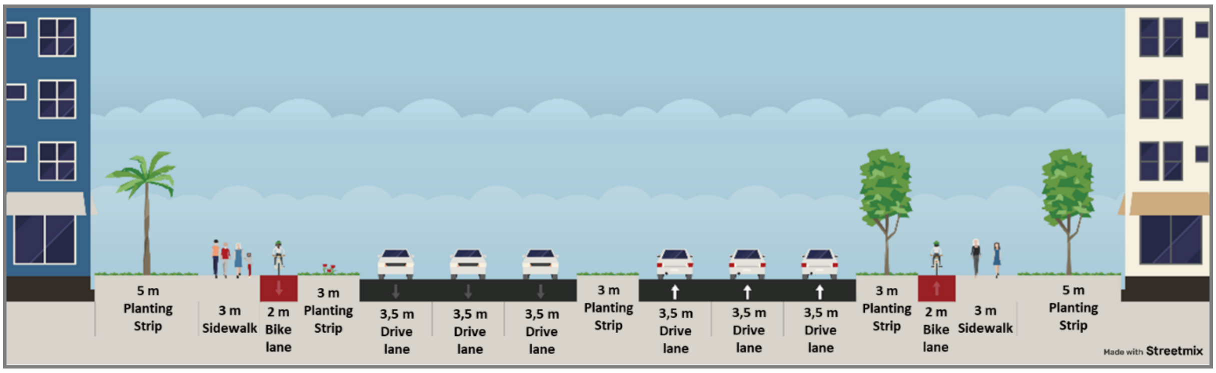
Residential Roads -Width 20m



Distributor Roads -Width 30m



Main Roads -Width 50m



Appendix 5h

Adaptive green time algorithm for Temporary Traffic Flow Metering at Metering A (VISVAP Module)

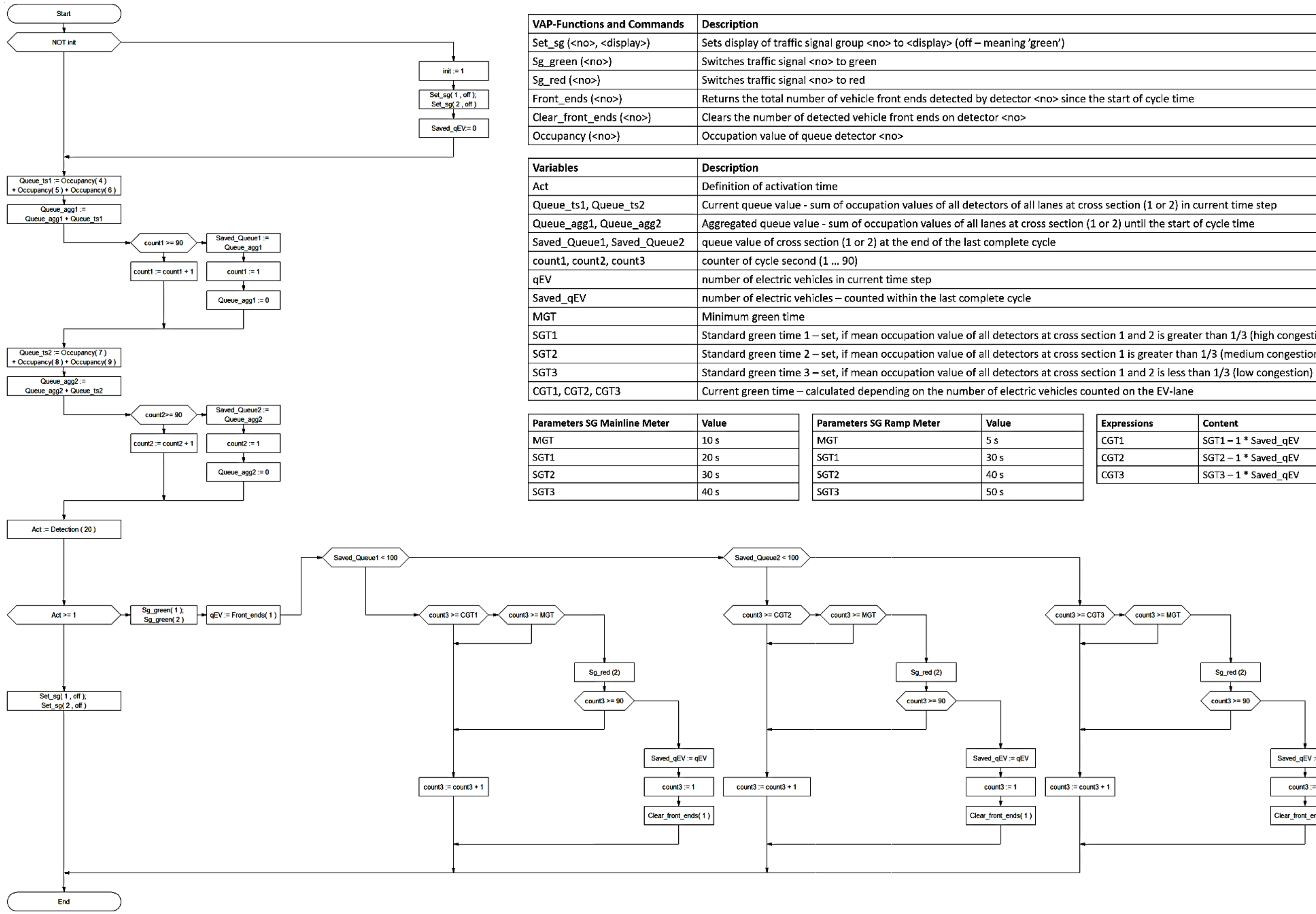
VAP-Functions and Commands	Description
Set_sg (<no>, <display>)	Sets display of traffic signal group <no> to <display> (off – meaning 'green')
Sg_green (<no>)	Switches traffic signal <no> to green
Sg_red (<no>)	Switches traffic signal <no> to red
Front_ends (<no>)	Returns the total number of vehicle front ends detected by detector <no> since the start of cycle time
Clear_front_ends (<no>)	Clears the number of detected vehicle front ends on detector <no>
Occupancy (<no>)	Occupation value of queue detector <no>

Variables	Description
Act	Definition of activation time
Queue_ts1, Queue_ts2	Current queue value - sum of occupation values of all detectors of all lanes at cross section (1 or 2) in current time step
Queue_agg1, Queue_agg2	Aggregated queue value - sum of occupation values of all lanes at cross section (1 or 2) until the start of cycle time
Saved_Queue1, Saved_Queue2	queue value of cross section (1 or 2) at the end of the last complete cycle
count1, count2, count3	counter of cycle second (1 … 90)
qEV	number of electric vehicles in current time step
Saved_qEV	number of electric vehicles – counted within the last complete cycle
MGT	Minimum green time
SGT1	Standard green time 1 – set, if mean occupation value of all detectors at cross section 1 and 2 is greater than 1/3 (high congestion)
SGT2	Standard green time 2 – set, if mean occupation value of all detectors at cross section 1 is greater than 1/3 (medium congestion)
SGT3	Standard green time 3 – set, if mean occupation value of all detectors at cross section 1 and 2 is less than 1/3 (low congestion)
CGT1, CGT2, CGT3	Current green time – calculated depending on the number of electric vehicles counted on the EV-lane

Parameters SG Mainline Meter	Value
MGT	10 s
SGT1	20 s
SGT2	30 s
SGT3	40 s

Parameters SG Ramp Meter	Value
MGT	5 s
SGT1	30 s
SGT2	40 s
SGT3	50 s

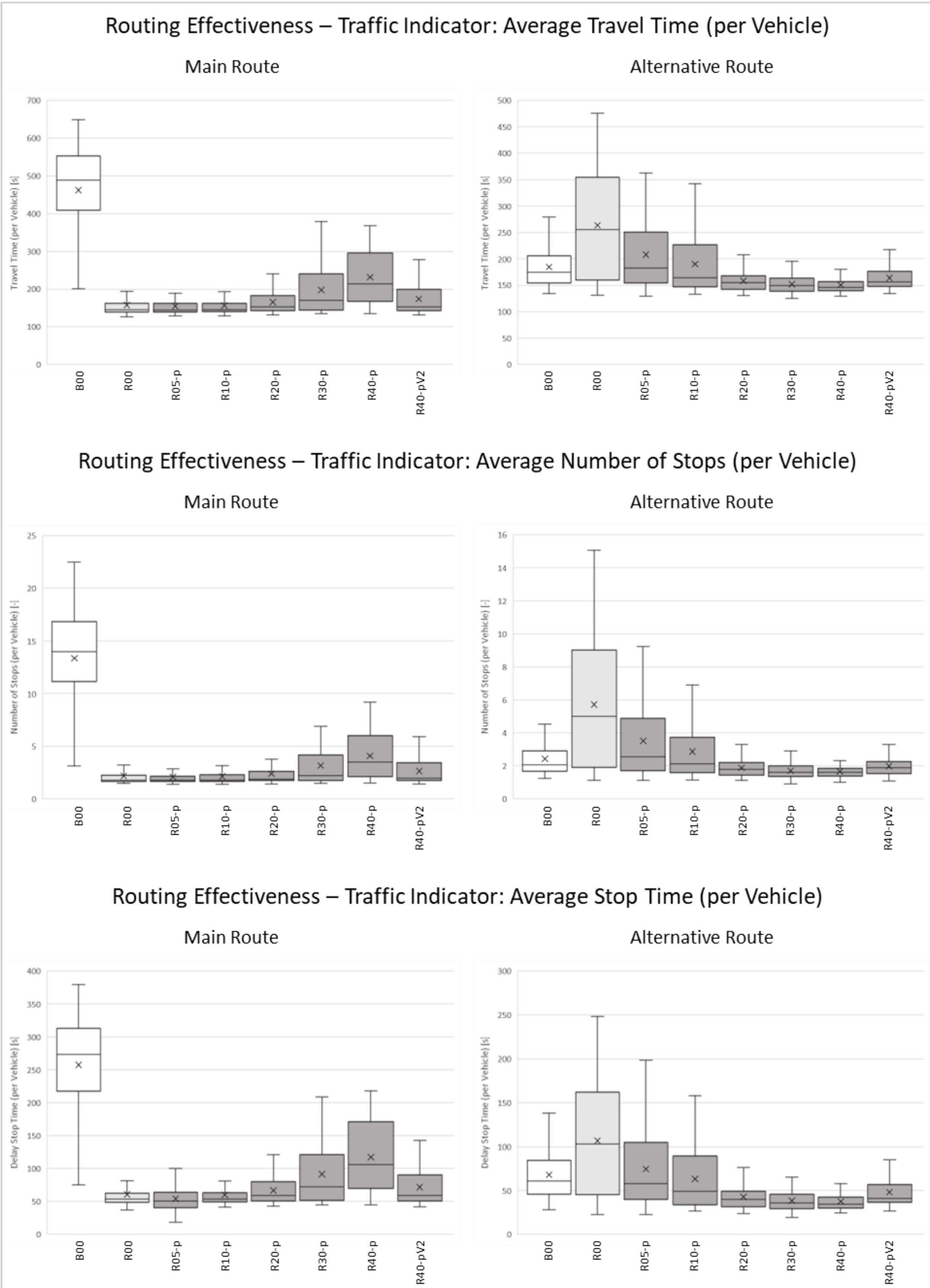
Expressions	Content
CGT1	SGT1 – 1 * Saved_qEV
CGT2	SGT2 – 1 * Saved_qEV
CGT3	SGT3 – 1 * Saved_qEV



