AIR QUALITY IMPROVEMENT IN URBAN AREAS USING TRAFFIC OPERATION MANAGEMENT

by

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Abstract

Air Quality Improvement in Urban Areas using Traffic Operation Management

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Clean air is becoming a valuable good while the exhausts and physical processes from road transportation cause more and more pollutants. Critical air pollutants like particulate matter, nitrogen oxides and volatile organic compounds have severe effects on the respiratory track for adults and children. To mitigate these adverse health effects, a strict set of regulations from the governments are in place. Especially the traffic sector provides a lot of opportunities to reduce the emissions of these pollutants.

The focus of this report is fast responding traffic operational measures. Compared to long term developments like emission standards for new vehicles, these measures are able to reduce emission significantly within a few years or shorter periods of time. A research on applied measures in Toronto, Canada and Karlsruhe, Germany, has shown, that alternative modes of transportation like cycling and public transit have the highest efficiency to reduce the burden of air pollution.

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1 INTRODUCTION

1.1 Background

To breathe is a basic instinct of mankind. While a deep breath of fresh air provides a bracing feeling, serious concerns about ambient air quality have arisen worldwide within the last decades. Facing this negative aspect of economic growth and the unavoidable by-products of an increasing standard of living, the major responsibility for adverse health effects is currently linked to air pollutants (World Health Organization, 2016). These pollutants are generated from combustion, industrial or mechanical processes, like heating, agriculture, and transportation. Their reduction and avoidance became a major challenge to ensure a sustainable growth. The highest concentrations of these pollutants are usually found in urban areas, close to their anthropogenic sources. In particular, the transportation sector, including passenger cars, goods moving trucks and public transit, is a high contributor to critical pollutants (Government of Canada, 2016). The firing of fossil fuels and the abrasion from breaks and tires on the roads generate gasses and particles which have negative effects on our health.

Focusing on road traffic, there is a multitude of possibilities to influence and to reduce these emissions. Besides technical improvement of the vehicles, there is also a variety of operational measures to reduce the environmental harm created by road traffic. Examples of currently applied measures from a municipality in Canada, the city of Toronto and from Germany, the city of Karlsruhe, will be introduced, analyzed, and compared to each other in later chapters of this report.

1.2 Report Organization

The organization of this report is depicted graphically in Figure 1.

Figure 1: Structure of the Report

The contents of the chapters are as follows:

Chapter 1: This chapter provides a brief background of the motivation for this report and its structure.

Chapter 2: This chapter presents a background of ambient air quality and traffic related pollutants, including their health effects, international thresholds, and examples for their generation.

Chapter 3: In this chapter, the national approaches of regulations and laws in Canada and Germany will be reviewed. This topic is of special importance, since the national regulations provide clear recommendations how to reduce air pollutants.

Chapter 4: To achieve a better understanding how to tailor efficient measures to reduce air pollutants, a background of the measurement systems will be provided in this chapter. Two analysis examples from Toronto, Canada and Karlsruhe, Germany, will display the local issues of the criteria air pollutants.

Chapter 5: This chapter will introduce and discuss a variety of traffic operational measures to reduce air pollutants. These measures are currently applied in Toronto and Karlsruhe.

Chapter 6: The measures from chapter 5 will be categorized and compared to each other, the conclusion of the report will be included in this section.

2 DEFINITION OF AIR QUALITY

2.1 Ambient Outdoor Air

The ambient air is a mixture of many gases and particles. In general, the atmosphere and its viable composition of gases is one of the greatest treasures of this planet. The most important component of the gassy envelope of the planet, to provide a live friendly environment, is oxygen (O_2). It makes up approximately one fifth or 20.95 percent of the atmosphere. Other major components are: nitrogen (N_2), 78.08 percent; argon (A), 0.93 percent; carbon dioxide (CO_2), 0.04 percent and water (H_2O) with regional variations between 0 to 4 percent. Other inert gases and compounds have a lesser ratio within this composition or appear only regional (Encyclopaedia Britannica, 2015).

Among these components, the air pollutants are also listed. With measurements on a scale of parts per million (ppm), or even as parts per billion (ppb) by volume and sometimes also as particle mass per reference volume, usually denoted in the unit $\mu g/m^3$, their regional appearance is highly fluctuating. For known compounds, these units are convertible (Natural Environment Research Council (NERC), 2013).

Despite these relative low scales to measure air pollutants, their effects on public health have a large impact and are often sensitive to small changes in the ambient air composition (World Health Organization, 2016). Clean air, or a high air quality, is usually defined in relation to health issues and the absence or only limited population of health affecting pollutants.

2.2 Development of Thresholds

The first international air quality guidelines (AQGs) to address the issue of health effects correlated to high concentrations of air pollutants were published by the World Health Organization (WHO) in 1987 (World Health Organization, 2005). Its main objectives were to provide a common standard for thresholds of key air pollutants and to offer guidance on reducing these. The increasing treasure trove of health-related datasets and an improved monitoring of air quality lead to a sharpening of the threshold values over the years. Adequate strategies on how to reduce certain pollutants were improved and first successes around the world were assigned (World Health Organization, 2005). The latest global update of the AQGs is from 2005.

The formulation of an air pollutant threshold is a complicated task. It is based on a risk assessment process which is usually subject to statistical analysis, the development standard and the economic interests of the assessing nation or institution (World Health Organization, 2005). For the statistical aspect, a correlation of local health records and measured air pollutant concentrations is a common approach. As an example, a study that analyzed the short-term changes in nitrogen dioxide (NO_2) and mortality in Canadian cities included the daily number of deaths for nonaccidental, cardiovascular and respiratory causes from cities with available air quality monitoring data. This data was available in 12 cities for a period of 19 years, from 1981 to 1999. The study also implemented adjustment curves for weather effects and other pollutants for an improved focus on the effect of NO_2 (Richard T. Burnett, 2004).

As this example suggests, there are many interfering factors in the statistical analysis that are complicated to include. Especially due to the given mixture of existing pollutants in the monitoring datasets there is a high uncertainty in the analysis for obtaining a threshold of a single pollutant. Some pollutants even obtain an indicator or marker function for further pollutants which are generated from the same sources but are more difficult to analyze. In this case, it is recommended to lower the threshold of a marker pollutant to include these indicated pollutants by only measuring the marker pollutant. An example for a marker of complex combustion-generated pollution mixtures is NO_2 (World Health Organization, 2005).

In the next section, the most relevant air pollutants with transportation as a major source of more than five percent contribution to the emission inventory and their threshold values according to the AQG from WHO, where applicable, will be described.

2.3 Air Pollutants in Detail

2.3.1 Nitrogen Dioxide (NO_2) and Nitrogen Oxides (NO_x)

Description: NO_x are gaseous emissions from combustion processes in air, of which NO_2 is the most frequently generated compound. It has a reddish-brown color and a pungent and irritating odour. It is involved in many further atmospheric reactions as for example the production of ground level ozone which is highly related to smog (Ontario Ministry of the Environment and Climate Change, 2017).

Traffic relation: The firing of fossil fuels in the engines of vehicles generates a high amount of NO_x. The contribution of the transportation sector to the overall NO_x inventory in Canada and Germany is within a ratio of one third up to more than a half (Environment and Climate Change Canada, 2016) (Umweltbundesamt, 2016).

Health risks: A long-term exposure to NO2 has a negative influence on the development of lung functions for children and increases symptoms of bronchitis for asthmatic children.

A short-term exposure to higher concentrations can have a direct affect of the pulmonary functions, especially for asthmatics (World Health Organization, 2005).

Other sources: Heating and power generation from the energy and industry sector.

Thresholds (WHO): 40 $\mu g/m^3$ annual mean; 200 $\mu g/m^3$ 1-hour mean

2.3.2 Particulate Matter $PM_{2.5}$ & PM_{10}

Description: Fine particles of solid materials and droplets of liquids are categorized according to their particular diameters. The category of $PM_{2.5}$ for example includes all fine particles smaller than 2.5 micrometers. These different size categories are important because of their different health effects. Between PM_{10} and $PM_{2.5}$ exists a certain interdependency, therefore the recommended measurement size is 2.5 micrometer. The particulate matter includes for example aerosols, ash, dust, fumes, pollen and smoke (Ontario Ministry of the Environment and Climate Change, 2017).

Traffic relation: The abrasion from tires on the road or from breaks produces fine particles. The by-products of firing fuel, especially diesel, in the engines of vehicles can also generate particulate matter. Another aspect is the disperse of already settled particles due to vehicle movements (Umweltbundesamt, 2016).

Health risks: Fine particles in the air can enter the respiratory tract. Their penetration depths into the respiratory system depends on their size, with a deeper penetration for smaller particles, as it can be seen in Figure 2. There is a certain likelihood that fine particles remain in the respiratory tracts and cause blockings with a reduction of the lung function (World Health Organization, 2005).

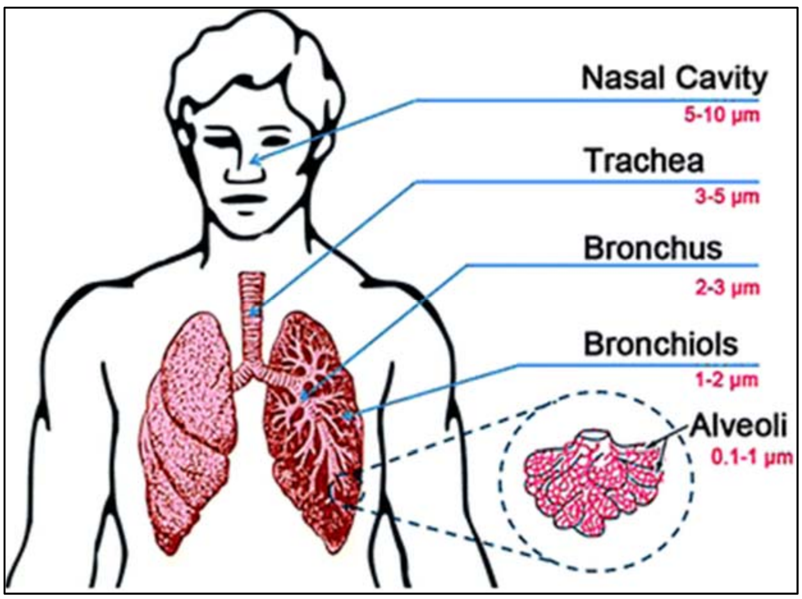


Figure 2: Lung penetration depth of particulate matter (Wang, 2015)

Other sources: Energy generation, industry and agriculture.

Thresholds (WHO): $PM_{2.5}$ 10 µg/m^3 annual mean; 25 µg/m^3 24-hour mean

PM_{10} 20 µg/m^3 annual mean; 50 µg/m^3 24-hour mean

2.3.3 Volatile Organic Compounds (VOC) & None Methane Volatile Organic Compounds (NMVOC)

Description: VOC are compounds which contain carbon components. They are usually released from drying out solvents or liquid fuels (Umweltbundesamt, 2016).

Traffic relation: An incomplete combustion of fuels in the engine can create VOCs or fuel droplets out of which VOCs can evaporate (Umweltbundesamt, 2016).

Health risks: VOCs are precursors of the formation of particulate matter and ground-level ozone, the main ingredients of smog (Environment and Climate Change Canada, 2016).

Other sources: Coatings, paints and polymers, construction work

Thresholds (WHO): NA – not listed

2.3.4 Ground-level Ozone (O_3)

Description: At ambient concentrations, O_3 is a colourless and odourless gas. It is a secondary pollutant, generated from photochemical reactions of NO_x and VOCs. It is a major component of smog. (Ontario Ministry of the Environment and Climate Change, 2017)

Traffic relation: The chemical precursors of O_3 are the traffic related pollutants NO_x and VOCs (see chapters 2.3.1 and 2.3.3).

Health risks: O_3 can cause lung and airway inflammation which might alter the performance of an individual. There is also a relation between high O_3 concentrations (exceeding 240 µg/m^3 as average of an 8-hour period) and respiratory morbidity in children (World Health Organization, 2005).

Other sources: The chemical precursors of O_3 are NO_x and VOCs (see chapters 2.3.1 and 2.3.3).

Threshold (WHO): 100 µg/m^3 8-hour mean

2.3.5 Carbon Monoxide (CO)

Description: CO is a colourless, tasteless and poisonous gas. It is primarily produced by incomplete burning processes of fossil fuels (Ontario Ministry of the Environment and Climate Change, 2017).

Traffic relation: Stop-and-go traffic and slow inconstant speeds decrease to efficiency of fuel combustion in vehicle engines and increase the CO emissions (Bellefleur & Gagnon, 2011).

Health risks: CO reduces the oxygen delivery within the blood stream. A high exposure can affect the visible perception, the working capacity and the learning ability (Ontario Ministry of the Environment and Climate Change, 2017).

Other sources: Energy generation and industry.

Guideline (WHO): 30 mg/m^3 1-hour mean; 10 mg/m^3 8-hour mean

2.3.6 Further Pollutants

The list of harmful or even toxic substances which can be dissolved in the ambient air is far longer then the few already mentioned. Some well known representatives of this list are for example Sulfur Oxides (SO_x) and Ammonia (NH_3). As Figure 4 and Figure 5 in the next section will show, their relation to road traffic is insignificantly low (<5 %). Consequently, they will not be discussed in this report. To address the burden of these pollutants, other solutions apart from the ones related to the traffic sector must be found.

