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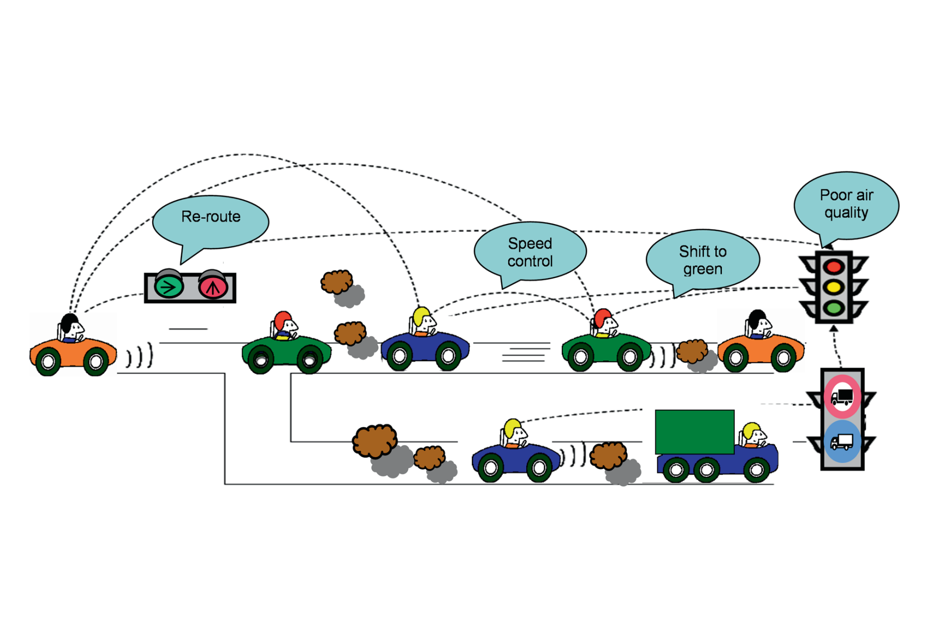

Using Co-operative Vehicle-Infrastructure Systems to Reduce Traffic Emissions and Improve Air Quality at Signalized Urban Intersections

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Mohamed Kamil Morsi Mahmod

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Cover picture: Environmentally friendly co-operative vehicle-infrastructure system

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Using Co-operative Vehicle-Infrastructure Systems to reduce traffic emissions and improve air quality at signalized urban intersections

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Chapter 1

Introduction

1.1 Background

Road transport has expanded the scope of human mobility, increasing the distances people travel. However, the recent increase in the number of vehicles has resulted in many adverse consequences in terms of safety, efficiency and the environment. Traffic accidents cause many fatalities and injuries every year. In the Netherlands, there were 750 fatalities in 2008 with 18,000 casualties admitted to the hospital annually (SWOV, 2008). With regard to efficiency, the increased traffic has led to severe congestion, which increases delay for travelers. At the EU level, the annual costs of congestion account about 100 billion Euro, which is 1% of the EU's GDP (EC, 2007).

Traffic contributes to four types of environmental problems (VROM, 2004). First, traffic is a major cause of deteriorating air quality in urban areas. Deteriorating air quality is caused mainly through the emissions of air pollutants, particularly Nitrogen Oxides (NO_x) and Particulate Matter (PM). It is well known that these pollutants can have serious health impacts if the ambient concentrations exceed certain limits (Nicolai et al., 2003). Second, traffic is a major contributor to the acidification of the natural environment. In particular, the emissions of NO_x and Sulfur Dioxide (SO_2) damage farm crops and buildings. Third, traffic is responsible for about one fifth of the EU's emissions of the greenhouse gas Carbon Dioxide CO_2, which contributes to climate change (EC, 2010). Fourth, traffic is the major source of noise pollution, which causes sleep disruption and contributes to certain cardiovascular diseases in the long-term (Selander, 2010).