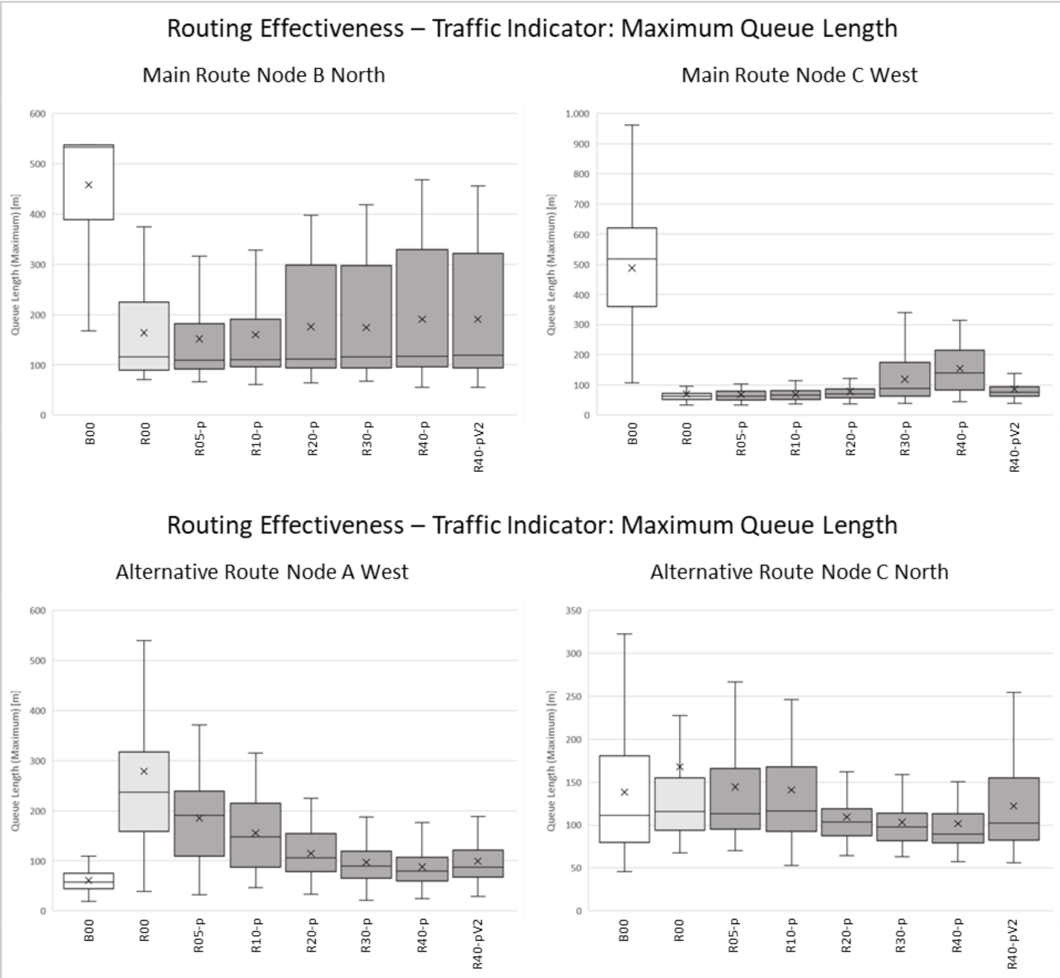
Appendix 5i

Detailed results for the measure <u>Temporary Re-Routing</u>: Boxplots and evaluation result tables for the evaluated indicators (effectiveness and attractiveness) from modelled scenarios

1. Boxplots Local Traffic Indicators (Effectiveness): Average Travel Time, Average Number of Stops, Average Stop Time



2. Boxplots Local Traffic Indicator (Effectiveness): Maximum Queue Length

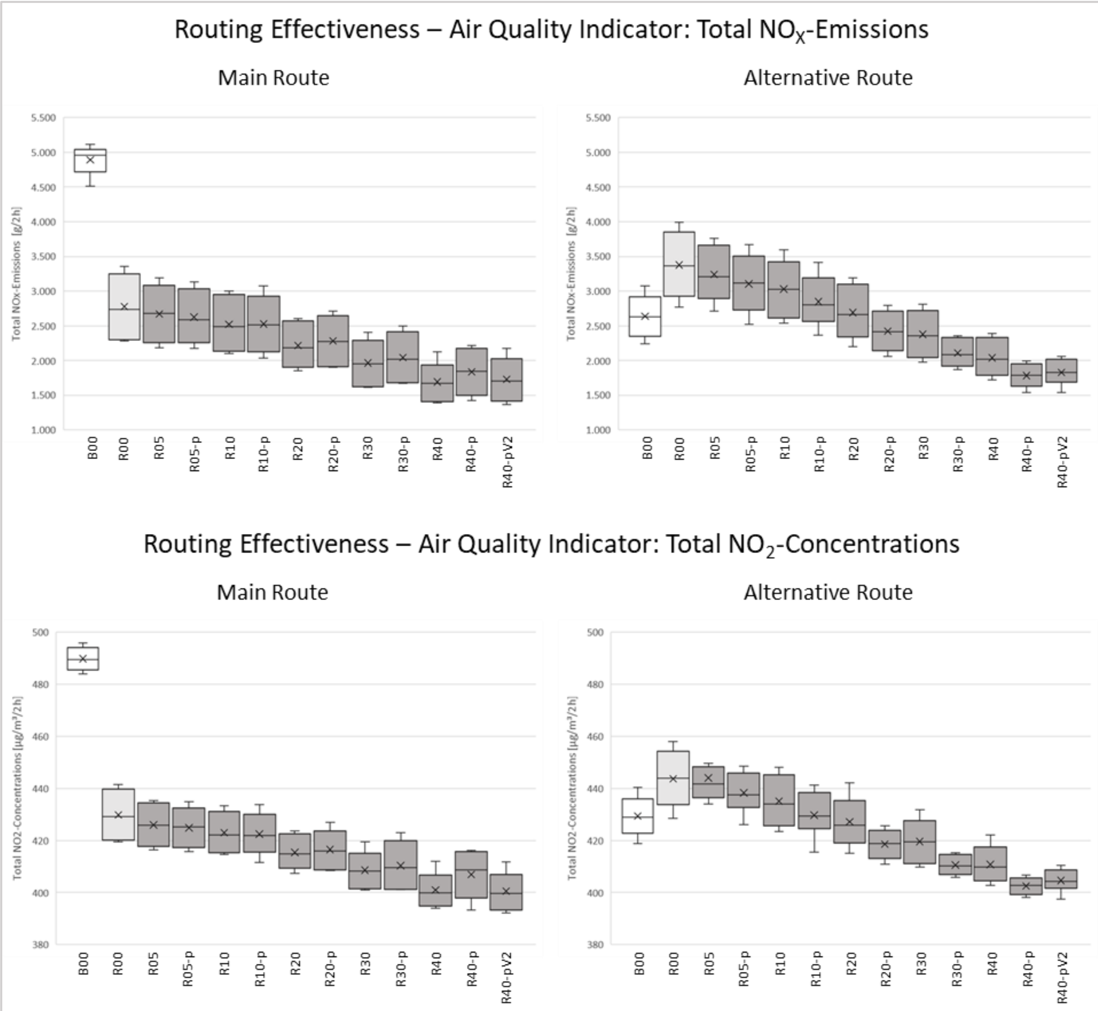


3. Evaluation Results Table Local Traffic Indicators (Effectiveness)

RE-ROUTING Activation Period (8:00-10:00)		B00	R00	R05p	R10p	R20p	R30p	R40p	R40v2p	R05p	R10p	R20p	R30p	R40p	R40v2p
		absolute	absolute	mean deviation from R00 (Δ)						mean deviation from B00 (Δ)					
Average Travel Time (All Vehicles)	Main Route	462,06	157,50	-2 %	-1 %	+5 % *	+25 % *	+47 % *	+10 % *	-66 % *	-66 % *	-64 % *	-57 % *	-50 % *	-62 % *
				p = 0,055	p = 0,881	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000
	Alternative Route	184,78	263,54	-21 % *	-28 % *	-40 % *	-42 % *	-43 % *	-38 % *	+13 % *	+3 %	-14 % *	-18 % *	-19 % *	-11 % *
				p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,003	p = 0,175	p = 0,000	p = 0,000	p = 0,000	p = 0,000
Average Number of Stops (All Vehicles)	Main Route	13,36	2,20	-5 % *	-2 %	+9 % *	+45 % *	+86 % *	+20 % *	-84 % *	-84 % *	-82 % *	-76 % *	-69 % *	-80 % *
				p = 0,017	p = 0,744	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000
	Alternative Route	2,43	5,71	-38 % *	-50 % *	-67 % *	-70 % *	-71 % *	-65 % *	+45 % *	+18 % *	-22 % *	-30 % *	-31 % *	-18 % *
				p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,001	p = 0,000	p = 0,000	p = 0,000	p = 0,000
Average Stop Time (All Vehicles)	Main Route	257,37	60,84	-11 %	-1 %	+10 % *	+51 % *	+93 % *	+18 % *	-79 % *	-77 % *	-74 % *	-64 % *	-54 % *	-72 % *
				p = 0,088	p = 0,957	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000
	Alternative Route	67,78	106,78	-30 % *	-41 % *	-60 % *	-64 % *	-65 % *	-55 % *	+10 %	-7 % *	-37 % *	-43 % *	-45 % *	-29 % *
				p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,491	p = 0,024	p = 0,000	p = 0,000	p = 0,000	p = 0,000
Maximum Queue Length (All Vehicles)	Main Route Hotspot 1 (Node B North)	458,46	163,75	-7 %	-2 %	+7 % *	+6 % *	+16 % *	+16 % *	-67 % *	-65 % *	-62 % *	-62 % *	-58 % *	-58 % *
				p = 0,100	p = 0,624	p = 0,013	p = 0,011	p = 0,002	p = 0,002	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000
	Main Route Hotspot 2 (Node C West)	487,77	70,20	-3 %	-2 %	+12 % *	+69 % *	+121 % *	+22 % *	-86 % *	-86 % *	-84 % *	-76 % *	-68 % *	-82 % *
				p = 0,822	p = 0,995	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000
	Alternative Route (Node A West)	60,69	278,65	-33 % *	-44 % *	-59 % *	-65 % *	-68 % *	-64 % *	+206 % *	+156 % *	+89 % *	+60 % *	+45 % *	+64 % *
				p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000
	Alternative Route (Node C North)	138,28	167,67	-14 % *	-16 %	-35 % *	-38 % *	-39 % *	-27 % *	+4 % *	+2 % *	-21 % *	-25 % *	-27 % *	-12 %
				p = 0,043	p = 0,069	p = 0,000	p = 0,000	p = 0,000	p = 0,002	p = 0,039	p = 0,040	p = 0,012	p = 0,001	p = 0,000	p = 0,190