2.4 Air Pollutants at a Glance

The topic of air pollution unites a variety of fairly different pollutants. Other than the fact that the pollutants have adverse health effects and can be dispersed in the ambient air, only a few common characteristics can be found. Figure 3 provides a comparative overview of the traffic related air pollutants from chapter 2.3. The characteristics for the comparison are their traffic related generation, their health effects and their WHO AQG thresholds including the averaging times.

	Source	Health	WHO Thresholds
NO2/NOx	Firing of fossil fuels	Lung development for children	40 µg/m^{3*a} 200 µg/m^{3*1h}
CO	Incomplete burning processes; Stop-and-Go traffic	Affected Oxygen delivery in blood &lacks in perception + focus	30 mg/m^3 1h 10 mg/m^3 8h
PM10/2.5	Mechanical processes like abrasion from tires and combustion (especially Diesel)	Blockings in the respiratory tracts	PM2.5: 10 µg/m^3*a; 25 µg/m^3*24h PM10: 20 µg/m^3*a; 50 µg/m^3*24h
VOC/ NMVOC	Incomplete combustion and evaporation from droplets	Precursors of PM and ground level O3, main component of smog	NA
O3	Generated as a secondary pollutant from NOx and VOC and sunlight	Lung and Airway inflammation; respiratory morbidity in children	100 µg/m^3 8h

Figure 3: Air Pollutants Overview

One further important characteristic for the topic of this report is a broad overview of air pollutants and their ratio of road traffic sources compared to all other major sources of emissions. This ratio provides valuable information to allocate the leverage of improvements within each sector. The graphs in Figure 4 and Figure 5 show these ratios for the major pollutants in Canada and Germany.

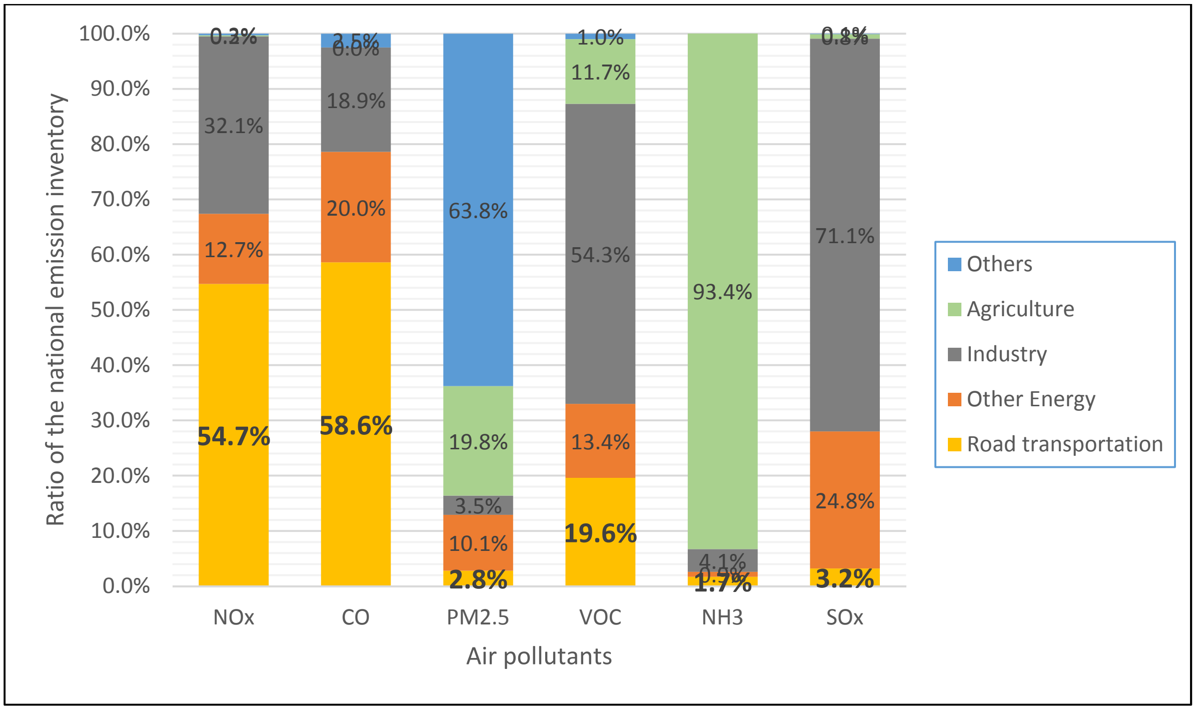


Figure 4: Traffic related air pollution per sector in Canada from 2014 (Environment and Climate Change Canada, 2016)

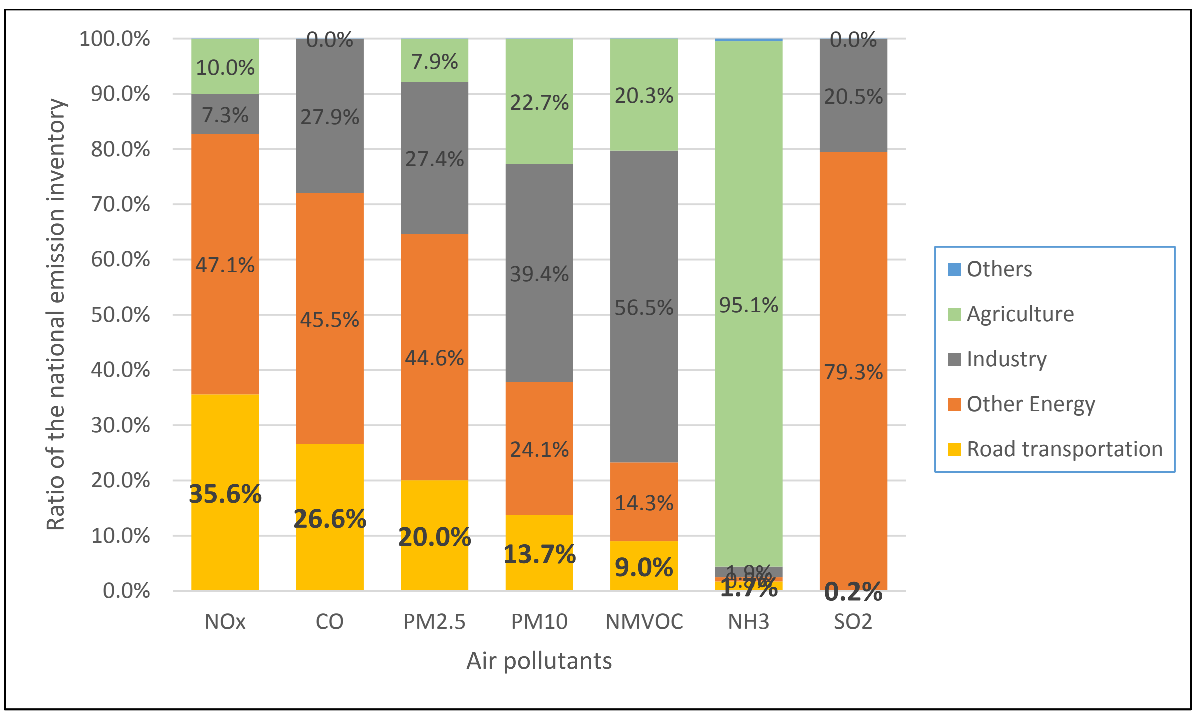


Figure 5: Traffic related air pollution per sector in Germany from 2014 (Umweltbundesamt, 2016)

The variations between the two nations have various backgrounds. One example can be the different composition of the national economies. In particular, the ratio of industrial sources like smelters can strongly affect the overall ratios. Another example is different methodologies to asses and account the sources. The higher ratio of the road traffic contribution for $PM_{2.5}$, in Germany can be explained by the higher rate of diesel fueled vehicles and the consideration of abrasion from tires on the road (Umweltbundesamt, 2016). The factor of tire abrasion in Canada is filed under the category 'Others' (Environment and Climate Change Canada, 2016).

Once the main sectors per pollutant are known, it becomes important to achieve sustainable improvements for each pollutant. The United Nations (UN) have published a toolkit to tackle the issue of urban air quality management. The recommended tools, in case of threshold exceeding emissions, are action plans. These action plans aim for fast and sustainable improvements to meet the emission targets (United Nations Environment Programme, 2006).

An efficient way to reduce the burden of air pollution in urban areas is the application of traffic related measures. Facing the high contribution of the transportation sector to air pollutants in Canada and Germany, it becomes clear that influences on the emissions from vehicles can have a strong impact. Especially fast responding operational measures, like signal coordination, the implementation of new bicycle facilities and other sustainable modes of transportation or road restrictions for trucks and low emission zones, can reduce the emissions to avoid the exceeding of thresholds.

Other air quality improvements in the traffic sector can be accomplished by increasing national standards on behalf of emission levels. Higher requirements for exhaust curing for motorized vehicles for example have a strong long term impact. Nevertheless, these long term, market related developments are not within the scope of this report.

Since urban roads represent a high ratio of public space within a city, their usage and operational requirements must be carefully regulated in the interest of the public. Certain applicable acts and regulations from Canada and Germany are presented in the next chapter.

3 REVIEW OF NATIONAL STANDARDS FROM CANADA AND GERMANY

The far-ranging adverse health effects of air pollutants and the complex trade-off between economic growth requires carefully evaluated regulations. While intergovernmental organizations like the WHO provide important research results and recommendations, the actual plans for action must be derived on a national or lower level of government. Especially for the focus of this report: an analysis of the threats of air pollutants related to the transportation sector and ways to reduce these pollutants by implementing suitable operational measures, the level of action reaches down to the municipalities. Two countries were picked as examples, to display and summarize the corresponding regulations and the level on which they were passed.

One further important point which goes hand in hand with the regulations is an efficient monitoring system to control the execution and the effects of the implemented regulation. A description of the national monitoring systems of the example nations, Canada and Germany, including an example analysis for the pollutant NO_2, will be helpful to understand the choice of certain traffic regulations which will be discussed in the next chapters.

3.1 Canadian Systems

Canada is a constitutional monarchy with the King or Queen of the Commonwealth realm as head of state and its government is based on a parliamentary democracy. The three levels of government are federal, provincial/territorial and municipal (Government of Canada, 2014).

Each of these levels of government have specific responsibilities and are able to pass laws within its range of influence. While the higher levels focus on providing laws of a framework character, the lower levels include more and more specific details.

3.1.1 National: Canadian Environmental Protection Act, 1999 (CEPA)

The Canadian Environmental Protection Act is one of the fundamentals for the protection of the environment in Canada and was passed by the federal government in 1999. In the preface of the act, it is described as:

“An Act respecting pollution prevention and the protection of the environment and human health in order to contribute to sustainable development”

And the first paragraph of its declaration states:

“It is hereby declared that the protection of the environment is essential to the well-being of Canadians and that the primary purpose of this Act is to contribute to sustainable development through pollution prevention.”

These meaningful words from the highest level of government emphasize the importance of the topic of pollution prevention. The whole act addresses a wide field of environmental related topics, which also includes air pollution. The most important paragraphs for the later topic can be found in Part 4 – Pollution Prevention, Part 5 – Controlling Toxic Substances, which includes a definition for pollutants and refers to a list in the appendix of the act where all toxic substances are listed, including the ones from chapter 2.3 of this report. Part 7 – Controlling Pollution and Managing Wastes of the report contributes especially to fuels, vehicle, engine and equipment emissions and international air pollution (Government of Canada, 1999).

Based on the CEPA, the Government of Canada also issued the Canadian Ambient Air Quality Standards (CAAQS). The CAAQS provide Canada wide thresholds for PM2.5 and O3 which are the main contributors for smog and the most significant health affecting pollutants in Canada (Environment and Climate Change Canada, 2013). The thresholds will be intensified over time and are listed in the table below:

Table 1: CAAQS Thresholds (Environment and Climate Change Canada, 2013)

Pollutants	**2015**	**2020**
$PM_{2.5}$ Annual	10 µg/m^3	8.8 µg/m^3
$PM_{2.5}$ for 24-hour	28 µg/m^3	27 µg/m^3
O_3 for 8-hour	63 ppb	62 ppb

To achieve these thresholds, the provinces and territories have to implement actions to reduce their emissions if required (Environment and Climate Change Canada, 2013).

- The Province of Ontario:

The Government of Ontario is aware of the risks of air pollution. It provides for example an air quality health index (AQHI) on its web space. This is a computed index based on the measured concentration of key pollutants like ground level O_3, $PM_{2.5}$ and NO_2. This index provides recommendations about outdoor activities for the population, with respect to the exposure of air pollutants (Ontario Ministry of the Environment and Climate Change, 2017).

3.1.2 Ontario: Ambient Air Quality Criteria (AAQCs) Standard

On the level of acts and standards from the provincial Government is first of all the Ambient Air Quality Criteria (AAQCs) standard to be mentioned. This standard provides thresholds for numerous air pollutants with respect to their different averaging time periods (Ontario Ministry of the Environment and Climate Change, 2012). The provincial thresholds for traffic related pollutants, as discussed in chapter 2.3, are given in the table below, except of a generalized threshold for VOC, which is not listed:

Table 2: AAQCs Threshold (Ontario Ministry of the Environment and Climate Change, 2012)

Pollutant	**Averaging Time**	**Threshold**
CO	8 Hour	13 ppm
	1 Hour	30 ppm
NO_2	24 Hour	200 µg/m^3
	1 Hour	400 µg/m^3
$PM_{2.5}$	24 Hour	30 µg/m^3
O_3	1 Hour	165 µg/m^3
		80 ppb

Compared to the CAAQS, the threshold for $PM_{2.5}$ is less strict. But the date when these standards were issued have to be accounted. In terms of application of these thresholds, the revised Canada wide standard was already applied for recently published local studies in Ontario (Ontario Ministry of the Environment and Climate Change, 2015).