Since thirty years ago, policy-makers have started to develop measures to reduce traffic emissions at the source (source policy). The development of catalytic converters has reduced the emissions from diesel- and gasoline-driven vehicles. This has been followed by many technical solutions to further reduce traffic emissions. One example is the use of particle filters which have reduced PM emissions. Another example is to improve the efficiency of fuel by reducing the amount of sulfur in the fuel (reducing PM and SO_2 emissions). Using biofuels, either by mixing it with fossil fuel or by using 100% biofuel, will also reduce CO_2 emissions (VROM, 2004). In the long term, the use of electric vehicles and hydrogen as a fuel may also contribute to the improvement of air quality. However, the air quality is expected to remain under pressure, particularly as a result of the anticipated further growth in traffic.

Over the past years, Intelligent Transportation Systems (ITS) have been used increasingly to manage and control road traffic. ITS can reduce traffic emissions through a better demand management including road pricing and access management. Road pricing was used to reduce traffic during peak periods, reducing congestion and hence emissions. Variable Message Signs (VMS) were used to inform drivers about speed limits on motorways. They were found to reduce speed variability and accordingly reduce traffic emissions (Keuken et al., 2010). Any ITS application that enhances modal shift such as Park and Ride scheme could also reduce emissions.

The recent developments in information and communication technologies have paved the way for the development of co-operative systems in ITS. Using co-operative systems, vehicles and road infrastructures can communicate with each other through Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I or I2V) communication. With V2V and V2I, information will be available about vehicles' locations and their surroundings as well as weather conditions. Therefore, co-operative systems can be used to improve road safety and efficiency. Moreover, co-operative systems can be used to make road traffic more environmentally friendly by reduce traffic emissions and improve air quality. For example, co-operative systems can provide personalized advice to drivers to avoid unnecessary acceleration and excessive speed as well as to select the most energy efficient route. Recent European projects (e.g., CVIS and SAFESPOT), focus on co-operative applications to improve traffic safety and traffic efficiency. Although traffic efficiency applications will help to reduce traffic emissions, larger benefits can be achieved using applications that specifically target environmental issues. Some environmentally friendly co-operative applications are under development as a part of an EU funded project called eCoMove (Vreeswijk et al., 2010). However, the environmental benefits of these applications have not been fully quantified.

1.2 Problem statement

Air pollution has become an increasingly serious problem due to its negative impacts on both public health and the environment. The problem of air pollution is more severe in urban areas where large amounts of population are vulnerable and high-rise buildings lead to poor emission dispersion conditions. To reduce these emissions, the EU directives 96/62/EC and 199/30/EC, updated by directive 2008/50/EC have set limit values for the concentration of several air quality components (EU, 1996, 1999, 2008).

In the Netherlands, the limit values for both NO_2 and PM_{10} in 2007 were exceeded in the busiest streets in large cities (i.e. about 200 km for NO_2 and 50 km for PM_{10}) (Velders and Diederen, 2009). The Dutch Government has agreed with the European Commission that concentrations must be below the limit values everywhere in the Netherlands by 2011 for PM_{10}, and by 2015 for NO_2. According to the National Air Quality Co-orporation Program (NSL), the EU limit values for NO_2 and PM_{10} can still be exceeded at specific locations by 2011 and 2015 (Beijk et al., 2010). Therefore, extra local measures are needed to help reduce the number of EU limit value violations.

1.3 Research objectives and Scope

1.3.1 Research objectives

The main goal of this thesis is to help improve the local air quality in an urban corridor using Co-operative Vehicle-Infrastructure Systems i.e. communication between in-vehicle and road-side unit systems. Figure 1.1 illustrates how co-operative systems can be used to reduce traffic emissions and improve air quality.

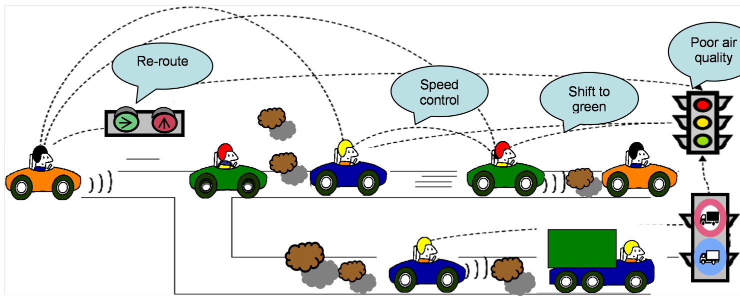


Figure 1.1: *Environmentally friendly co-operative vehicle-infrastructure system*

Figure 1.1 shows that in the case of poor local air quality, vehicles can co-operate to adapt their speeds and inter-vehicle distance. On the other hand, vehicles and traffic signals can mutually adjust their action to produce, for instance, a green wave. Furthermore, traffic signals can re-route or filter the traffic (by not allowing high emitter vehicle such as trucks) or even allowing the traffic to move faster.