* significant values (Paired Wilcoxon Rank Test, Confidence Level: 95%)

4. Boxplots Local Air Quality Indicators (Effectiveness): Total NO_X-Emissions and NO_2-Concentrations

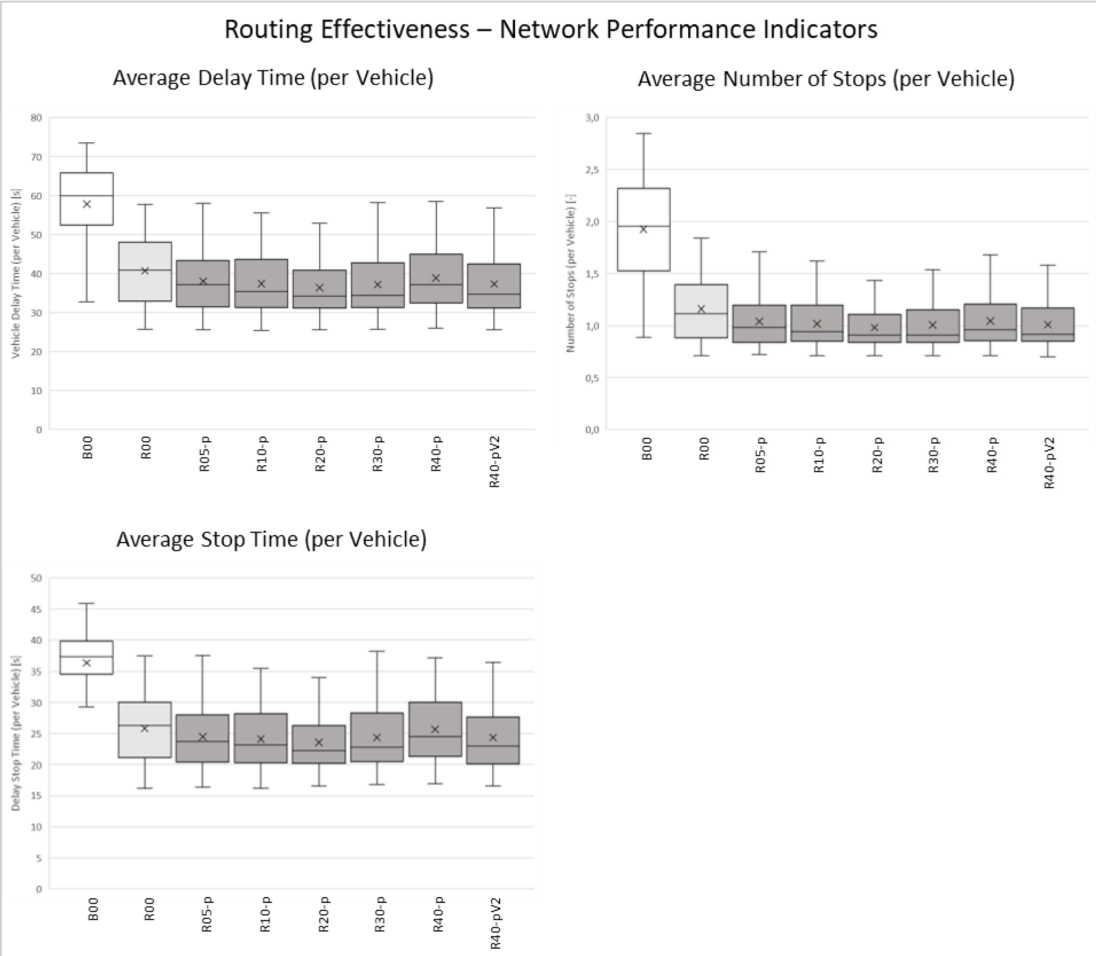


5. Evaluation Results Table Local Air Quality Indicators (Effectiveness)

RE-ROUTING Activation Period (08:00-10:00)		R05p	R10p	R20p	R30p	R40p	R40v2p	R05p	R10p	R20p	R30p	R40p	R40v2p
		mean deviation from R05 (Δ)	*mean deviation from R10 (Δ)*	*mean deviation from R20 (Δ)*	*mean deviation from R30 (Δ)*	*mean deviation from R40 (Δ)*	*mean deviation from R40 (Δ)*	*mean deviation from B05 (Δ)*	*mean deviation from B10 (Δ)*	*mean deviation from B20 (Δ)*	*mean deviation from B30 (Δ)*	*mean deviation from B40 (Δ)*	*mean deviation from B40 (Δ)*
Total NOx Emissions	**Main Route**	-2 %	+0 %	+3 % *	+4 %	+8 % *	+2 %	-43 % *	-42 % *	-42 % *	-41 % *	-38 % *	-41 % *
		p = 0,125	p = 0,422	p = 0,039	p = 0,055	p = 0,008	p = 0,273	p = 0,004	p = 0,004	p = 0,004	p = 0,004	p = 0,004	p = 0,004
	Alternative Route	-4 % *	-6 % *	-10 % *	-11 % *	-13 % *	-10 % *	+24 % *	+20 % *	+15 % *	+14 % *	+12 % *	+15 % *
		p = 0,004	p = 0,004	p = 0,004	p = 0,004	p = 0,004	p = 0,004	p = 0,004	p = 0,004	p = 0,004	p = 0,004	p = 0,004	p = 0,004
Total NO_2 Concentrations	**Main Route**	0 %	0 %	+0 %	+0 %	+1 % *	0 %	-12 % *	-11 % *	-11 % *	-10 % *	-8 % *	-9 % *
		p = 0,074	p = 0,473	p = 0,231	p = 0,191	p = 0,008	p = 0,191	p = 0,004	p = 0,004	p = 0,004	p = 0,004	p = 0,004	p = 0,004
	Alternative Route	-1 % *	-1 % *	-2 % *	-2 % *	-2 % *	-1 % *	+3 % *	+2 % *	+1 % *	+0 %	+0 %	+1 % *
		p = 0,020	p = 0,008	p = 0,004	p = 0,004	p = 0,004	p = 0,004	p = 0,004	p = 0,008	p = 0,004	p = 0,098	p = 0,074	p = 0,004

* significant values (Paired Wilcoxon Rank Test, Confidence Level: 95%)

6. Boxplots Network Performance Indicators (Effectiveness): Average Travel Time, Average Number of Stops, Average Delay Stop Time

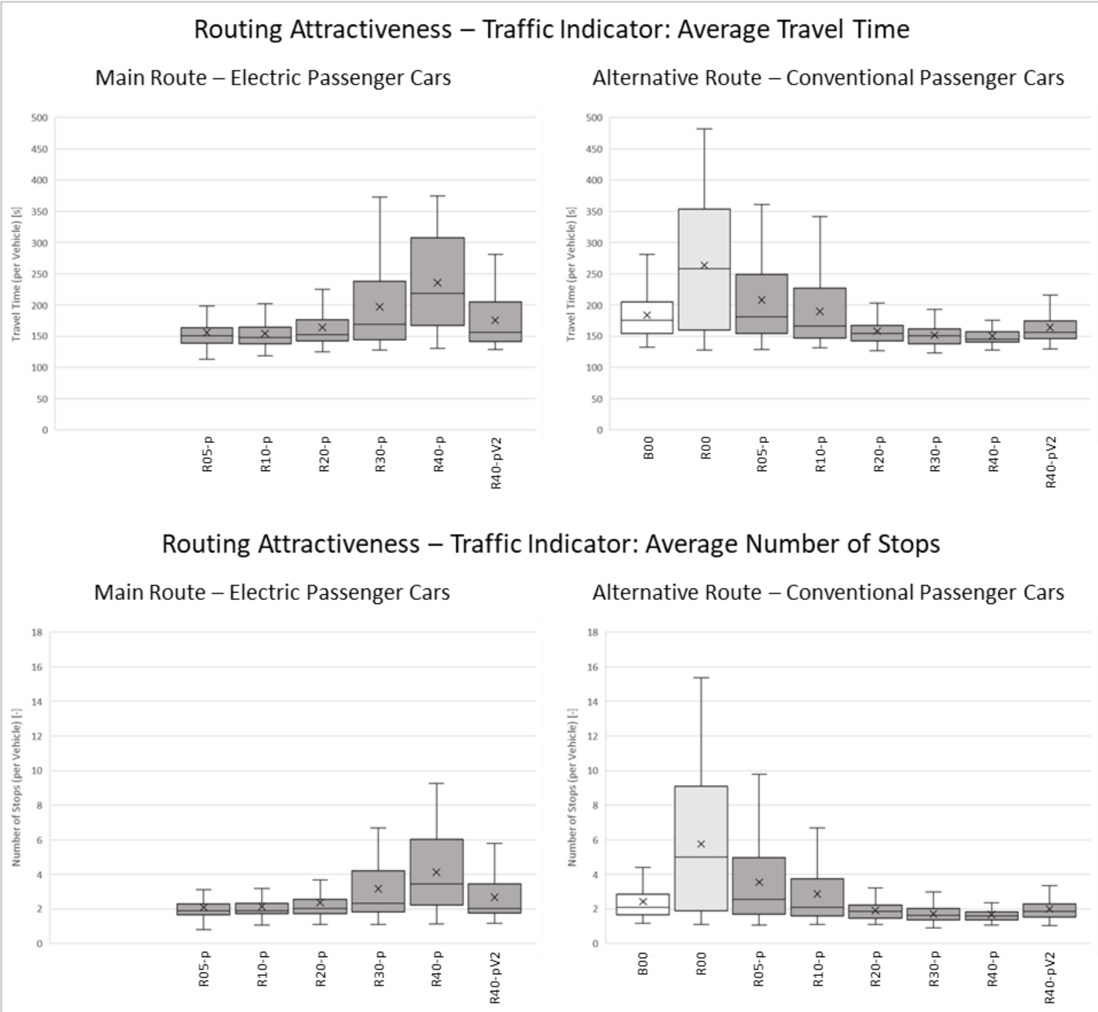


7. Evaluation Results Table Network Performance Indicators (Effectiveness)

RE-ROUTING Activation Period (8:00-10:00)		B00	R00	R05p	R10p	R20p	R30p	R40p	R40v2p	R05p	R10p	R20p	R30p	R40p	R40v2p
		absolute	*absolute*	*mean deviation from R00 (Δ)*						*mean deviation from B00 (Δ)*					
Network Performance (All Vehicles)	Number of Stops per Vehicle	1,93	1,16	-10 % *	-12 % *	-15 % *	-13 % *	-10 % *	-13 % *	-46 % *	-47 % *	-49 % *	-48 % *	-46 % *	-48 % *
				p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000
	Stop Time per Vehicle	36,34	25,81	-5 % *	-7 % *	-9 % *	-6 % *	-1 %	-6 % *	-33 % *	-34 % *	-35 % *	-33 % *	-29 %	-33 % *
				p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,683	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,683	p = 0,000
	Delay Time per Vehicle	57,78	40,71	-7 % *	-8 % *	-11 % *	-9 % *	-5 % *	-8 % *	-34 % *	-35 % *	-37 % *	-36 % *	-33 % *	-35 % *
				p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,008	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,008	p = 0,000