Further acts and standards address the duties for industries to monitor and mitigate their emissions (Government of Ontario, 2016), or determine mandatory emission control test for vehicles (Ontario Ministry of the Environment and Climate Change, 2015). Other regulations corresponding to the air pollution from the transportation sector apparently do not exist. Considering the high contribution to air pollution from the transportation sector, as seen in chapter 2.4, a clear requirement for action plans to take this sector into account by demanding fast responding operational measures is not given at this level of government.

Nevertheless, the province operates a wide-ranging monitoring network for various air pollutants. The 39 ambient air monitoring stations are located at strategically important points to reflect the pollution levels in rural and urban areas and along road-sides in real time. Four of these monitoring stations are located in Toronto (Ontario Ministry of the Environment and Climate Change, 2017).

- The City of Toronto:

Toronto is the largest city in Ontario and even in Canada. It has approximately 2.8 million residents, a high cultural diversity, a prospering economy and a high expected growth rate for the next decades (City of Toronto, 2017). The area and the city districts of Toronto can be seen in Figure 6. Toronto is located on the shore of Lake Ontario, one of the Great Lakes in North America. The position mark 'Kennedy Road & Lawrence Avenue East' in the figure represents the air quality monitoring station Toronto East, which will be referred to in chapter 4.3.

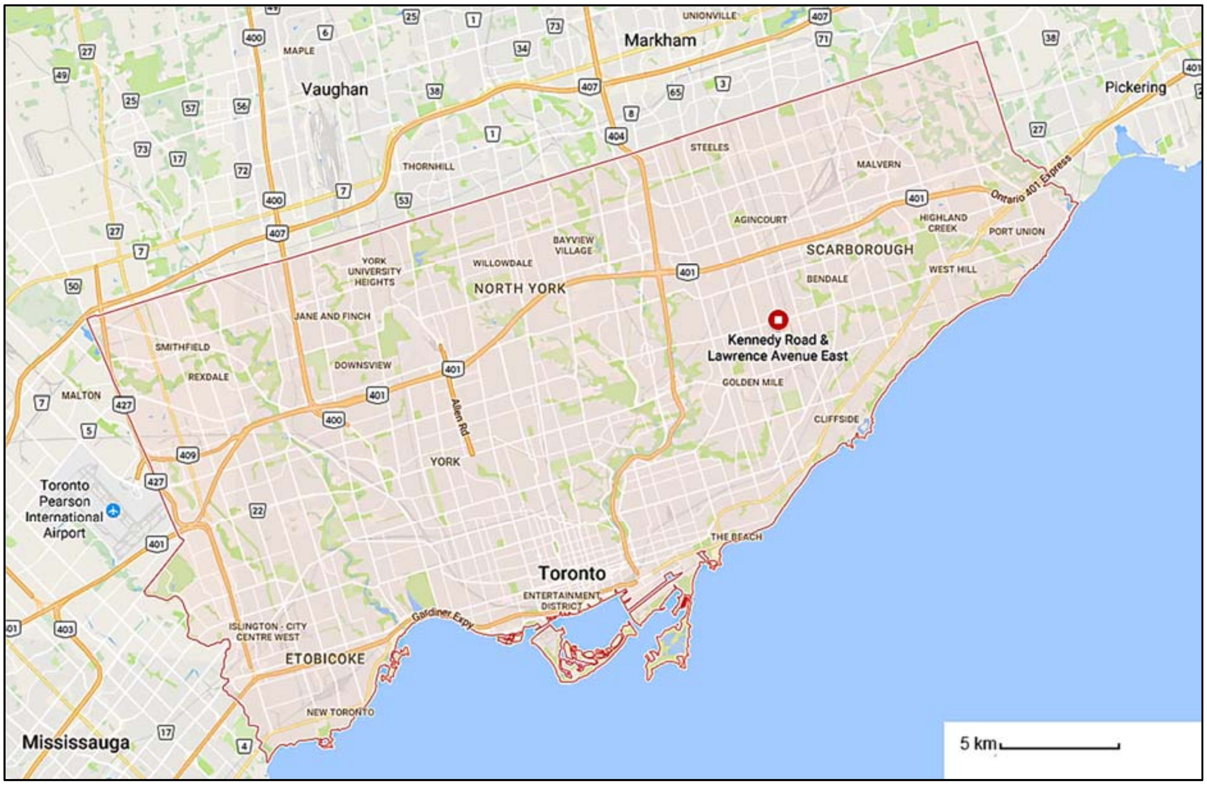


Figure 6: City of Toronto

To provide a healthy and progressive environment, the level of air pollution is one of the important factors which the city can influence and improve. Another important aspect for the quality of live for the people and the economy is the transportation network and its ability to satisfy the need of transportation. Since these two objectives are closely related, it is among the responsibilities of the municipality to conduct risk assessments and to find reasonable trade-offs between both interests.

3.1.3 Toronto: Climate Change, Clean Air and Sustainable Energy Action Plan

The City of Toronto has published a climate change, clean air and sustainable energy action plan, back in 2007. This plan formulates the encouraged goal to reduce the air pollution level (Toronto Energy Efficiency Office, 2007):

> *'The reduction target for locally generated smog causing pollutants is 20%, from 2004 levels, by 2012 for the Toronto Urban Area.'*

The suggested actions to reach this goal are on the one hand linked to programs like greening the city with new vegetation to enhance the fresh air circulation and dispersion of air pollutants to reduce their concentrations. On the other hand, measures that reduce the emission of smog related pollutants at the first place are promoted as well. These measures focus on transportation related measures, since this sector has a high potential for short-term projects to accelerate the achievement of a lower air pollution level (Toronto Energy Efficiency Office, 2007). Some of these short-term projects initiated by this action plan and further traffic related measures applied in the city will be discussed in chapter 5.1. The action plan itself only outlined the topics and fields of possible improvements, but did not state any details of the applicability or impacts of these.

3.1.4 Toronto's 2012 Greenhouse Gas and Air Quality Pollutant Emissions Inventory

The latest report from the municipality to address the topic of air pollution is a pollutant emissions inventory report from 2014, discussing the evaluated datasets from 2012. The results of this report state that the encouraged goal of reducing the air pollution from 2004 by 20% until 2012 has failed. The evaluated reduction merely accomplished a decrease of 2.8% (Chief Corporate Officer, 2014).

However, this result is based on a vague assumption. Due to a lack of updated air pollution emissions from the transportation sector, the used datasets of this major source remained unchanged from the last evaluated datasets from 2008. Considering the fact, that approximately 80.5% of the air pollutant emissions are generated from cars and light trucks (35.5%) and heavy trucks (45%), this missing data update denies a reasonable evaluation.

The latest emission inventory report from the municipality from December 2015 therefore only discussed the topic of green house gas emissions. Updates for the air pollution emissions from the transportation sector were still missing (Chief Corporate Officer, 2015). Despite of well known statistics of the pollution levels at the monitoring stations, the inventory reports are based on theoretically calculated emissions from each sector. According to a letter from the Director of Policy and Programs of the Toronto Atmospheric Fund (Purcell, 2016), the grief issue in this case is based on the missing information from understaffed transportation services. Given this headache, the design and tailoring of precisely targeted measures in the transportation sector are not yet possible.

3.2 German Systems

Germany is a federal state, consisting of 16 Federal Laender, with a parliamentary democracy. The Federal Parliament passes laws that are applicable for the whole state and passes regulations that have to be adapted by the Federal Laender, but can be influenced according to their local requirements (Federal Office for Migration and Refugees, 2016).

3.2.1 National: Federal Immision Control Act (BImSchG)

The most important law on behalf of air pollution in Germany is the Federal Immision Control Act (ger.: Bundes-Immisionsschutzgesetz). The purpose of this Act is to protect human beings, animals, plants and the environment. It addresses the mitigation and avoidance of harmful emissions like noise, vibration, greenhouse gases or air pollution. Furthermore, it states the responsibilities of the executive powers, the inclusion of the public in decision making processes and the requirements for measuring and monitoring emissions. One of its main principles in mitigating and avoiding emissions is to target the sources according to their ratio of contribution to certain pollutants. This principle is also known as the polluter-pays-principle (Bundesministerium der Justiz und für Verbraucherschutz, 2013).

The BImSchG is a base law and covers environmental issues in breadth. To specify on certain topics and limitations in depth, like thresholds for the pollution from certain sources, it legitimates the Federal Government to pass administrative regulations. These regulations have to be made under the consideration of all parties of interest. Furthermore, the threshold levels for immissions have to protect the environment, the emission thresholds have to be achievable by using the current state of the technology. Besides the thresholds, these regulations also have to provide certain monitoring standards to control the emissions and immissions.

On behalf of the responsibilities for the executive powers, the act specifically demands a monitoring, based on the regulations provided in the additional administrative regulations. In case of exceeded thresholds, special action plans to sustainably reduce the immissions are required.

3.2.2 National: 39th Federal Immission Control Ordinance (39. BImSchV)

The 39. BImSchV is one of the administrative regulations described in the prior section. Its focus are air quality standards and emission thresholds. Among the first named, thresholds for immissions on an ordinary level and for dangerous alarm levels (A) are given for a variety of pollutants. The immission thresholds for the traffic related pollutants, as discussed in chapter 2.3, and their corresponding averaging times are given in Table 3.

Table 3: 39. BImSchV Pollutant Thresholds, Germany (Bundesministerium der Justiz und für Verbraucherschutz, 2013)

Pollutant	**Averaging Time**		**Threshold**
CO	8 Hour		10 mg/m^3
	1 Year		40 $\mu g/m^3$
NO_2	1 Hour	(18 exceeds per year)	200 $\mu g/m^3$
	1 Hour	(A)	400 $\mu g/m^3$
PM_{10}	24 Hour	(35 exceeds per year)	50 $\mu g/m^3$
	1 Year		40 $\mu g/m^3$
$PM_{2.5}$	1 Year		25 $\mu g/m^3$
O_3	8 Hour		120 $\mu g/m^3$
	1 Hour	(A)	240 $\mu g/m^3$

The 39. BImSchV does not provide a generalized threshold for VOC. Another specialty in the German regulation is the permission to exceed the thresholds of certain pollutants, here PM_{10} and NO_2, several times per year. These exceptions might have been granted due to special occasions like the first days of the school holidays that cause a strong increase of the traffic volumes, or New Years Day which is affected by high concentrations of air pollutants due to fireworks. The number of granted exceeds might help to avoid serious issues and conflicts with the environmental laws on these otherwise joyful days and might prevent a worsen image for the traffic or the environmental laws, depending on the point of interest.

3.2.3 Baden-Württemberg

The point of execution of the 39. BImSchV is at the Federal States of Germany. In the Federal State of Baden-Württemberg for example, the State Institute for the Environment, Measurements and Nature Conservation (ger. Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg; LUBW) is responsible for operating the state-wide monitoring system and to consult and coordinate the four Administrative Districts. The four Administrative Districts are in charge to issue clean air action plans.

- The City of Karlsruhe:

The City of Karlsruhe is a mid-sized city in the south west of Germany, close to the French boarder and along the River Rhine. It is a part of the Administrative District Karlsruhe and the third largest city in the Federal State of Baden-Wuerttemberg. Among its population of approximately 300,000 residents is a high ratio of students from the technical faculties, a specialty of the city. Two famous inventors who changed at least the world of transportation were born in Germany. There were on the one hand Karl Drais (1785-1851), the inventor of the 'Draisine', an early form of the bicycle, and on the other hand Karl Friedrich Benz (1844-1929), the inventor of the Motorcar, the first modern automobile (Stadt Karlsruhe, 2017). The area and the city districts of Karlsruhe can be seen in Figure 7. The position mark 'L605' in the figure represents the air quality monitoring station "Rheinhold-Frank-Strasse" which will be referred to in chapter 4.4.

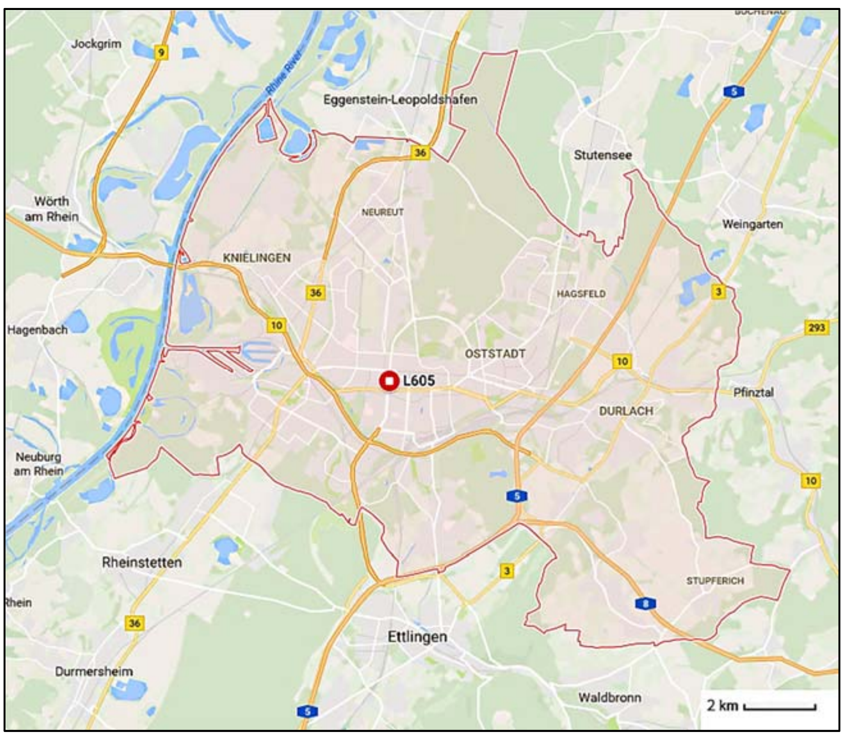


Figure 7: City of Karlsruhe

3.2.4 Karlsruhe: Clean Air Action Plan Karlsruhe

As a consequence of air quality measurements from 2002 to 2004, the City of Karlsruhe became the target of a clean air action plan in March 2006. As described in section 3.2.1, this was necessary due to exceeded threshold levels. The critical air pollutants in the city are NO_2 and PM_{10}. To reduce these critical pollutants, the clean air action plan provides a list of almost 20 measures for a sustainable improvement of the air quality. Some of these measures aim to reduce the air pollution levels within the whole city, some others aim for a reduction specifically at the location of the worst measurement results, close to the stationary monitoring station Rheinhold-Frank-Strasse.

The described measures are of various kinds and rang from improvements of the city fleet to route limitations for trucks and a low emission zone with restricted access for vehicles that do not meet certain exhaust standards. Other measures aim for sustainable long term developments like new cycling facilities and an improved public transit to motivate a mode shift of the commuters. Some of these measures will be selected for a detailed discussion in chapter 5.2.

A first and a second update of the action plan was published in 2008 and 2012. The updated results of the air quality monitoring assigned first improvements, but did not yet meet the thresholds of 39. BImSchV. In the meantime, some of the thresholds were even tightened due to new gained knowledge of the adverse health effects of air pollution. The updates for the action plan re-evaluated some of the old measures and partially increased their limitations. Also, new measures were added while the old measures from the first action plan were still active. The development of the key air pollutants, NO_2 and PM_{10}, for the city of Karlsruhe are analyzed in the next section.

4 ANALYSIS AND MONITORING OF CRITICAL POLLUTANTS

4.1 Inventory of Pollutants

A common approach for governments to gain knowledge about their pollution levels is the computation of pollution inventories. These inventories are based on mathematical models to evaluate the overall mass of emitted pollutants. This requires information of overall fuel burning or other processes that generate pollutants from the main sectors like energy, traffic, agriculture, etc. The accumulated results from all sectors provide a valuable knowledgebase to determine the ratios for these sectors and to allocated reduction targets. This approach is useful to reduce emissions, but lacks in spatial precision, since only the main polluters are take into concern. Local pollution sources like fire wood heating in single houses or the effects of traffic cannot be located with this approach to predict reliable immission levels for roads or neighborhoods (Inner City Fund International, 2007).

4.2 Monitoring Systems

Monitoring stations for the composition of ambient air provide a detailed knowledge of pollutant concentrations at their specific spots. This is a valuable information since pollutant distributions within the ambient air and their dispersion and deposition are hardly predictable, even with the advanced modelling techniques that are available nowadays. With variables like local weather conditions (wind, temperature, humidity) and a mix of stationary and instationary pollutant sources like chimneys or exhaust pipes, a simple spot measurement still provides the best information of local immissions (Crouse, Goldberg, & Ross, 2009).

A strategic positioning of these monitoring stations can help to gain more information about the correlation of pollutant sources and their affected immission area. For example, monitoring stations with a road proximity provide predominantly information about vehicle emissions etc. Another advantage of spot measurements is gain detailed knowledge of the total immissions from various sources, to ensure that environmental and health related standards, as discussed in chapter 3, are meet. This applies especially in urban areas where a lot of different sources accumulate the pollution levels (Ontario Ministry of the Environment and Climate Change, 2017).

4.3 Analysis Example of Smog Related Pollutants in Toronto, Canada

In addition to annual inventory reports, a careful monitoring of the current air pollution is one of the keys to react to adverse health effects from these and also to prevent the exceeding of thresholds. A real time monitoring is required to trigger smog alerts and other warnings, especially for the vulnerable groups among the population. Furthermore, it enables short-term actions to reduce the pollutions.

As an example of the possible analyses from monitoring data sets, the air quality monitoring station with the closest proximity to a major road in Toronto was picked. It is located in Scarborough, an eastern district of Toronto. The exact location close to the intersection of Lawrence Avenue East and Kennedy Road can be seen in the maps below (Figure 8).

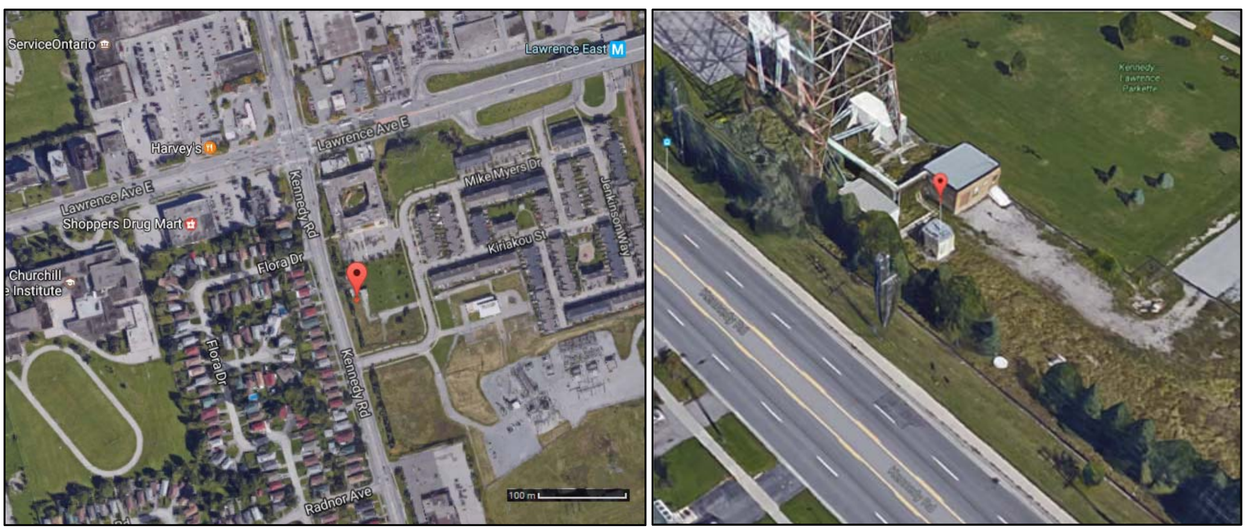


Figure 8: Air Quality Monitoring Station Toronto Downtown

As Figure 8 shows, a stripe of vegetation like trees and bushes shield the monitoring station from the road. According to (Janhäll, 2015), the measurement of pollutants emitted from the road traffic and immitted at this monitoring station might be influenced by the vegetation. This influence however will not be taken into account while analyzing the monitoring data. Compared to the three other stationary monitoring locations, the chosen one still provides the best representation for traffic related pollutants.

To conduct an analysis of the air pollution concentrations which were measured at the monitoring station Toronto East, only the pollutants of local concern were chosen. These are the traffic related pollutants NO_2 and $PM_{2.5}$ as well as the secondary pollutant O_3. The analysis year 2004 was chosen as it is the reference level of the Climate Change, Clean Air and Sustainable Energy Action Plan. The year 2012 was the dedicated goal line to achieve the proposed reduction plans of the action plan and 2016 is the most recent already completed year at the time of this analysis.

The historical data of these pollutants is available as comma separated values files (csv) which are supported by MS Excel®. These files contain general information about the monitoring station like its location, a specific station ID, the air intake height or the measuring unit and pollutant name. The pollution data is listed as hourly concentrations. The layout of an example spreadsheet can be found in Appendix 1. To prepare the spreadsheet for the analysis, the comma separation was rearranged into several columns. The columns in the spreadsheet provide the hourly concentrations and the rows contain the dates of the analysis period.

To simplify the analysis a Visual Basic for Applications (VBA) tool was coded to write the triplet of date, hour and pollution concentration into three columns, each row representing one hour. The code of this tool can be found in Appendix 2.

To achieve comparable results between the different years, only the most recent thresholds were used to gain knowledge over the exceeded pollution levels. The averaging times of 8 hours and 24 hours always refer to one calendar day. In case of the 8 hours' average, a moving average over the daytime was computed with the constraint of maximum one exceeding result per day. This constraint for the moving averages was implemented in another VBA tool (see Appendix 3). The 24 hours' average covers the calendar day from midnight to midnight. The averaging and the comparison with the thresholds was processed by using basic MS Excel® tools.

The results of the analysis are given in Table 4.

Table 4: Pollution Analysis Toronto East

Pollutant	**Averaging Time**	**Threshold**	**2004**	**2012**	**2016**
NO_2	24 Hour	200 µg/m³ 101 ppb [1)]	0	0	0

	1 Hour	400 µg/m³ 202 ppb [1]	0	0	0
$PM_{2.5}$	24 Hour	28 µg/m³ [2]	10	0	1
	1 Year	10 µg/m³ [2]	≈ 7.3	≈ 6.1	≈ 6.9
O_3	1 Hour	165 µg/m³ 80 ppb	2	12	4
	8 Hour	63 ppb [2]	6	20	12

1) The unit conversion is based on an average temperature of 10°C and was computed with an online tool (Natural Environment Research Council (NERC), 2013).
2) The threshold values of the more recent CAAQS were used for all corresponding years

The evaluated monitoring data show some clear improvements for $PM_{2.5}$. The daily averaged exceeding of the recently installed 28 µg/m³ threshold was reduced from 10 times per year to 0 or 1 for the other analysis years. The annual average levels were alternating with an overall reduction tendency. The averages from all years were 27 to 39 per cent below the threshold level. This is a strong indicator that $PM_{2.5}$ is not a constant problem, but might be harmful in combination with special weather statements on a couple of days per year.

The pollutant was not critical at this station. In none of the three analyzed years was neither the daily nor the hourly threshold violated.

In contrast to the other pollutants, the amount of dispersed O_3 in the air around the monitoring station has an increasing tendency. Both given averaging periods assign a higher number of exceeding with factors from two to six times compared to the reference year 2004. This high factor nevertheless is only the consequence of the few exceeding overall in 2004. Since O_3 as a secondary pollutant is dependent on VOC and NOx concentrations and sunlight, the local weather conditions should be included in order to allocate the reasons for the increasing number of exceedance. This step was not accomplished in this report since O_3 is only indirectly effected by traffic.

An interesting finding of the analysis supports the fact, that O_3 is generated in the combination with sunlight. The hours covered by the moving average window to compute the 8 hour mean with threshold exceedance in 2012 all start in the morning period between 7:00 to 11:00 am as the histogram in Figure 9 shows.

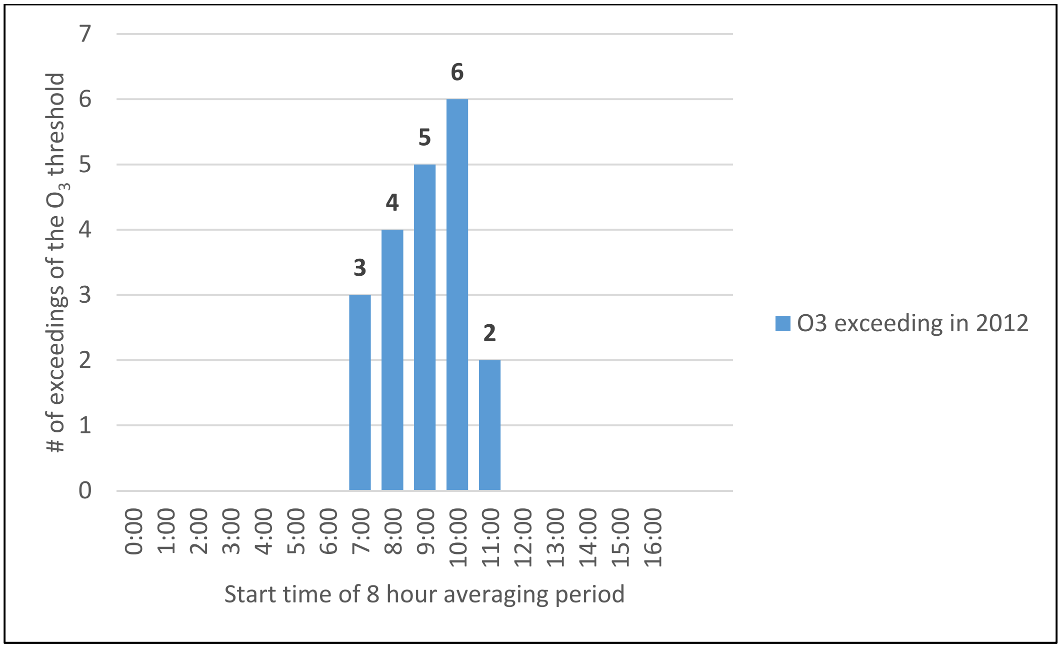


Figure 9: O_3 exceeding start times for 8-hour mean

The timeline of the histogram stops at 4:00 pm, since the 8-hour averaging period is only to be analyzed within one calendar day. Adding the corresponding 8-hour intervals to the start time distribution of the 20 analyzed averaging periods, the times of highest sunlight intensity around the early afternoon are covered (Lin, Yu, & Chang, 2014). Another supporting aspect is that all 20 exceeds in 2012 are during the second half of spring and the summer month. The exceeding dates are from mid May to late August.