* significant values (Paired Wilcoxon Rank Test, Confidence Level: 95%)

8. Boxplots Attractiveness Indicators: Average Travel Time, Average Number of Stops (ZE-PC vs. PC)



9. Evaluation Results Table Attractiveness Indicators

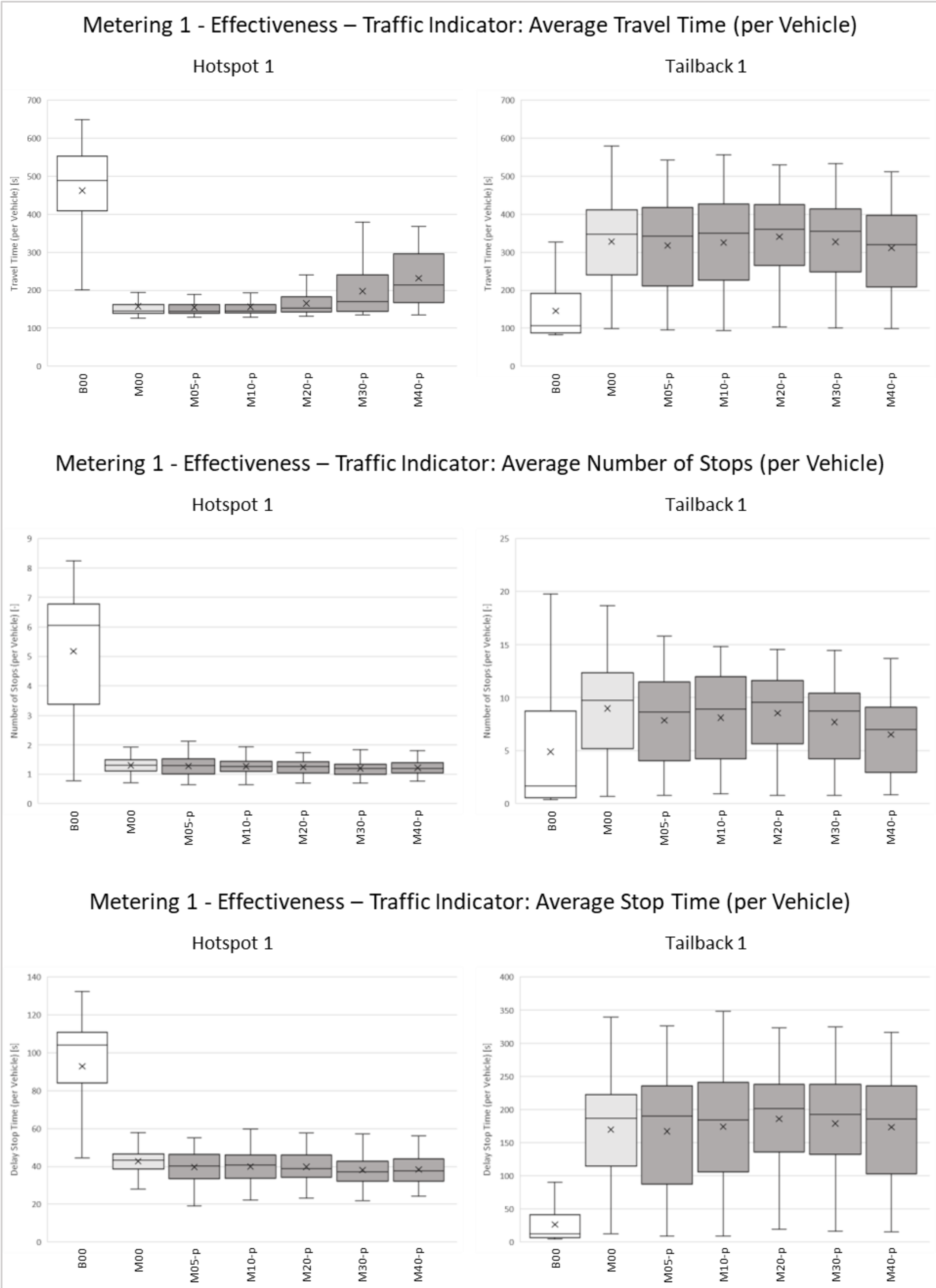
RE-ROUTING Activation Period (8:00-10:00)	Comparison	Explanation	R00	R05p	R10p	R20p	R30p	R40p	R40v2p
Travel Time	PC (with vs. without privilege)	*without prio. PC = on the alternative route with prio. PC = on the alternative route*	263,62	-21 % *	-28 % *	-40 % *	-42 % *	-43 % *	-38 % *
				p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000
	ZE-PC (with vs. without privilege)	*without prio. ZE-PC = on the alternative route with prio. ZE-PC = on the main route*	263,62	-42 % *	-42 % *	-39 % *	-26 % *	-12 %	-34 % *
				p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,098	p = 0,000
	ZE-PC vs PC (both with privilege)	*with prio. PC = on the alternative route with prio. ZE-PC = on the main route*		-34 % *	-23 % *	+3 % *	+23 % *	+36 % *	+7 % *
				p = 0,000	p = 0,000	p = 0,046	p = 0,000	p = 0,000	p = 0,025
Number of Stops	PC (with vs. without privilege)	*without prio. PC = on the alternative route with prio. PC = on the alternative route*	5,75	-39 % *	-50 % *	-67 % *	-70 % *	-71 % *	-65 % *
				p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000
	ZE-PC (with vs. without privilege)	*without prio. ZE-PC = on the alternative route with prio. ZE-PC = on the main route*	5,75	-64 % *	-63 % *	-59 % *	-45 % *	-28 %	-54 % *
				p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,055	p = 0,000
	ZE-PC vs PC (both with privilege)	*with prio. PC = on the alternative route with prio. ZE-PC = on the main route*		-69 % *	-34 % *	+20 % *	+46 % *	+59 % *	+25 % *
				p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000

* significant values (Paired Wilcoxon Rank Test, Confidence Level: 95%)

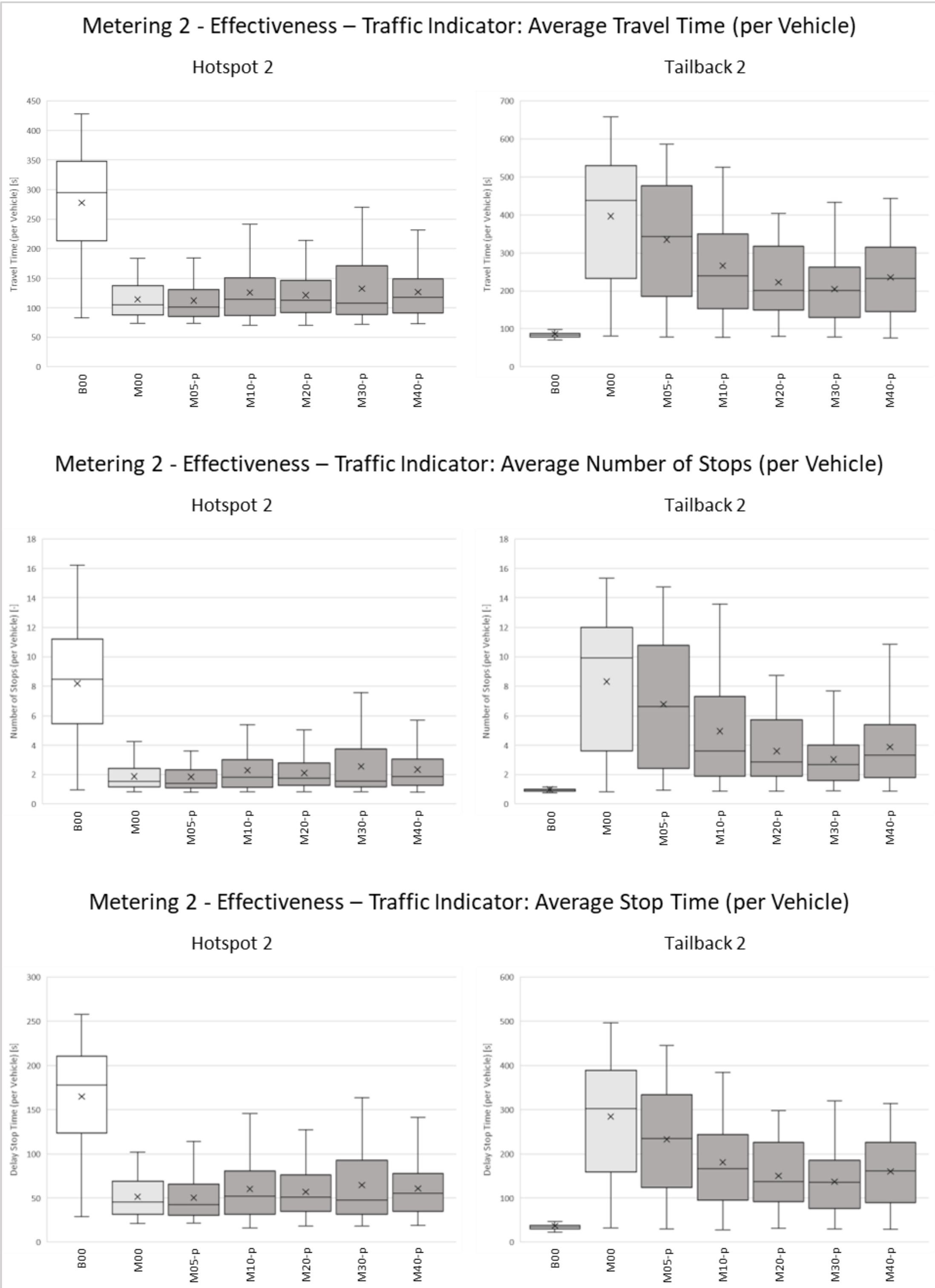
Appendix 5j

Detailed results for the measure <u>Temporary Metering</u>: Boxplots and Boxplots and evaluation result tables for the evaluated indicators (effectiveness and attractiveness) from modelled scenarios

1. Boxplots Local Traffic Indicators (Effectiveness) Metering 1: Average Travel Time, Average Number of Stops, Average Stop Time



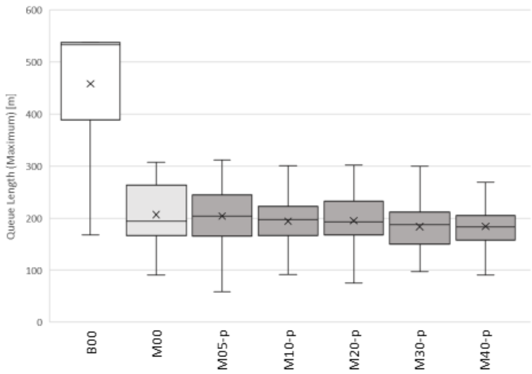
2. Boxplots Local Traffic Indicators (Effectiveness) Metering 2: Average Travel Time, Average Number of Stops, Average Stop Time