One last part of the analysis addresses the occurrence of smog. The two main contributors of this noxious mixture of gases are O_3 and PM (Environment and Climate Change Canada, 2014). Given the analysis year 2004, when both analyzed pollutants exceeded their thresholds several times, the dates of the individual exceeds were compared in Table 5.

Table 5: Dates of $PM_{2.5}$ and O_3 threshold exceedance in 2014

Date	**$PM_{2.5}$ 24-hour avg.**	**O_3 8-hour avg.**
12.05.2004		x
13.05.2004	x	x
14.05.2004	x	
07.06.2004	x	
08.06.2004	x	x
21.07.2004	x	x
22.07.2004	x	
26.08.2004	x	
27.08.2004	x	
04.09.2004	x	x
15.09.2004	x	
23.09.2004		x

The result is a critical correlation between both pollutants. On four out of six days with thresholds exceeds from O3, the PM2.5 threshold was violated as well. This indicates a high risk for smog. The actual occurrence of smog events is based on more components and can not be derived from these two pollutants only. This further analysis is not part of this report, but could be accomplished based on the same methodologies derived for the conducted analysis.

Overall, this example analysis of the critical pollutants for the City of Toronto in important years provides a first insight to the complexity of this topic and some indicators for the current state of air pollution in the City of Toronto. To derive significant findings and to predict air pollution trends, additional analysis steps and the inclusion of more data would be required. Still, the here derived findings are not in conflict with the common research results of the last decades and therefore support these works.

4.4 Analysis Example of NO_2 and PM_{10} Concentrations in Karlsruhe, Germany

To conduct an analysis of the air pollution concentrations at the monitoring station Karlsruhe Road, only the pollutants of local concern were chosen. These are the traffic related pollutants NO_2 and $PM_{2.5}$. The analysis year of 2006 was chosen as it is the first year with an active clean air action plan. The year 2012 represents the year of the latest update of the action plan and 2016 is the most recent already completed year at the time of this analysis. The location of the monitoring station is just next to the curb of the arterial road ‘Rheinhold-Frank-Strasse’ and its close surroundings can be seen in Figure 10.

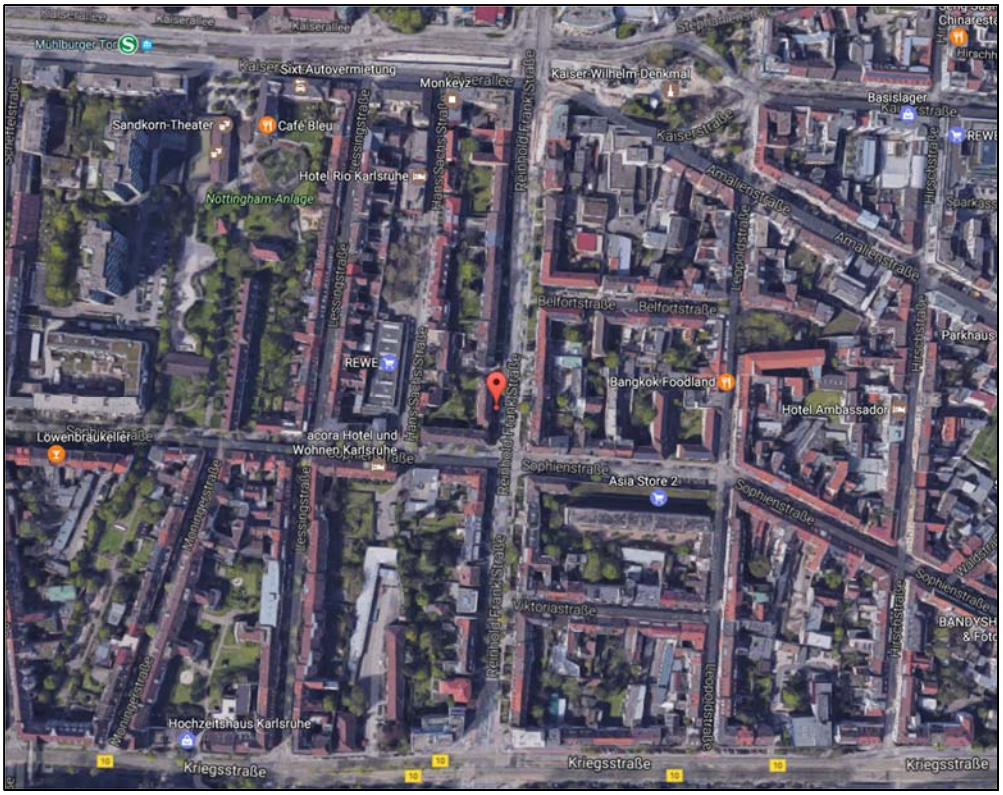


Figure 10: Monitoring Station Rheinhold-Frank-Strasse

The historical data of these pollutants is available in the format of automatically generated MS Excel® spreadsheets, published by the LUBW. These spreadsheets contain general information about the monitoring station like a specific station ID, the measuring unit, averaging period and pollutant name. The pollution data is listed with averages depending on the lowest time resolution requested for the threshold comparison in 39. BImSchV. The particulate matter for example is only available in 24 hour average periods, representing calendar days. All datasets for one averaging period are listed underneath each other. The layout of an example spreadsheet can be found in Appendix 4.

To achieve comparable results between the different years, only the most recent thresholds were used to gain knowledge over the exceeded pollution levels. The averaging and the comparison with the thresholds was processed by using basic MS Excel® applications and a VBA tool like the one in Appendix 3 with minor adjustments of cell links and under the consideration of the new averaging periods. The results of the threshold analysis are given in Table 6.

Table 6: Analysis Results Karlsruhe

Pollutant	**Averaging Time**	**Threshold**	**2006**	**2012**	**2016**
NO_2	1 Year	40 $\mu g/m^3$	52.8	49.6	37.8
	1 Hour (18 exceeds per year)	200 $\mu g/m^3$	0	1 (0)	0
	1 Hour (A)	400 $\mu g/m^3$	0	0	0
PM_{10}	24 Hour (35 exceeds per year)	50 $\mu g/m^3$	36 (1)	8 (0)	1 (0)
	1 Year	40 $\mu g/m^3$	29.9	21.8	18.6
$PM_{2.5}$	1 Year	25 $\mu g/m^3$	NA	NA	12.7

The analysis results show a clear reduction trend for both pollutants. The annual average concentration of NO_2 and PM_{10} decreased by approximately one third within the decade from 2006 to 2016.

The NO_2 threshold for the hourly averaging period was only exceeded once in 2012. This exceedance however is not critical, since the German 39. BImSchV allows up to 18 exceeds per year for this pollutant before reduction measures are required. The annual average for this pollutant is in contrast more critical. The threshold of 40 $\mu g/m^3$ was only in the last analysis year not violated. Since it is an annual average, a systematic reduction of this pollutant was required to accomplish this achievement.

Less problematic was the measured PM_{10} concentration. The annual average was already in the first analyzed year more the 25% below the threshold level. In 2016 were the annual averages for PM_{10} and the added measurements of $PM_{2.5}$ approximately on a 50% level of the allowed values. The daily thresholds still assign a few exceeds per year, but except of 2006, the 35 allowed exceeds of the corresponding regulation were not violated.

Additional to the threshold analysis, a plot of the hourly concentrations of NO_2 on the day of exceedance in 2012 was generated and is given below in Figure 11.

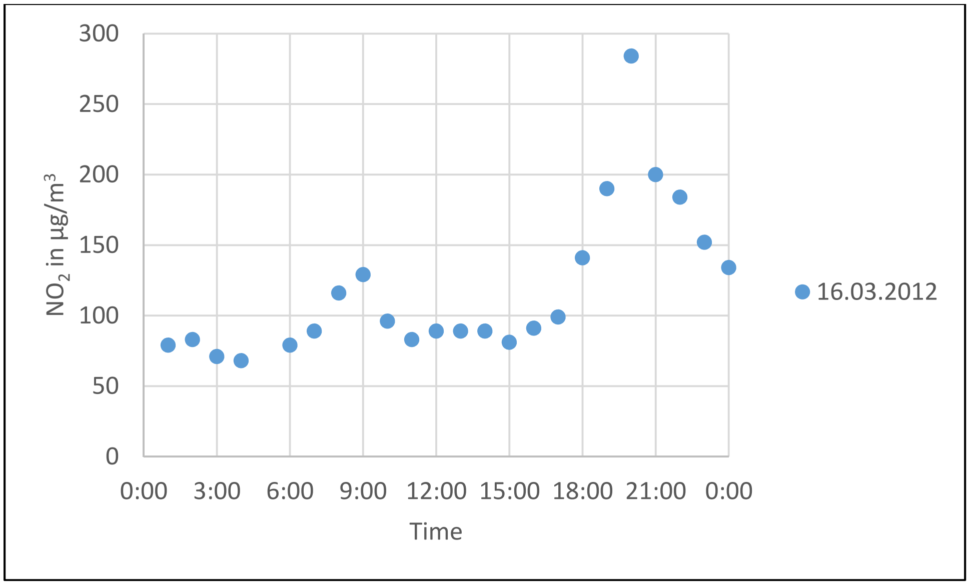


Figure 11: NO_2 hourly plot of concentration values

This type of plot displays the strong traffic relation of NO_2. The morning peak hour, typically between 7:00 to 9:00 am is clearly represented in the plot. The late evening peak after 6:00 pm on this day is related to a high volume of recreational traffic on this route. The Rheinhold-Frank-Strasse is one of the access routes to the downtown area of the city and also a connector to a big sports venue. Hence, a special event might be a good explanation of the unusually high evening peak which led to the threshold exceeding on this Friday in 2012. A research in the local news archive did even provide two special events. On the one hand was a football match of the local team on this evening, on the other hand was this Friday the first day of the Easter school vacations (ka-news GmbH 2017, 2017).

Overall, the air pollution at this monitoring station shows a strong improvement. This improvement was accomplished by applying a lot of traffic related measures in this important arterial road and its surroundings. Some of these measures will be discussed in section 0, in the next chapter.

5 BACKGROUND OF AIR QUALITY RELATED TRAFFIC OPERATIONS

In this chapter, a variety of traffic operations which affect air quality and the exhaust of emissions from vehicles will be introduced. The chosen methods are currently applied in Toronto, Canada and Karlsruhe, Germany. In a general background section, key statistics of the transportation sector will be provided for a better understanding and comparison of the local differences of both cities.

5.1 Background of Air Quality Related Traffic Operations in Toronto

The City of Toronto with approximately 2.8 million residence has to satisfy an immense traffic demand (City of Toronto, 2017). An overview of the modal split for all commuting trips in Toronto in 2006 is given in Figure 12.

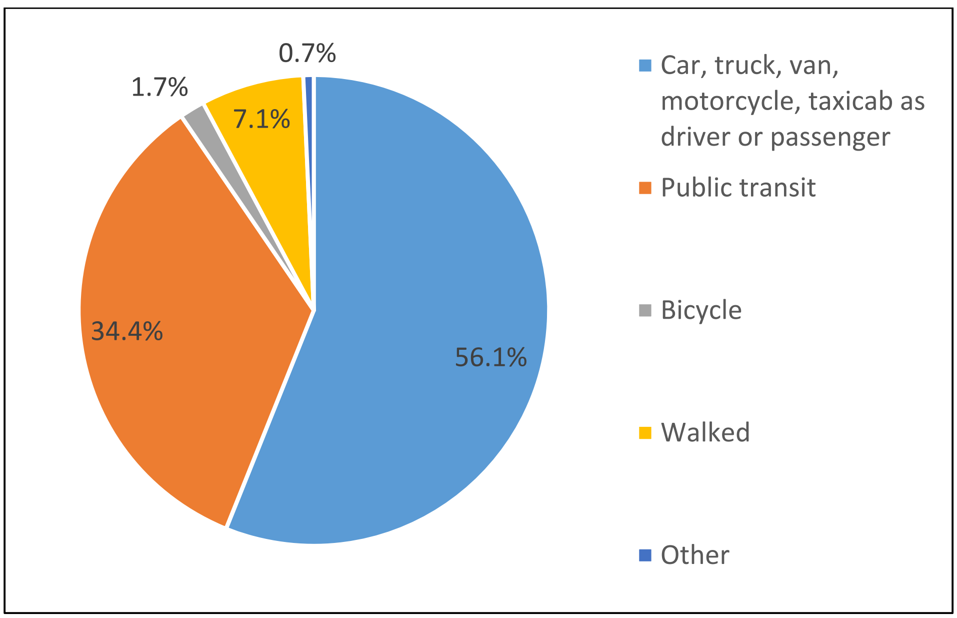


Figure 12: Modal Split of Trips - Toronto – 2006 (City of Toronto, 2015)

The majority of trips, done by almost 1,2 million commuters, were travelled with motorized individual vehicles in 2006. The public transit sector had a strong one-third mode share out of all trips and the active modes of transportation like walking and cycling made up less then 10% of all commuting trips.

The base year of 2006 represents the most recent statistics published by the City of Toronto. Although more recent statistics from Statistics Canada, based on the census data from 2011, are available for the modal spilt, this year was chosen to achieve a consistency with the other datasets in the following overview. On behalf of the mode share, no major changes between 2006 and 2011 for the overall mode share were assessed. The changes per mode were less than 2% between 2006 and 2011 (Statistics Canada, 2013).

The total emissions of the criteria air pollutants NO_x and total particulate matter (TPM) which were evaluated for the reference year 2004 of the Toronto Climate Change, Clean Air and Sustainable Energy Action Plan are given in Table 7. The TPM describes all particles of fine and coarse matter, commonly called dust. The annotation 'total' means that road and tire abrasion effects are included in the inventory values.

Table 7: Traffic contribution to the emission inventory, Toronto 2004 (Inner City Fund International, 2007)

Pollutants	**Total Inventory (tonnes)**
NO_x	26,519
TPM (total)	767

The emission inventory is computed with a theoretical model, based on the total vehicle kilometers travelled within the city and a set of different pollution classes for the vehicle categories. The average emissions per vehicle class and kilometer are given in Table 8.

Table 8: Emissions per vehicle class and kilometer, Toronto 2004 (Inner City Fund International, 2007)

Vehicle Class	**NO_x (g/km)**	**TPM (Total) (g/km)**
Passenger Car - Diesel	0.552	0.080
Passenger Car – Gas	0.502	0.016
Heavy Duty Vehicle	4.887	0.135
Others (Light trucks, motorcycles)	0.728	0.020

The emissions per vehicle class and kilometer values can be used to estimate the efficiency of the following measures. Due to the outdated fleet composition and the increased emission standards, these values might have been reduced considerably. A comparison of the development of vehicle emissions per kilometer from Germany between 2003 and 2012 has already caused a decreased emission of NO_x of approximately 40% for gasoline fueled passenger cars and 50% for heavy duty vehicles. The emissions for TPM were even reduced by three quarters for passenger cars, both diesel and gasoline fueled and for heavy duty trucks were even reductions of up to 85% accomplished.

An overestimation of the efficiency with the Canadian values is therefor likely, but still provides a rough scale of measurement.

5.1.1 Cycling - Promotion and Facilities

The first alternative in planning emission reductions should always be their avoidance. Given the potential of active modes of transportation like walking or cycling, this alternative is at least partially given. The implementation of cycling facilities like cycle lanes or cycle tracks provides higher safety levels for cyclists and improves the comfort of riding a bicycle, in particular in urban areas. The City of Toronto has already done a lot to provide new cycling facilities and to promote cycling as a mode of transportation with a lot of benefits. The development plan of the City of Toronto was published in 2001 with ambitious targets. The development of a cyclist friendly environment in the city should be carried by six spokes (City of Toronto, 2001):

- Bicycle Friendly Streets
- Bikeway Network
- Safety and Education
- Promotion
- Cycling and Transit
- Bicycle Parking

One of the goals of the plan was to implement a 1,000 km bikeway network. Back in 2001, only 166 km of this network did already exist. A statistic from 2014 stated an overall network length of 848 km. This is an increase of over 50 km per year. Despite of this strong development, the response from the population is moderate at best. The overall cycling mode share among the commuters is still around 2%. But there are high variations between the city districts and neighborhoods. In some areas, the cycling mode share even reaches up to 20% (City of Toronto, 2015).

Cycling has a lot of benefits to strengthen a sustainable city development. A great advantage for the dense downtown cores is the reduced space need to park bicycles compared to other vehicles. Another important factor are the smaller dimensions of cycle lanes (1,50 m) compared to general purpose lanes, their high capacity to accommodate up to 2,000 cycling trips and the low costs if they can be realized by a simple restriping of the given roadway (City of Toronto, 2001).

In terms of air pollution, cycling has multiple positive effects. On the one hand, new generated cycling trips do not produce additional air pollution and on the other hand can car trips be converted to cycling trips. In particular short distance car trips of less than 5 km distance have a high likelihood to be converted once an improved environment for cyclists is provided. For these distances, the bicycle is considered the fastest mode of transportation for a whole trip from door to door, since the access times of bicycle and the required time to find a parking spot are usually less then for other vehicles (City of Toronto, 2001). These short distance trips are also considered to cause significantly higher air pollution then medium and long distance trips due to engine warm up periods that influence the effectivity of fuel burning processes (de Nazelle, Morton, Jerrett, & Crawford-Brown, 2010).

A recently conducted study to analyze the effects of a new cycle lane in Toronto has shown the high potential of substituting car trips with cycle trips. The Bloor Street West bike lanes were established in August 2016 in a cyclists' friendly neighborhood. The arterial road with two lanes in each direction was converted to a road with one lane in each direction, a cycle lane and on-street parking facilities between the cycle lane and the traffic. To ensure a high traffic flow performance, the road was widened up at the intersections by prohibiting the on-street parking to provide turning lanes for the motorized vehicle traffic (City of Toronto, 2017).

The study results have shown an increase of 36% of cycle trips to a total volume of 4,500 trips per day. As a consequence of the new road design and the increased cyclist rate, the motorized vehicle volume was reduced by 22% to 20,000 vehicles per day (City of Toronto, 2017). Assuming an average trip length of 3 km of the reduced 4,500 vehicles, Table 9 provides an estimation of the total air pollution reduction. An additional assumption was that only passenger cars were substituted by the increased number of cyclists and that the data represent an average day.

Table 9: Effect of Bloor St W bike lane

	NO_x [t]	TPM [t]
Vehicles	4500	
Distance [km]	3	
Days in the year	365	
Passenger Car - Gas	2,47	0,08
Inventory reduction (t/a)	2,47	0,08
Ratio of City inventory	0,01%	0,01%

The estimated reduction of 2.5 tonnes of NOx and 80 kg of TPM is only a minor effect for the city wide emission inventory, but considering the desired network of 1000 km bike ways in the city, this effect has a strong multiplicator. Since the bike lanes were also just recently implemented, an increase of cyclists who follow up this new trend is still likely.

Overall, the implementation of cycle lanes has only low, or medium costs, dependent on the required work. Between restriping as the cheapest alternative up to a widening of the road as the costliest alternative is a wide margin. The investment in cycle lanes has a good payoff for a city, since it reduces not only harmful pollutants for all residents but also improves the safety standards for the cyclists.

5.1.2 Improvements of Transit

A strong public transit is an important instrument to move a high number of people in an efficient way. It provides people without an own car the ability to commute long distances and helps to reduce the monetary costs of commuting, compared to private cars considering their full costs, including gasoline, insurance, payoff, etc. .

The main improvement on behalf of traffic, related to the public transit, is the reduced road surface space per person. A common transit bus only requires the road space of two passenger cars but can move up to 50 people (Toronto Transit Commission, 2017). Other alternatives like track based streetcars, LRT or subways can even multiply this factor of persons per vehicle. Considering modern approaches of signaling with the focus on reducing the personal waiting times, a transit priority at signals can speed up the various forms of transit on the street level. An advanced signaling can also speed up the subway. Currently a new form of signals is installed to replace the old block distance system to reduce the headway between subways. This automatic train control (ATC) system will enable a capacity increase of 25% by 2019 (Thompson, 2016).

These forms of speed improvement have two positive effects for the public transit. On the one hand, the travel time for a trip will be reduced and the service gains competitiveness compared to other modes of transportation, on the other hand, a higher capacity of transit vehicles can be realized with reduced headways. This is especially for transit services which suffer from peak hour congestions like the downtown subway lines important.

Estimating a 25% increase of the number of subway users due to the unlocked capacity improvements, this could take up to 50 million vehicle trips from the road per year. Table 10 shows the impacts of this estimation, under the consideration that only passenger cars will be substituted for average trip length of 5 km.

Table 10: Effect of ATC for subways

	NOx [t]	**TPM [t]**
Vehicles	50,000,000.00	
Distance [km]	5	
Passenger Car - Gas	125,50	4,00
Inventory reduction (t/a)	125,50	4,00
Ratio of City inventory	0,47%	0,52%

This massive reduction of car trips could reduce the air pollution for the City of Toronto by approximately 0.5%. Since the subway only consumes electricity, a direct air pollution along the route can be avoided. On behalf of the city-wide inventory, the air pollution caused by electricity production will still have a certain offset.

The implementation costs for the ATC are certainly high, but promise an even higher payoff due to reduced operational costs of this automated system. The efficiency on behalf of the air quality improvement can be considered good, despite of the high capital expenditures, the reduction effects are likely to take place where a lot of people live, close to the subway station, which reduces the exposure for a lot of people.

5.1.3 Coordination of Signals, Evaluation of the City-wide Improvements between 2012-2015

At the 2,300 traffic signals in the City of Toronto are 50 human live spans wasted every year from people who are waiting for a traffic light to turn green and to continue their journey. This massive delay time is one of the downsides of the high traffic demand which requires signalization and coordination to flow. The implementation of traffic signals at junctions helps to increase this flow by providing a dedicated time period for all movements. With the help of advanced optimization tools, it became possible to let a platoon of vehicles starting with a green light at the first junction to pass a whole series of junctions without stopping for a red light. This type of rout optimization along multiple traffic lights is called coordination.

Due to changes in the road network and variations in the traffic demand, the coordination planning has to be adjusted in frequent intervals to meet the needs of the current traffic configurations. A well-done coordination can bring high benefits for the major traffic streams along coordinated routes due to reduced travel times, higher average speeds and less stops.

The higher average speed and the reduced number of stops also have a positive influence on air quality. Fuel is not unnecessarily burned and the combustion processes during a steady drive is more efficient than stop and go traffic.

A reasonable estimation with clear numbers for the air quality improvement was not possible due to different computational approaches from the City of Toronto to allocate the fuel consumption and the greenhouse gas emissions in Table 11.

Table 11: Effect of traffic signal coordination between 2012-2015 in Toronto (City of Toronto, 2017)

MOE	Comparison of Annual Statistics			
	Before	After	Difference	% Difference
Total Delay (hr)	29,602,734	26,947,609	-2,655,125	-9.0%
Stops (#)	2,521,545,180	2,263,312,799	-258,232,382	-10.2%
Average Speed (km/h)	28.4	29.5	+1.09	3.9%
Total Travel Time (hr)	59,111,134	56,495,934	-2,615,199	-4.4%
Fuel Consumed (l)	297,920,462	283,237,069	-14,683,393	-4.9%
Emissions (kg)	6,807,440	6,474,993	-332,447	-4.9%

The costs to achieve this massive optimization of the traffic flow were calculated to be $3.4 million. This represents a financial expenditure of $1.25 to reduce the total delay by one hour, or to have one vehicle one less on the road (City of Toronto, 2017). Hence this measure effects all types of vehicles, the efficiency for air pollution can be considered very high.

5.1.4 Street Sweepers to Reduce Particulate Matter

Street sweeping is an important aspect of road maintenance. It helps to keep the roads clean an benefits the roadway aesthetics in urban areas. Furthermore, it removes accumulations of dirt and leaves in the fall season to avoid blockings of the drainage system. A well-functioning drainage is important to avoid water accumulations on the street which reduces drivers comfort and may affect pedestrians on the sidewalk. During dry weather periods, street sweeping also helps to remove coarse particles from the road surface. These particles, generated from abrasion effects between the road surface and tires can affect the friction of the road.

Modern street sweepers are even able to remove fine particulate matter and to sustainably reduce the PM10 and PM2.5 concentrations dispersed on the road by passing vehicles. This type of modern street sweepers was tested in a local study, using an artificial tunnel environment, by the City of Toronto. Their efficiency is at least 27% higher than other street sweepers. This helps to sustainably reduce TPM concentrations. A clear measure for the city-wide impact was not possible due to missing information about the street sweeping schedules and the actual amount of deposited particles on the road (City of Toronto, 2016).

The efficiency of this measure to reduce air pollution is considered to be medium, due to the high costs of modern street sweepers with an improved PM reduction. Furthermore, this measure does not help to reduce the emissions and only brings relief by reducing existing pollutants.

5.1.5 City of Toronto Idling Control By-law

The City of Toronto has recently passed an intensified by-law to prohibit the idling of vehicles. This common behaviour of drivers who wait for someone to pick up or to warm up their engine during the cold month, causes a lot of unnecessary emissions. The recently issued by-law even include transit vehicles, and generally prohibits idling times longer than 60 seconds for parked vehicles (City of Toronto, 2017). A clear accounting of this measure is not possible due to missing data of drivers who used to keep their vehicles idling and the effect and enforcement of this law.

The efficiency of this measure is unclear at best. Nevertheless, it is a good symbol to promote an environmental behaviour.

5.2 Background of air quality related traffic operations from Karlsruhe

The City of Karlsruhe has a very balanced mode share. Within the last 15 years, a strong improvement of the public transit and the cycling network took place. This led to a mode change for many residents and reduced the dominating position of the private vehicles (Stadt Karlsruhe, 2013). An overview of the modal split for all trips in Karlsruhe in 2012 is given in Figure 13.