3. Boxplots Local Traffic Indicators (Effectiveness) Metering 1 and 2: Maximum Queue Length

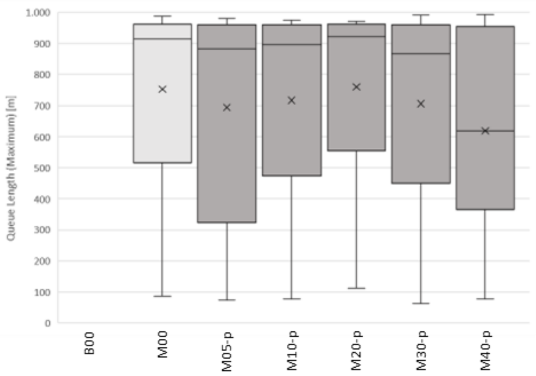
Metering 1 - Effectiveness – Traffic Indicator: Queue Length (Maximum)

Node B North (Hotspot 1)

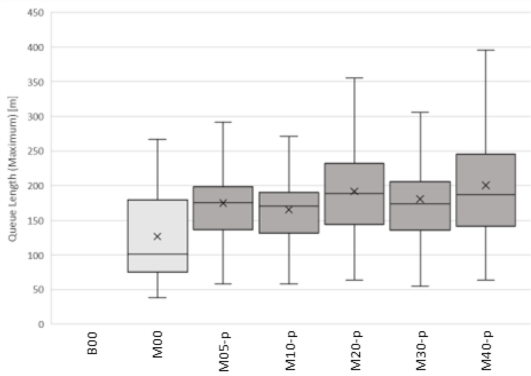


Metering 1 - Effectiveness – Traffic Indicator: Queue Length (Maximum)

Mainline Meter (Tailback 1)

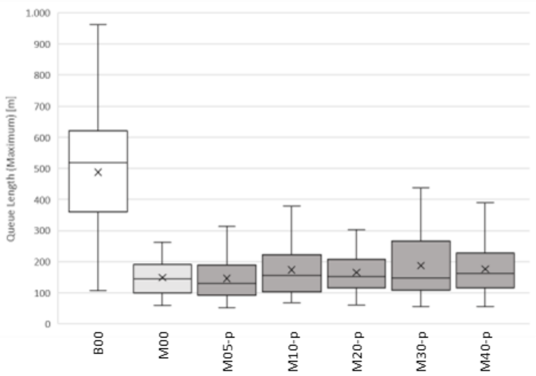


Ramp Meter

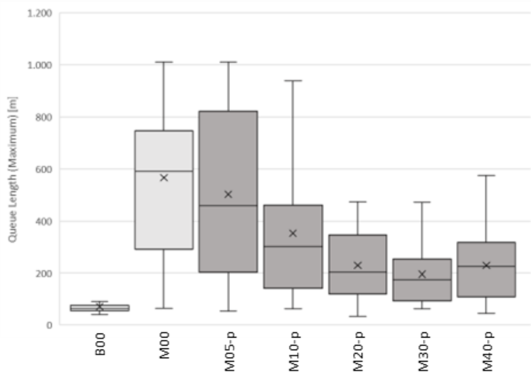


Metering 2 - Effectiveness – Traffic Indicator: Queue Length (Maximum)

Node C West (Hotspot 2)



Node B West (Tailback 2)

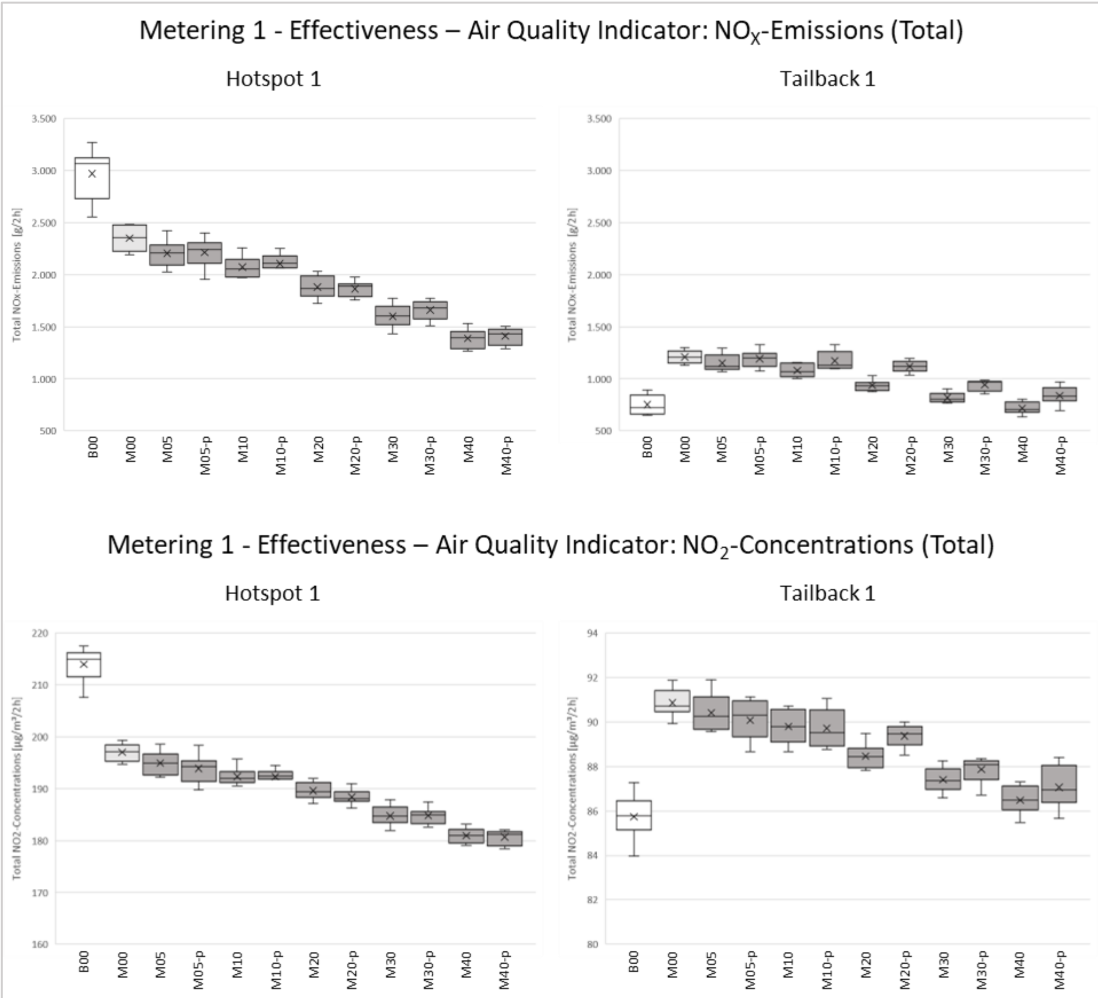


4. Evaluation Results Table Local Traffic Indicators (Effectiveness) Metering 1 and 2

METERING		B00	M00	M05p	M10p	M20p	M30p	M40p	M05p	M10p	M20p	M30p	M40p
Activation Period (8:00-10:00)		*absolute*	*absolute*	*mean deviation from M00 (Δ)*					*mean deviation from B00 (Δ)*				
Average Travel Time (All Vehicles)	Hotspot 1	184,23	88,10	-5 % *	-4 % *	-5 % *	-7 % *	-7 % *	-54 % *	-54 % *	-55 % *	-56 % *	-55 % *
				p = 0,002	p = 0,011	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000
	Tailback 1	145,27	327,56	-3 %	-1 %	+4 % *	0 %	-5 % *	+118 % *	+124 % *	+135 % *	+125 % *	+114 % *
				p = 0,119	p = 0,643	p = 0,013	p = 0,814	p = 0,039	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000
	Hotspot 2	277,83	114,03	-2 %	+10 %	+6 %	+16 % *	+11 % *	-60 % *	-55 % *	-56 % *	-52 % *	-54 % *
				p = 0,094	p = 0,246	p = 0,105	p = 0,017	p = 0,010	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000
	Tailback 2	86,31	396,86	-16 % *	-33 % *	-44 % *	-48 % *	-41 % *	+288 % *	+208 % *	+158 % *	+137 % *	+173 % *
				p = 0,001	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000
Average Number of Stops (All Vehicles)	Hotspot 1	5,17	1,30	-2 %	-2 %	-5 % *	-8 % *	-7 % *	-75 % *	-75 % *	-76 % *	-77 % *	-77 % *
				p = 0,308	p = 0,218	p = 0,034	p = 0,002	p = 0,008	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000
	Tailback 1	4,90	8,97	-12 % *	-10 % *	-5 %	-14 % *	-27 % *	+60 % *	+65 % *	+74 % *	+57 % *	+33 % *
				p = 0,001	p = 0,030	p = 0,084	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000
	Hotspot 2	8,19	1,87	-2 %	+22 %	+12 %	+37 % *	+25 % *	-78 % *	-72 % *	-74 % *	-69 % *	-72 % *
				p = 0,144	p = 0,244	p = 0,090	p = 0,011	p = 0,004	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000
	Tailback 2	0,98	8,32	-18 % *	-40 % *	-57 % *	-64 % *	-53 % *	+593 % *	+406 % *	+267 % *	+209 % *	+295 % *
				p = 0,001	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000
Average Stop Time (All Vehicles)	Hotspot 1	92,76	42,70	-7 % *	-7 % *	-7 % *	-11 % *	-10 % *	-57 % *	-57 % *	-57 % *	-59 % *	-59 % *
				p = 0,001	p = 0,018	p = 0,001	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000
	Tailback 1	26,60	169,63	-1 %	+3 %	+10 % *	+6 % *	+2 %	+529 % *	+555 % *	+599 % *	+573 % *	+553 % *
				p = 0,331	p = 0,150	p = 0,000	p = 0,004	p = 0,219	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000
	Hotspot 2	164,61	51,42	-2 %	+17 %	+10 %	+25 % *	+18 % *	-70 % *	-63 % *	-66 % *	-61 % *	-63 % *
				p = 0,098	p = 0,210	p = 0,103	p = 0,018	p = 0,011	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000
	Tailback 2	36,44	284,38	-18 % *	-36 % *	-47 % *	-52 % *	-44 % *	+538 % *	+396 % *	+311 % *	+275 % *	+339 % *
				p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000
Maximum Queue Length (All Vehicles)	Hotspot 1 (Node B North)	458,46	206,92	-1 %	-6 %	-6 %	-11 % *	-11 % *	-56 % *	-58 % *	-57 % *	-60 % *	-60 % *
				p = 0,330	p = 0,069	p = 0,056	p = 0,001	p = 0,002	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000
	Tailback 1 Main Meter		752,89	-8 % *	-5 % *	+1 %	-6 % *	-18 % *	no relevant comparison				
				p = 0,002	p = 0,046	p = 0,226	p = 0,004	p = 0,000					
	Tailback 1 Ramp Meter		126,66	+38 % *	+31 % *	+52 % *	+43 % *	+58 % *	no relevant comparison				
				p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000					
	Hotspot 2 (Node C West)	487,77	149,41	-2 %	+16 %	+11 %	+26 % *	+18 % *	-70 % *	-64 % *	-66 % *	-62 % *	-64 % *
				p = 0,162	p = 0,184	p = 0,063	p = 0,004	p = 0,003	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000
	Tailback 2 (Node B West)	70,76	566,57	-11 %	-38 % *	-59 % *	-65 % *	-59 % *	+610 % *	+398 % *	+225 % *	+176 % *	+225 % *
				p = 0,114	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000