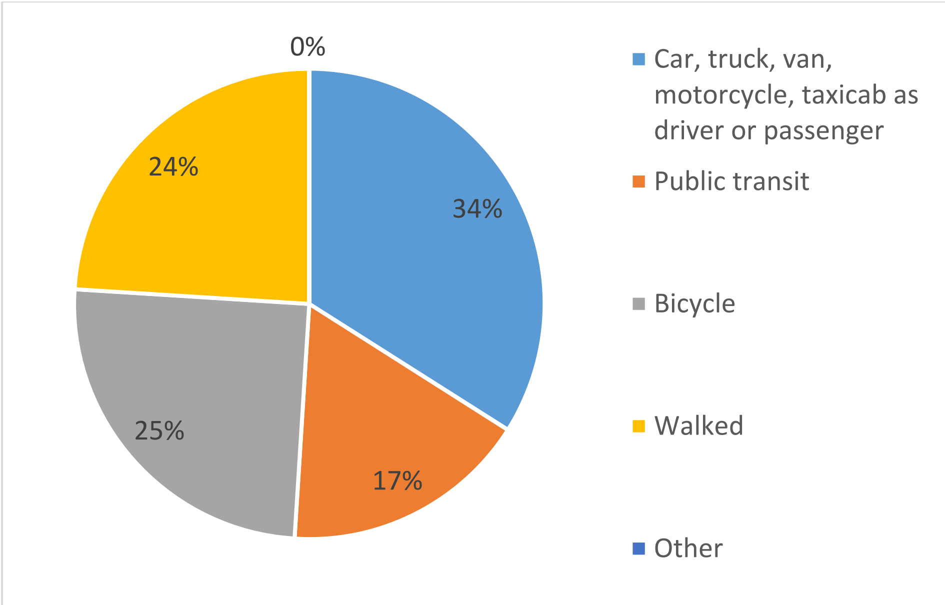


Figure 13: Modal Split of Trips – Karlsruhe – 2012 (Stadt Karlsruhe, 2013)

The majority of trips in 2012 was still done by private vehicles, but this majority is based on a comparable thin one-third mode share. The public transit sector had less than 20%, but this ratio was accomplished by busses and a mixed light rail transit (LRT) and streetcar system and without a mass transportation service like a subway. The active modes of transportation like walking and cycling made up almost half of all trips.

In 2012, the last update of the local air quality action plan was made and the given modal split represents the most recently published data of the mode shares. The other datasets for this overview are also based on traffic conditions and compositions from 2012.

The total emissions of the criteria air pollutants NO_x and PM_{10} are given in Table 12. The annotation 'total' for PM_{10} means that road and tire abrasion effects are included in the inventory values.

Table 12: Traffic Contribution to the Emission Inventory, Karlsruhe 2012 (Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg, 2015)

Pollutants	**Total Inventory (tonnes)**
NO_x	1,502
PM_{10} (total)	150

The emission inventory is computed with a theoretical model, based on the total vehicle kilometers travelled within the city and a set of different pollution classes for the vehicle categories. The average emissions per vehicle class and kilometer are given in Table 13. These values are based on traffic statistics for the Federal State of Baden-Württemberg in general. A specific difference for the fleet composition in the City of Karlsruhe is not expected.

Table 13: Emissions per Vehicle Class and Kilometer, Karlsruhe 2012 (Büringer & Schmidtmeier, 2014)

Vehicle Class	**NO_x (g/km)**	**PM_{10} (Total) (g/km)**
Passenger Car - Diesel	0.553	0.024
Passenger Car - Gas	0.182	0.011
Heavy Duty Vehicle	3.667	0.100
Others (Light trucks, motorcycles)	0.600	0.050

The emissions per vehicle class and kilometer values can be used to estimate the efficiency of the following measures. The data from 2012 should provide reasonable estimations, although the composition of the vehicle fleet and the increased emission standards are likely to cause an overestimation.

5.2.1 Cycling - Promotion and Facilities

The City of Karlsruhe was recently honoured with the title ‘Cycling Capital of the South’ in Germany. This achievement was the result of a consequent realization of an ambiguous development plan. The Karlsruhe 20 Points Concept was passed in 2005 with the goal to sustainably increase the mode share of cycling. The 20 points focussed on these formal goals and a set of general measures. Among these measures were the requirement to analyze improvement potentials for cyclists combined with every single construction work for maintenance purposes and to develop a wide-spread cycling network. The results of the applied 20 points concept were an increase of 9 % cycling mode share among the overall modal split of trips between 2002 to 2012 (Stadt Karlsruhe, 2013).

The traffic effects of cycling in Karlsruhe are similar to the ones already discussed in chapter 5.1.1.

To provide an example for the emission reductions accomplished in Karlsruhe, the effects measured at permanent cyclists counting facility in the downtown area were evaluated. This facility is located on one of the major cycling routes through the city and next to one of the biggest shopping centers. One your after the installation of this facility, a total number of almost 1,5 million cyclists passed by this spot and was counted (Stadt Karlsruhe, 2013). Assuming that all cycle trips on this route have replaced motorized vehicle trips of 3 km and reflecting on the mixed fleet composition of gasoline and diesel fueled cars, the emission reductions are given in Table 14.

Table 14: Effects of Cycling in Karlsruhe (Stadt Karlsruhe, 2013) (Büringer & Schmidtmeier, 2014)

	NOx [t]	**TPM [t]**
Vehicle Trips	1,446,000	
Distance [km]	3	
Passenger Car - Diesel [39%]	0.743	0.032
Passenger Car - Gas [69%]	0.544	0.034
Inventory reduction [t/a]	0.74	0.03
Ratio of City inventory	0.05%	0.02%

The effect of this measure compared to the city-wide inventory is very small. Considering the high ratio of cyclists which were attracted by new cycle lanes and promotions like this public counter the overall effects are estimated to by significantly higher.

The costs for the new cycle network were often combined with anyways required maintenance works and the overall efficiency of cycling is also in Karlsruhe very high.

5.2.2 Improvements of transit

Karlsruhe is well known for its far reaching transit network. In particular, the special form of the track based transit services became famous due to the development of the Karlsruhe System. This first of a kind system is a combination of LRT and regional train. To improve the service and comfort for its users, the Karlsruhe Transport Authority (KVV) has bought rail way capacities for its vehicles. This allows the KVV transit vehicles to collect riders from all of the region on the heavy rail tracks and to bring them directly to their desired destinations in the downtown area of the city after the vehicles have changed the heavy rail system to the LRT system which both operate on the same track gauge (Karlsruher Verkehrsverbund GmbH, 2017).

This special system already attracted a lot of transit users. Additional improvements to reduce the air pollution instead substituting car trips with transit trips are modernizations for the bus fleet. Overall, the allocated potential of emission reductions in the transit sector were assumed to be 1-2% of the total NO_2 concentrations (Stadt Karlsruhe, 2006).

The efficiency of this measure is medium to high since, since the transit vehicles still produce emissions and the capital expenditures for new vehicles and tracks are very high.

5.2.3 Coordination of traffic signals

The measure of advanced traffic signaling in Karlsruhe follows the same principles as the one from Toronto (see chapter 5.1.3). The estimated NO_2 reduction within the City of Karlsruhe was 2-4%. This includes signal coordination within the city and a doorman signaling on the important entrance routes to the city. This special concept is comparable to a ramp metering and only allows a certain number of vehicles to enter the city. If the demand is higher than the supply, the formation of the queue will start outside of the critical residential areas where air pollutants have less effects to the residents (Stadt Karlsruhe, 2006).

5.2.4 Implementation of low emission zones

A special arrangement to avoid air pollution in the critical areas of a city are so called low emission zones. These zones prohibit the access of vehicles with insufficient emission standards. The latest update of the air quality action plan in Karlsruhe has intensified the regulations to enter the downtown core of the city. Only vehicles with emission standards of 'EURO 4' or better are allowed to enter the zone which can be seen in Figure 14.

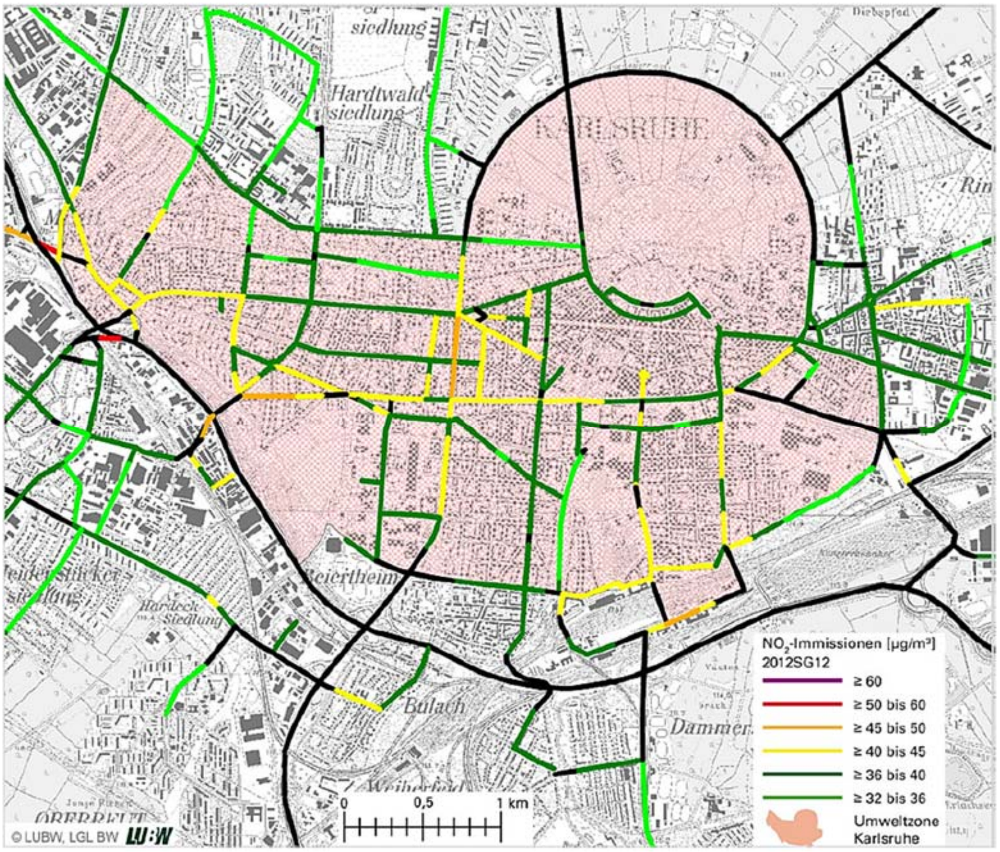
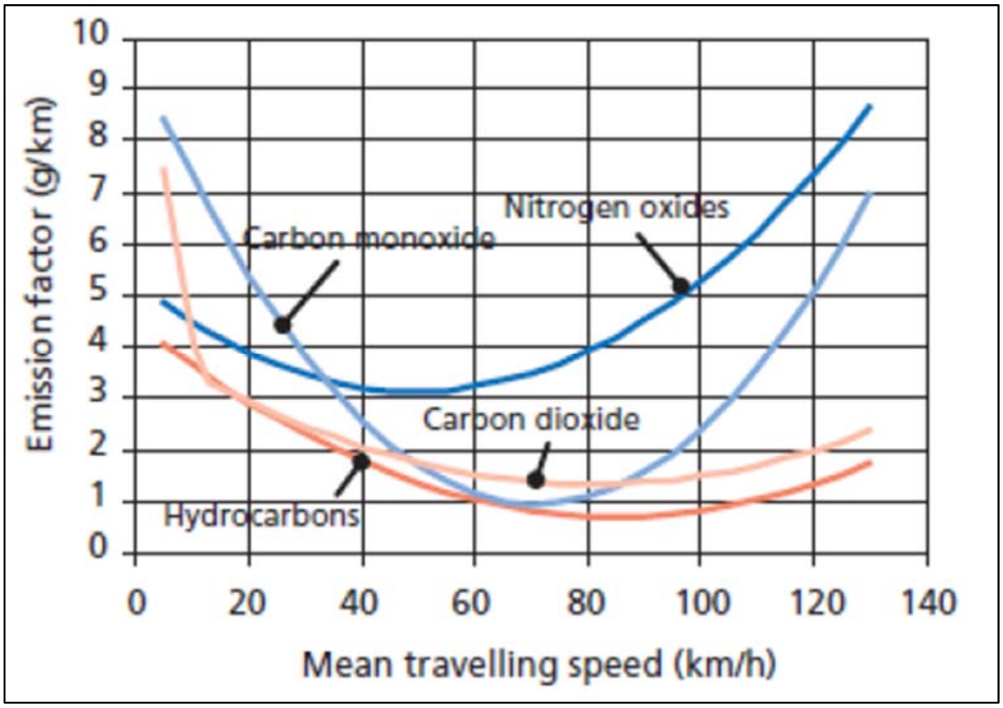


Figure 14: Low Emission Zone in Karlsruhe (Stadt Karlsruhe, 2012)

The required emission standard was required for all diesel fueled vehicles build after 2005 and gasoline fuelled vehicles after 1992. This strong limitation of traffic was justified by the adverse health effects of the residents. The estimated reductions of this zone are 3.2% less NO_2 and 2.1% less PM_{10} (Stadt Karlsruhe, 2006). This is a strong improvement of the local air quality. Considering the low percentage of prohibited vehicles among the total fleet and the possibility to buy a newer vehicles with sufficient emission standards for the affected parties will not lead to a significant relieve of the traffic demand. This measure only targets the air pollution with a strong impact.

5.3 Traffic Calming

A wide-spread rumor on behalf of air quality improvement is the positive effect of traffic calming. As Figure 15 shows, the lowest air pollution emissions can be accomplished on speed between 50 to 70 km/h, dependent on the type of pollution.



Note: Values for nitrogen oxides (NO_x) and hydrocarbons (HC) have been multiplied by 10 and those for carbon dioxide (CO_2) have been divided by 100.

Figure 15: Effects of Traffic Calming (Bellefleur & Gagnon, 2011)

The effect of traffic calming usually aims to reduce the speed limits to 30 or 40 km/h. This might only have positive effects if the traffic flow improves and becomes more steady.

6 COMPARISON OF TRAFFIC OPERATIONS - AIR QUALITY RELATED: CANADA AND GERMANY

6.1 Comparison of Thresholds

For an effective comparison of the traffic related measures which were discussed in chapter 5, a prior comparison of the different threshold levels will be a valuable background.