* significant values (Paired Wilcoxon Rank Test, Confidence Level: 95%)

5. Local Air Quality Indicators (Effectiveness) Metering 1: Total NO_X-Emissions and NO_2-Concentrations

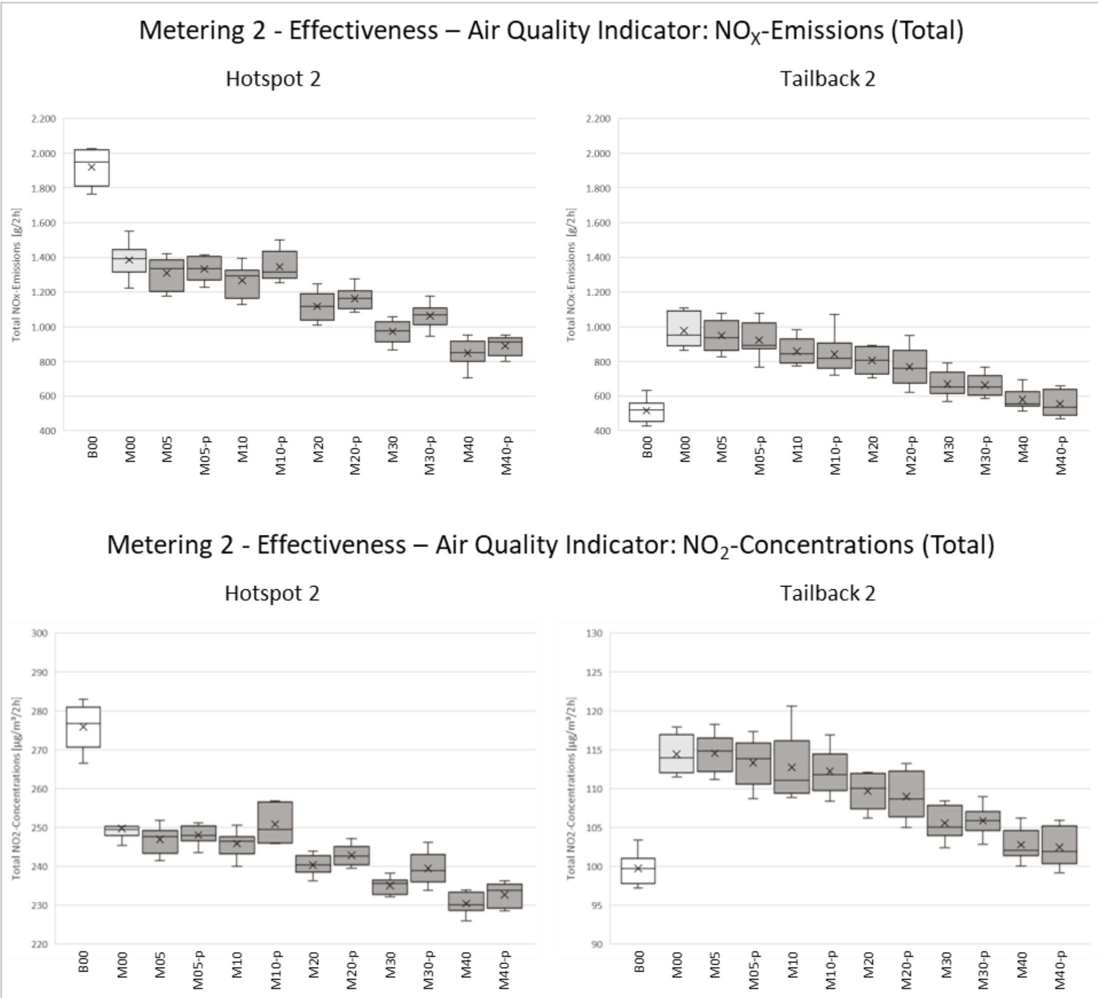


6. Evaluation Results Table Local Air Quality Indicators (Effectiveness) Metering 1

METERING Activation Period (8:00-10:00)		M05p	M10p	M20p	M30p	M40p	M05p	M10p	M20p	M30p	M40p
		mean deviation from M05 (Δ)	*mean deviation from M10 (Δ)*	*mean deviation from M20 (Δ)*	*mean deviation from M30 (Δ)*	*mean deviation from M40 (Δ)*	*mean deviation from B05 (Δ)*	*mean deviation from B10 (Δ)*	*mean deviation from B20 (Δ)*	*mean deviation from B30 (Δ)*	*mean deviation from B40 (Δ)*
Total NO_X Emissions	Hotspot 1	+0 %	+2 %	-1 %	+4 %	+2 %	-21 % *	-21 % *	-21 % *	-20 % *	-20 % *
		p = 0,422	p = 0,156	p = 0,098	p = 0,055	p = 0,125	p = 0,004	p = 0,004	p = 0,004	p = 0,004	p = 0,004
	Tailback 1	+4 %	+9 % *	+20 % *	+15 % *	+17 % *	missing data for comparison				
		p = 0,125	p = 0,008	p = 0,004	p = 0,004	p = 0,004					
Total NO_2 Concentrations	Hotspot 1	-1 % *	0 %	-1 %	+0 %	0 %	-8 % *	-8 % *	-8 % *	-7 % *	-6 % *
		p = 0,020	p = 0,527	p = 0,055	p = 0,320	p = 0,156	p = 0,004	p = 0,004	p = 0,004	p = 0,004	p = 0,004
	Tailback 1	0 %	0 %	+1 % *	+1 % *	+1 % *	missing data for comparison				
		p = 0,125	p = 0,473	p = 0,012	p = 0,027	p = 0,027					

* significant values (Paired Wilcoxon Rank Test, Confidence Level: 95%)

7. Local Air Quality Indicators (Effectiveness) Metering 2: Total NO_X-Emissions, Total NO_2-Concentrations

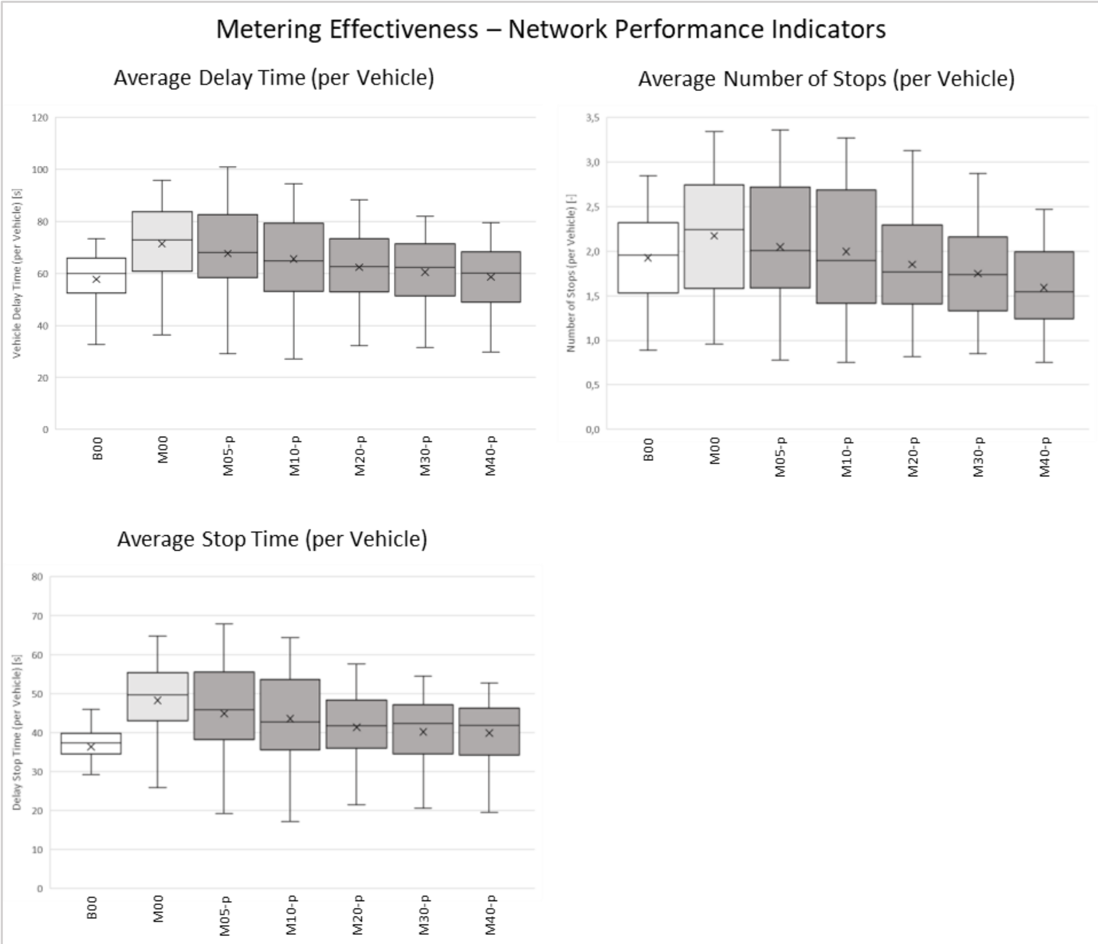


8. Evaluation Results Table Local Air Quality Indicators (Effectiveness) Metering 2

METERING Activation Period (8:00-10:00)		M05p	M10p	M20p	M30p	M40p	M05p	M10p	M20p	M30p	M40p
		mean deviation from M05 (Δ)	*mean deviation from M10 (Δ)*	*mean deviation from M20 (Δ)*	*mean deviation from M30 (Δ)*	*mean deviation from M40 (Δ)*	*mean deviation from B05 (Δ)*	*mean deviation from B10 (Δ)*	*mean deviation from B20 (Δ)*	*mean deviation from B30 (Δ)*	*mean deviation from B40 (Δ)*
Total NO_X Emissions	**Hotspot 2**	+2 %	+6 % *	+4 %	+9 % *	+5 %	-26 % *	-21 % *	-25 % *	-23 % *	-24 % *
		p = 0,191	p = 0,020	p = 0,098	p = 0,008	p = 0,191	p = 0,004	p = 0,004	p = 0,004	p = 0,004	p = 0,004
	Tailback 2	-3 %	-2 %	-5 %	-1 %	-4 %	+85 % *	+77 % *	+84 % *	+79 % *	+76 % *
		p = 0,191	p = 0,320	p = 0,320	p = 0,422	p = 0,320	p = 0,004	p = 0,004	p = 0,004	p = 0,004	p = 0,004
Total NO_2 Concentrations	**Hotspot 2**	+0 %	+2 % *	+1 %	+2 % *	+1 %	-8 % *	-6 % *	-8 % *	-7 % *	-6 % *
		p = 0,320	p = 0,012	p = 0,055	p = 0,004	p = 0,098	p = 0,004	p = 0,004	p = 0,004	p = 0,004	p = 0,004
	Tailback 2	-1 % *	0 %	-1 %	+0 %	0 %	+13 % *	+13 % *	+13 % *	+12 % *	+11 % *
		p = 0,027	p = 0,371	p = 0,473	p = 0,371	p = 0,422	p = 0,004	p = 0,004	p = 0,004	p = 0,004	p = 0,004