Table 15: Comparison of Thresholds (World Health Organization, 2005) (Ontario Ministry of the Environment and Climate Change, 2012) (Bundesministerium der Justiz und für Verbraucherschutz, 2013)

Pollutant	**Averaging Time**	**WHO**	**Toronto**	**Karlsruhe**
CO	1 Hour	30 mg/m^3	37 mg/m^3 (org. 30 ppm)	*NA*
	8 Hours	10 mg/m^3	16 mg/m^3 (org. 13 ppm)	10 mg/m^3
NO_2	1 Hour	200 $\mu g/m^3$	400 $\mu g/m^3$	200 $\mu g/m^3$ (18 exceeds p.a.) 400 $\mu g/m^3$ (Alarm)
	24 Hours	*NA*	200 $\mu g/m^3$	*NA*
	1 Year	40 $\mu g/m^3$	*NA*	40 $\mu g/m^3$
O_3	1 Hour	*NA*	165 $\mu g/m^3$ 80 ppb	240 $\mu g/m^3$ (Alarm)
	8 Hours	100 $\mu g/m^3$	130 $\mu g/m^3$ (org. 63 ppb)	120 $\mu g/m^3$
PM_{10}	24 Hours	50 $\mu g/m^3$	(50 $\mu g/m^3$)	50 $\mu g/m^3$ (35 exceeds p.a.)
	1 Year	20 $\mu g/m^3$	*NA*	40 $\mu g/m^3$
$PM_{2.5}$	24 Hours	25 $\mu g/m^3$	28 $\mu g/m^3$	*NA*
	1 Year	10 $\mu g/m^3$	10 $\mu g/m^3$	25 $\mu g/m^3$

The diversity of different thresholds and averaging times is very complex. A simplification could be that the recommended thresholds of the WHO are the strictest. In many cases these thresholds were adapted by the two nations. In case of variations from the WHO recommendations, Germany has slightly lower and therefor more intense thresholds than Canada.

6.2 Comparison and Ranking of Measures and Conclusion

The most effective measures in both nations to reduce air pollutants are measures that target a mode shift. Especially the mode of cycling has a high potential since bicycles are operated without any emissions. The acceptance of this mode is significantly higher in Germany than it is in Canada. This might change during the next decades considering development proposals and the delayed effects of promotions.

The shift to public transit is especially in Canada a highly accepted measure to reduce the vehicle based emissions. Although transit vehicles still have a significant contribution to the air pollution, the high occupancy rates of these vehicles reduces the emissions per trip significantly.

Traffic optimizations like signal coordination have an comparably high effect. This effect is still possible since most trips are still travelled by motorized vehicles. Compared to developments of cycling and transit networks, these measures are fast responding with an significant impact. Their sustainability on the downside is only given when they are frequently repeated due to changes in the traffic routs and centers of demand and supply.

Additional measures like street sweeping or the prohibition of idling seem to be only a drop in a barrel, but are important to promote the topic. Their effects are only local and only for a short time, but to reduce the air pollutant concentrations in critical areas every bit helps.

Far-ranging measures like low emission zones have a strong limiting character and need a careful evaluation. Still, they can accomplish the best reductions for critical areas.

Overall, the analysis examples have shown that both cities assigned a positive trend in the last years. But to ensure the health of their residents, more improvements are required.

Appendices

Appendix 1: Example Layout Monitoring Datasets 'Toronto East'

	A	B	C	D	E	F	G	H	I	J	K	L
1	Toronto East (33003)											
2	Hourly Fine Particulate Matter [PM2.5] Concentrations											
3	From	January 1 2004										
4	To	December 31 2004 EST										
5	Station	Toronto East (33003)										
6	Address	Kennedy Rd./lawrence Ave. E.										
7	Latitude	43,747917										
8	Longitude	-79,274056										
9	Air Intake Height	4 metres										
10	Elevation	168 metres										
11	Pollutant	Fine Particulate Matter [PM2.5]										
12	Method	TEOM 1400AB operated at 30Â°C with SES										
13	Unit	micrograms per cubic metre (micrograms/m3)										
14	Remarks	-999 for missing data. 9999 for invalid data.										
15	Station ID	Pollutant	Date	H01	H02	H03	H04	H05	H06	H07	H08	H09
16	33003	Fine Particulate Matter	01.01.2004	3	2	3	2	2	1	0	0	1
17	33003	Fine Particulate Matter	02.01.2004	1	3	3	3	5	5	6	7	10
18	33003	Fine Particulate Matter	03.01.2004	1	1	0	0	5	7	8	9	12
19	33003	Fine Particulate Matter	04.01.2004	6	2	2	3	3	3	0	0	2
20	33003	Fine Particulate Matter	05.01.2004	0	0	0	0	0	0	1	2	4
21	33003	Fine Particulate Matter	06.01.2004	1	1	1	1	2	1	2	4	3
22	33003	Fine Particulate Matter	07.01.2004	3	3	1	0	0	0	1	2	3
23	33003	Fine Particulate Matter	08.01.2004	4	2	1	3	5	4	4	7	21
24	33003	Fine Particulate Matter	09.01.2004	3	4	4	1	0	0	1	2	4
25	33003	Fine Particulate Matter	10.01.2004	6	5	5	4	5	4	9	14	8
26	33003	Fine Particulate Matter	11.01.2004	3	2	3	1	2	4	2	3	4
27	33003	Fine Particulate Matter	12.01.2004	9	10	11	13	14	16	22	25	21
28	33003	Fine Particulate Matter	13.01.2004	1	4	5	4	3	0	0	0	0
29	33003	Fine Particulate Matter	14.01.2004	3	2	3	3	1	1	2	2	5
30	33003	Fine Particulate Matter	15.01.2004	4	3	5	5	3	5	4	4	5

General Information

Appendix 2: VBA Code One Column

```
Private Sub One_Column()

    Dim r As Integer 'read row
    Dim s As Integer 'read column
    Dim i As Integer 'write row
    Dim j As Integer 'write column
    Dim o As Integer 'row with first values

    o = 15 'change here
    r = o 'first values
    s = 4  'date
    i = o 'one below table head
    j = 31 'column fix

    Cells(i - 1, j) = "values"
    Cells(i - 1, j - 1) = "hour"
    Cells(i - 1, j - 2) = "dates"

    Do While Cells(r, s) <> ""
        Do While Cells(r, s) <> ""
            Cells(i, j) = Cells(r, s)
            Cells(i, 29) = Cells(r, 3)
            Cells(i, 30) = Cells(o - 1, s)
            i = i + 1
            s = s + 1
        Loop
        r = r + 1
        s = 4
    Loop

End Sub
```

Appendix 3: VBA Code Constraint max. One Exceeding per Day

```
Private Sub Constraint_Once_per_Day()
Dim r As Integer 'read row
Dim s As Integer 'read column
Dim i As Integer 'write row
Dim j As Integer 'write column
Dim o As Integer 'row with first values
Dim t As Integer 'column of 8h average
Dim day As Variant


o = 16 'change here
r = o 'first values
s = 29  'date
t = 35 'analysis column for dayly exceeds (8h or 24h+2)
i = o 'one below table head
j = 49 'column fix
day = ""

Cells(i - 2, j) = "8-hour avg"
Cells(i - 1, j + 2) = "values"
Cells(i - 1, j + 1) = "hour"
Cells(i - 1, j) = "dates"


Do While Cells(r, s) <> ""
    If Cells(r, t) > 5 Then 'check if exceeds
        If Cells(r, s) <> day Then 'check date
            day = Cells(r, s) 'new date
            Cells(i, j) = day 'write date
            Cells(i, j + 1) = Cells(r, s + 1) 'write hour
            Cells(i, j + 2) = Cells(r, t) ' write exceeded value
            i = i + 1 'write in  next line
        End If
    End If
    r = r + 1 'read next row
Loop

i = o 'reset counter
r = o 'reset counter
```

```
Cells(i - 2, j + 3) = "24-hour avg"
Cells(i - 1, j + 3) = "date"
Cells(i - 1, j + 4) = "hour"
Cells(i - 1, j + 5) = "value"

Do While Cells(r, s) <> ""
    If Cells(r, t + 2) > 5 Then 'check if exceeds
        If Cells(r, s) <> day Then 'check date
            day = Cells(r, s) 'new date
            Cells(i, j + 3) = day 'write date
            Cells(i, j + 4) = Cells(r, s + 1) 'write hour
            Cells(i, j + 5) = Cells(r, t + 2) ' write exceeded value
            i = i + 1 'write in  next line
        End If
    End If
    r = r + 1 'read next row
Loop

i = o 'reset counter
r = o 'reset counter

Cells(i - 2, j + 6) = "1-hour"
Cells(i - 1, j + 6) = "date"
Cells(i - 1, j + 7) = "hour"
Cells(i - 1, j + 8) = "value"

Do While Cells(r, s) <> ""
    If Cells(r, t - 2) > 5 Then 'check if exceeds
            Cells(i, j + 6) = day 'write date
            Cells(i, j + 7) = Cells(r, s + 1) 'write hour
            Cells(i, j + 8) = Cells(r, t - 2) ' write exceeded value
            i = i + 1 ' write in next line
    End If
    r = r + 1 'read next row
Loop

End Sub
```

Appendix 4: Example Layout Monitoring Datasets Karlsruhe Road

	A	B	C	D	E	F	G
1	KA_PM	Messstelle	Komponente / Einheit	Datum / Uhrzeit	Wert	Aggregationszeitraum	Aggregationsart
2	53277	Karlsruhe Reinhold-Frank-Straße	Schwebstaub PM 10 (Gravimetrie) µg/m³	2006-01-01	192	1 Tag	Einzelwert
3	53277	Karlsruhe Reinhold-Frank-Straße	Schwebstaub PM 10 (Gravimetrie) µg/m³	2006-01-02	30	1 Tag	Einzelwert
4	53277	Karlsruhe Reinhold-Frank-Straße	Schwebstaub PM 10 (Gravimetrie) µg/m³	2006-01-03	34	1 Tag	Einzelwert
5	53277	Karlsruhe Reinhold-Frank-Straße	Schwebstaub PM 10 (Gravimetrie) µg/m³	2006-01-04	33	1 Tag	Einzelwert
6	53277	Karlsruhe Reinhold-Frank-Straße	Schwebstaub PM 10 (Gravimetrie) µg/m³	2006-01-05	20	1 Tag	Einzelwert
7	53277	Karlsruhe Reinhold-Frank-Straße	Schwebstaub PM 10 (Gravimetrie) µg/m³	2006-01-06	34	1 Tag	Einzelwert
8	53277	Karlsruhe Reinhold-Frank-Straße	Schwebstaub PM 10 (Gravimetrie) µg/m³	2006-01-07	39	1 Tag	Einzelwert
9	53277	Karlsruhe Reinhold-Frank-Straße	Schwebstaub PM 10 (Gravimetrie) µg/m³	2006-01-08	53	1 Tag	Einzelwert
10	53277	Karlsruhe Reinhold-Frank-Straße	Schwebstaub PM 10 (Gravimetrie) µg/m³	2006-01-09	69	1 Tag	Einzelwert
11	53277	Karlsruhe Reinhold-Frank-Straße	Schwebstaub PM 10 (Gravimetrie) µg/m³	2006-01-10	61	1 Tag	Einzelwert
12	53277	Karlsruhe Reinhold-Frank-Straße	Schwebstaub PM 10 (Gravimetrie) µg/m³	2006-01-11	71	1 Tag	Einzelwert
13	53277	Karlsruhe Reinhold-Frank-Straße	Schwebstaub PM 10 (Gravimetrie) µg/m³	2006-01-12	62	1 Tag	Einzelwert
14	53277	Karlsruhe Reinhold-Frank-Straße	Schwebstaub PM 10 (Gravimetrie) µg/m³	2006-01-13	65	1 Tag	Einzelwert
15	53277	Karlsruhe Reinhold-Frank-Straße	Schwebstaub PM 10 (Gravimetrie) µg/m³	2006-01-14	71	1 Tag	Einzelwert
16	53277	Karlsruhe Reinhold-Frank-Straße	Schwebstaub PM 10 (Gravimetrie) µg/m³	2006-01-15	83	1 Tag	Einzelwert
17	53277	Karlsruhe Reinhold-Frank-Straße	Schwebstaub PM 10 (Gravimetrie) µg/m³	2006-01-16	100	1 Tag	Einzelwert
18	53277	Karlsruhe Reinhold-Frank-Straße	Schwebstaub PM 10 (Gravimetrie) µg/m³	2006-01-17	62	1 Tag	Einzelwert
19	53277	Karlsruhe Reinhold-Frank-Straße	Schwebstaub PM 10 (Gravimetrie) µg/m³	2006-01-18	30	1 Tag	Einzelwert
20	53277	Karlsruhe Reinhold-Frank-Straße	Schwebstaub PM 10 (Gravimetrie) µg/m³	2006-01-19	44	1 Tag	Einzelwert
21	53277	Karlsruhe Reinhold-Frank-Straße	Schwebstaub PM 10 (Gravimetrie) µg/m³	2006-01-20	36	1 Tag	Einzelwert
22	53277	Karlsruhe Reinhold-Frank-Straße	Schwebstaub PM 10 (Gravimetrie) µg/m³	2006-01-21	21	1 Tag	Einzelwert
23	53277	Karlsruhe Reinhold-Frank-Straße	Schwebstaub PM 10 (Gravimetrie) µg/m³	2006-01-22	25	1 Tag	Einzelwert

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