* significant values (Paired Wilcoxon Rank Test, Confidence Level: 95%)

9. Network Performance Indicators (Effectiveness) Metering: Average Travel Time, Average Number of Stops, Average Delay Stop Time

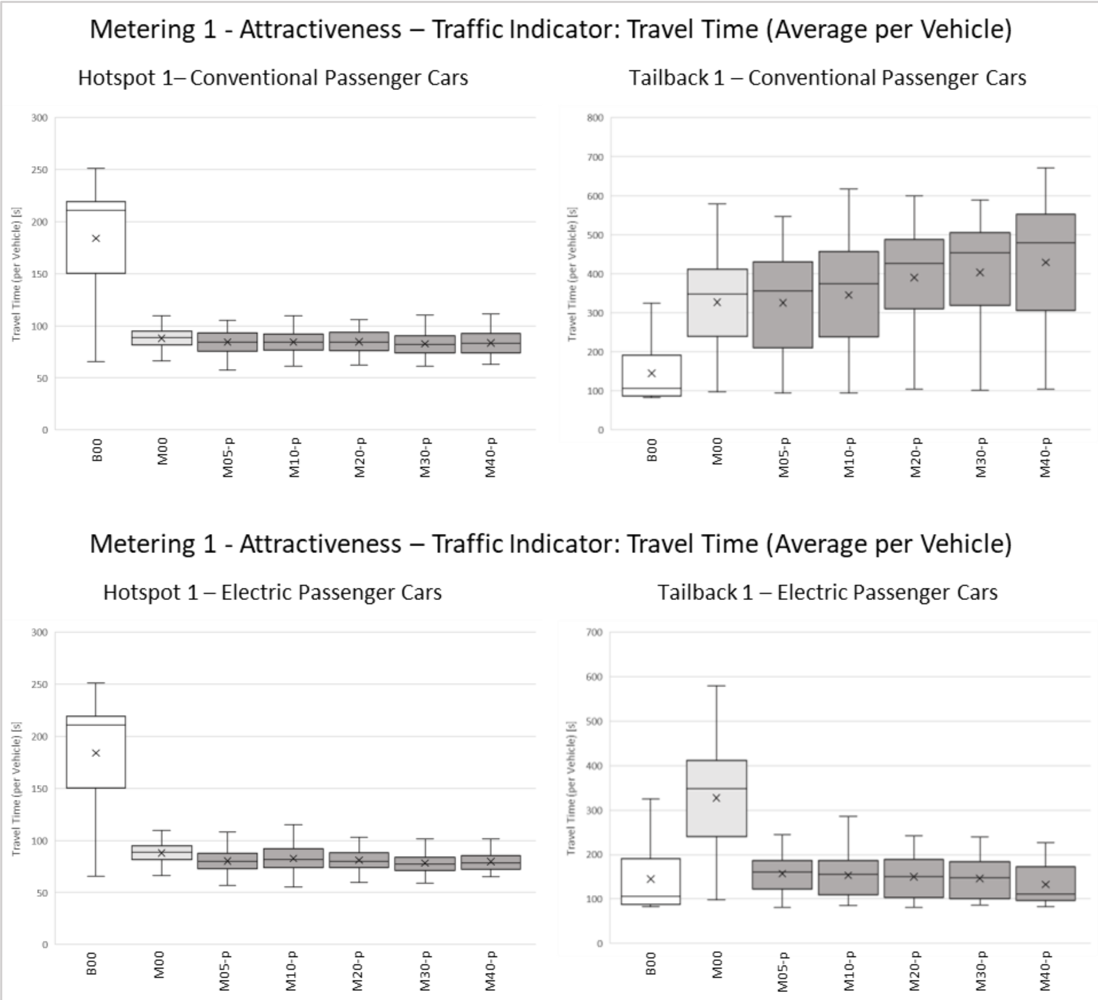


10. Evaluation Results Table Network Performance Indicators (Effectiveness) Metering

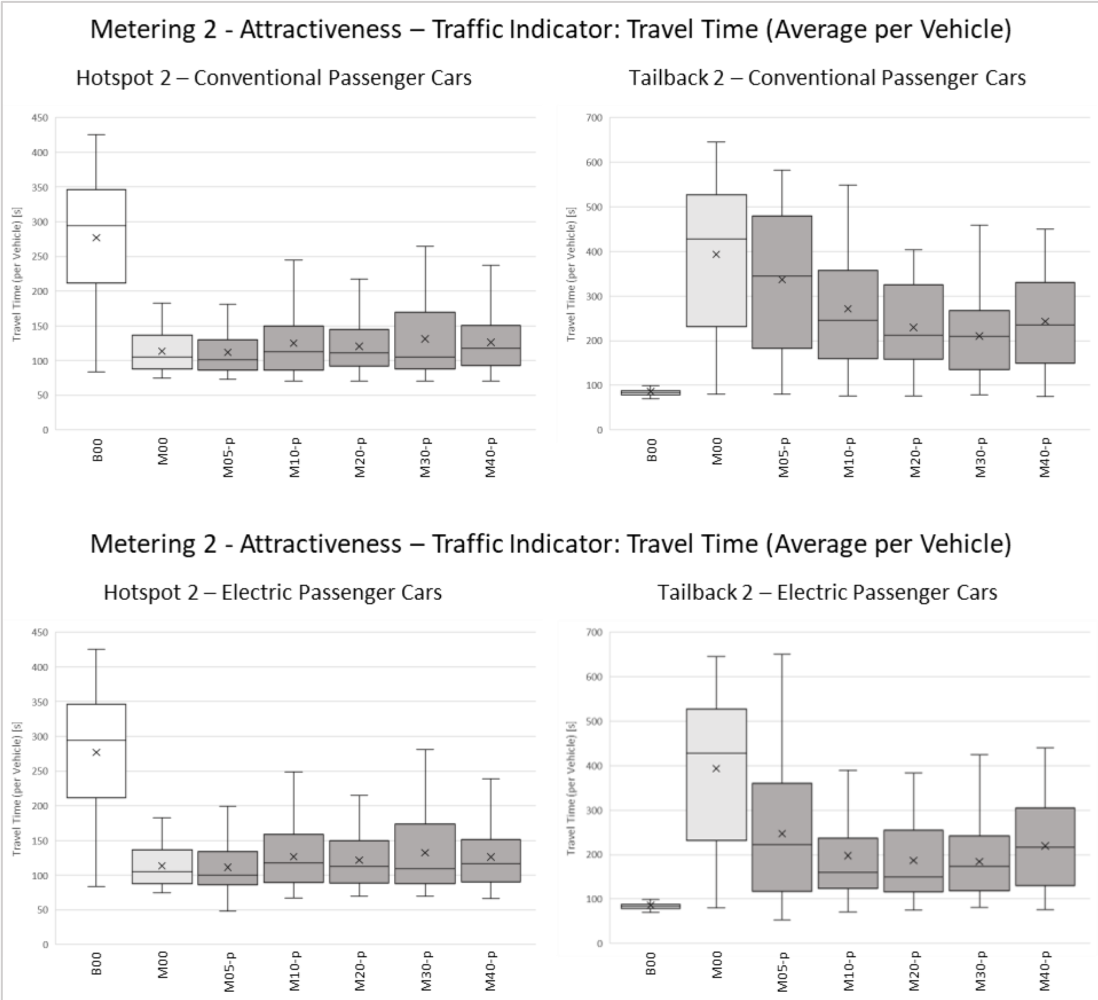
METERING Activation Period (8:00-10:00)		B00	M00	M05p	M10p	M20p	M30p	M40p	M05p	M10p	M20p	M30p	M40p
		absolute	*absolute*	*mean deviation from M00 (Δ)*					*mean deviation from B00 (Δ)*				
Network Performance (All Vehicles)	Number of Stops per Vehicle	1,93	2,17	-6 % *	-8 % *	-15 % *	-19 % *	-27 % *	+6 % *	+4 %	-4 % *	-9 % *	-17 % *
				p = 0,001	p = 0,005	p = 0,000	p = 0,000	p = 0,000	p = 0,035	p = 0,107	p = 0,000	p = 0,000	p = 0,000
	Stop Time per Vehicle	36,34	48,29	-7 % *	-10 % *	-14 % *	-17 % *	-17 % *	+24 % *	+20 % *	+14 % *	+11 % *	+10 % *
				p = 0,001	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000
	Delay Time per Vehicle	57,78	71,44	-5 % *	-8 % *	-13 % *	-15 % *	-18 % *	+17 % *	+13 % *	+8 % *	+5 % *	+2 % *
				p = 0,004	p = 0,001	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,049

* significant values (Paired Wilcoxon Rank Test, Confidence Level: 95%)

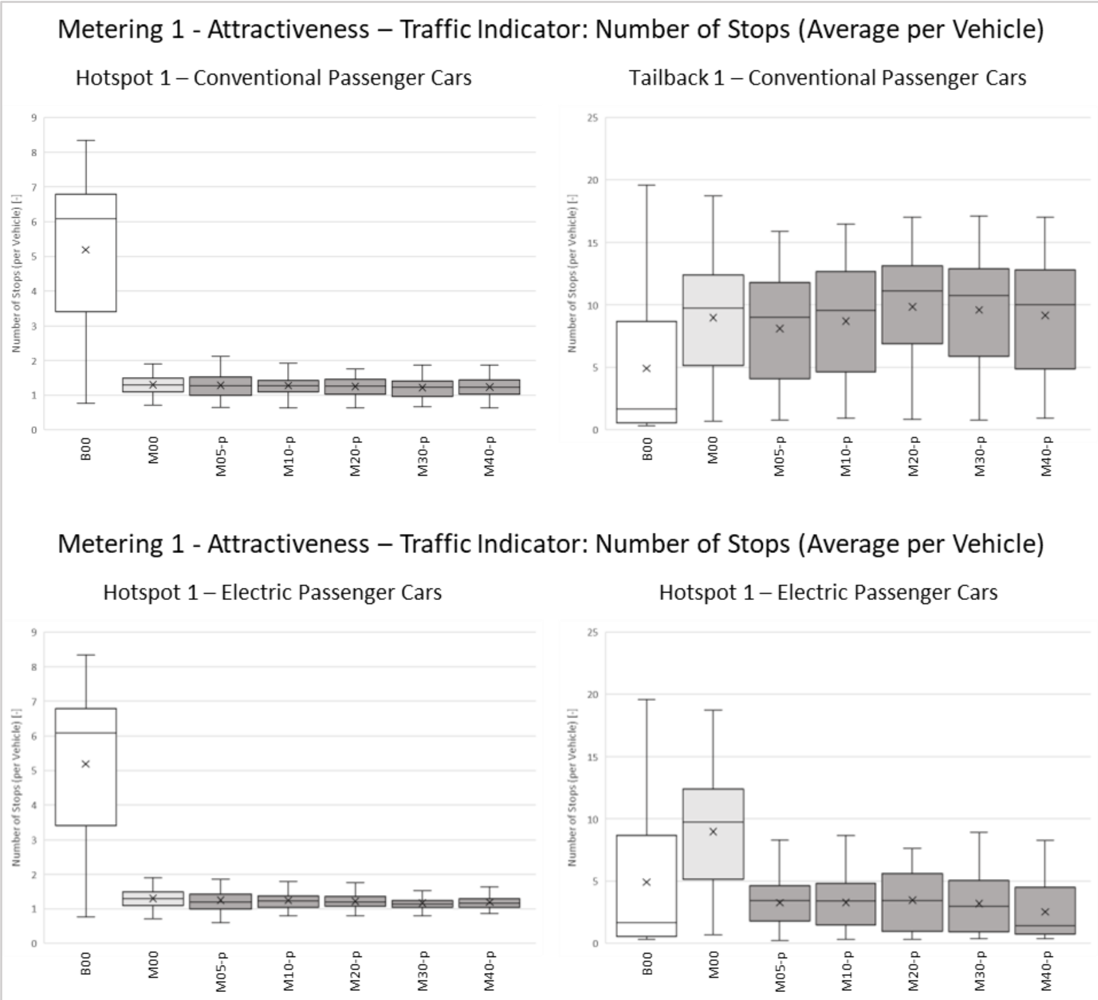
11. Attractiveness Indicators Metering 1: Average Travel Time (ZE-PC vs. PC)



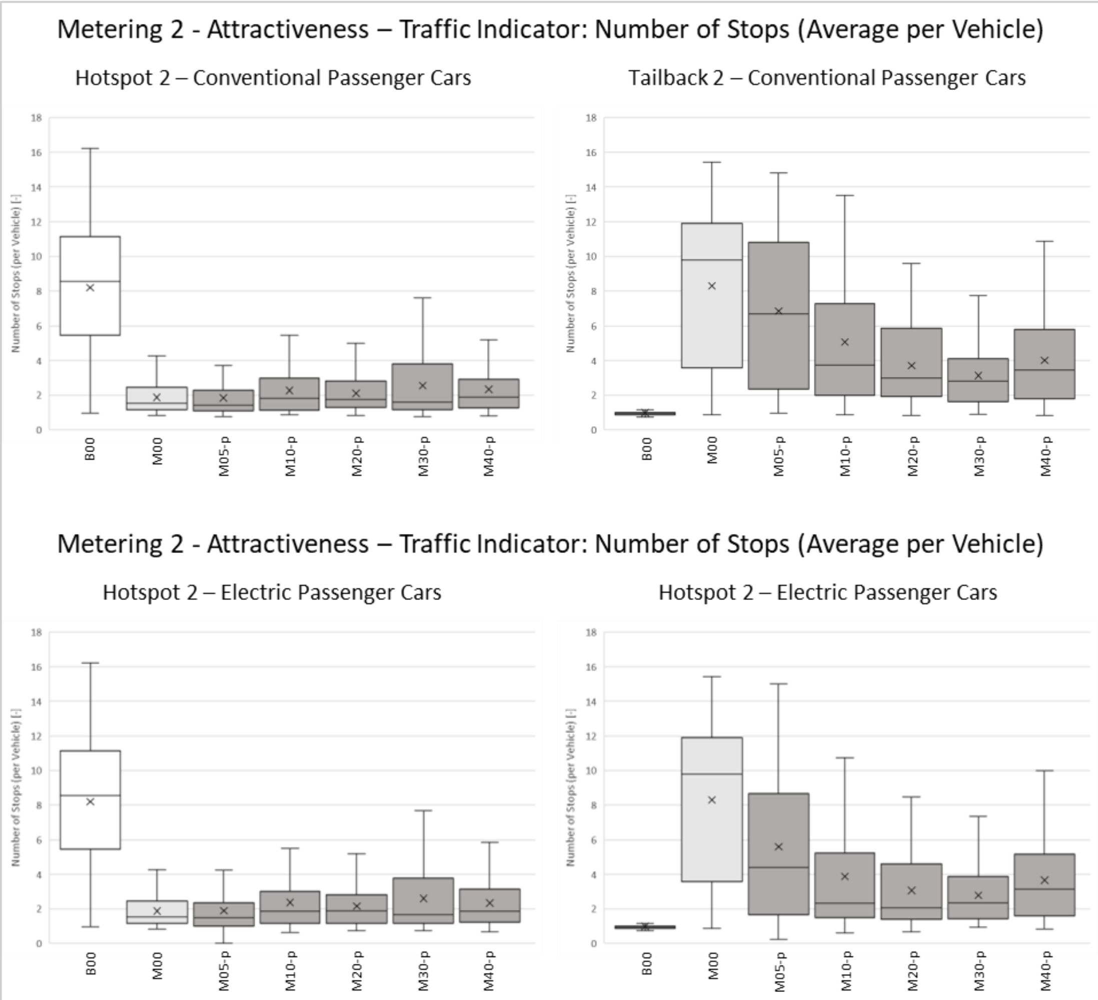
12. Attractiveness Indicators Metering 2: Average Travel Time (ZE-PC vs. PC)



13. Attractiveness Indicators Metering 1: Average Number of Stops (ZE-PC vs. PC)



14. Attractiveness Indicators Metering 2: Average Number of Stops (ZE-PC vs. PC)



15. Evaluation Results Table Attractiveness Indicators Metering 1 and 2

METERING Activation Period (8:00-10:00)			Comparison	M00	M05p	M10p	M20p	M30p	M40p
Travel Time	Metering 1	Hotspot 1	PC (with vs. without privilege)	87,91	-4 % *	-4 % *	-4 % *	-6 % *	-5 % *
					p = 0,005	p = 0,017	p = 0,003	p = 0,000	p = 0,001
			ZE-PC (with vs. without privilege)	87,91	-9 % *	-6 % *	-8 % *	-11 % *	-9 % *
					p = 0,000	p = 0,001	p = 0,000	p = 0,000	p = 0,000
			ZE-PC vs PC (both with privilege)		-5 % *	-2 % *	-4 % *	-5 % *	-5 % *
					p = 0,000	p = 0,005	p = 0,000	p = 0,000	p = 0,000
		Tailback 1	PC (with vs. without privilege)	327,25	-1 %	+6 % *	+19 % *	+23 % *	+31 % *
					p = 0,431	p = 0,015	p = 0,000	p = 0,000	p = 0,000
			ZE-PC (with vs. without privilege)	327,25	-52 % *	-53 % *	-54 % *	-55 % *	-60 % *
					p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000
			ZE-PC vs PC (both with privilege)		-52 % *	-56 % *	-62 % *	-64 % *	-69 % *
					p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000
	Metering 2	Hotspot 2	PC (with vs. without privilege)	113,48	-2 %	+10 %	+6 %	+16 % *	+11 % *
					p = 0,104	p = 0,254	p = 0,119	p = 0,020	p = 0,011
			ZE-PC (with vs. without privilege)	113,48	-2 %	+12 %	+7 %	+17 % *	+11 % *
					p = 0,065	p = 0,160	p = 0,075	p = 0,011	p = 0,010
			ZE-PC vs PC (both with privilege)		-1 %	+1 % *	+1 % *	+1 %	0 %
					p = 0,466	p = 0,029	p = 0,042	p = 0,093	p = 0,308
		Tailback 2	PC (with vs. without privilege)	393,35	-14 % *	-31 % *	-42 % *	-46 % *	-38 % *
					p = 0,002	p = 0,000	p = 0,000	p = 0,000	p = 0,000
			ZE-PC (with vs. without privilege)	393,35	-37 % *	-50 % *	-53 % *	-53 % *	-44 % *
					p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000
			ZE-PC vs PC (both with privilege)		-27 % *	-27 % *	-19 % *	-13 % *	-10 % *
					p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000
Number of Stops	Metering 1	Hotspot 1	PC (with vs. without privilege)	1,30	-2 %	-2 %	-4 %	-7 % *	-5 % *
					p = 0,323	p = 0,291	p = 0,053	p = 0,005	p = 0,023
			ZE-PC (with vs. without privilege)	1,30	-4 %	-5 %	-6 % *	-11 % *	-9 % *
					p = 0,090	p = 0,078	p = 0,019	p = 0,000	p = 0,001
			ZE-PC vs PC (both with privilege)		-2 %	-3 % *	-2 % *	-4 % *	-4 % *
					p = 0,122	p = 0,022	p = 0,017	p = 0,001	p = 0,004
		Tailback 1	PC (with vs. without privilege)	8,98	-10 % *	-3 %	+10 % *	+7 % *	+2 %
					p = 0,009	p = 0,464	p = 0,000	p = 0,002	p = 0,375
			ZE-PC (with vs. without privilege)	8,98	-64 % *	-63 % *	-61 % *	-64 % *	-72 % *
					p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000
			ZE-PC vs PC (both with privilege)		-60 % *	-62 % *	-65 % *	-67 % *	-72 % *
					p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000
	Metering 2	Hotspot 2	PC (with vs. without privilege)	1,87	-2 %	+22 %	+12 %	+36 % *	+25 % *
					p = 0,169	p = 0,244	p = 0,106	p = 0,012	p = 0,003
			ZE-PC (with vs. without privilege)	1,87	+1 %	+26 %	+15 %	+39 % *	+25 % *
					p = 0,796	p = 0,161	p = 0,051	p = 0,004	p = 0,005
			ZE-PC vs PC (both with privilege)		+2 %	+4 % *	+3 % *	+2 % *	0 %
					p = 0,267	p = 0,003	p = 0,013	p = 0,020	p = 0,294
		Tailback 2	PC (with vs. without privilege)	8,30	-18 % *	-39 % *	-55 % *	-62 % *	-52 % *
					p = 0,001	p = 0,000	p = 0,000	p = 0,000	p = 0,000
			ZE-PC (with vs. without privilege)	8,30	-33 % *	-53 % *	-63 % *	-67 % *	-56 % *
					p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000
			ZE-PC vs PC (both with privilege)		-18 % *	-24 % *	-17 % *	-11 % *	-9 % *
					p = 0,000	p = 0,000	p = 0,000	p = 0,000	p = 0,000

* significant values (Paired Wilcoxon Rank Test, Confidence Level: 95%)