1.3.2 Scope

This thesis focuses on the development and evaluation of an environmentally friendly co-operative system to improve local air quality. The evaluation is performed using a modeling framework consisting of traffic, emission and dispersion models. Such a modeling evaluation is needed to assess the potential effectiveness of the system before the real implementation. In general models are faster and cheaper than field experiments. Moreover, models give the possibility to evaluate more scenarios than those possible in field experiments.

The assessment is limited to the impact of the system on one intersection. The impact is evaluated in terms of traffic flow as well as traffic emissions and concentration levels. No attention is paid to the impact of the system on the network level. It is assumed that the system can be used to help reduce local traffic emissions and concentration levels at hot-spot locations such as busy street.

The fleet composition considered in this thesis includes Light Duty Vehicles (LDVs) and Heavy Duty Vehicles (HDVs). Modern vehicles such as hybrid vehicles are not considered, although the number of these vehicles has recently increased.

Analysis of communication data is no part of this research. Wireless communications between in-vehicle systems and road-side units are assumed to be reliable without any delay in the exchanged data. Also, no detailed information about implementation issues is provided in this research. Furthermore, human factors such as acceptance or behavioral adaptation are not considered.

1.4 Research approach and questions

To achieve the main goal in this thesis, the approach will be to:

- develop a modeling framework of traffic, emission and dispersion models;
- develop an indicator for local air quality;
- develop an algorithm for influencing the traffic via road-side and in-vehicle systems;
- evaluate the operation of the algorithm using the modeling framework.

The development of the modeling framework is essential to investigate the impact of the system. Choices for models to be used should be made according to the level of detail needed in this thesis. For traffic modeling, different levels can be considered including microscopic, macroscopic and mesoscopic simulation models. For emission modeling, various calculation methods are used such as aggregated emission factors and average speed. For dispersion modeling, different models exits depending on the accuracy and the time scale required for concentration calculation. The corresponding research question to answer is:

What are the most suitable traffic flow, emission and dispersion models to support the development and evaluation of a co-operative vehicle-infrastructure system to improve local air quality in urban traffic?

If co-operative systems are considered to improve air quality, an indicator for local air quality is needed. Based on this indicator the local air quality can be marked as poor or good and hence it can be decided whether or not the system should be activated. The indicator can be based on emissions levels or concentration levels of air pollutants. The corresponding research question is:

What are the air quality criteria to decide when the system is needed and when it will contribute to lower pollutant concentrations?

Traffic emissions are related to the speed of vehicles and the amount of acceleration and deceleration. Maintaining a constant speed and reducing the amount of acceleration and deceleration will reduce the traffic emissions per kilometer. Consequently, a reduction in traffic emissions and fuel consumption can be obtained if drivers receive information about, for example, the traffic signal status and adapt their speed and acceleration profile accordingly. The development of the algorithm will be based on the use of communication between in-vehicle systems and road-side units. The main goal is to influence traffic flow and change drivers' behavior in real-time. The corresponding research question is:

Which traffic control algorithms can be used to reduce traffic emissions and improve local air quality in urban traffic?

To evaluate the impact of the developed algorithm, the modeling framework will be used. The impact of the algorithm will be evaluated in terms of traffic emissions and local concentration levels. Moreover, the side-effects of the algorithm on traffic efficiency will be tested. The corresponding research question is:

What is the potential effect of the algorithm on traffic emissions and local concentration levels and what are the side-effects on traffic efficiency?

1.5 Relevance

1.5.1 Scientific relevance

The main scientific contribution of this thesis is the development of a modeling framework of traffic, emission and dispersion models to investigate the impact of traffic on local air quality. Today, while various models are available about the influence of traffic emissions on the air quality, partly in a relation to meteorological conditions, little is know about the dynamic relationship between air quality and traffic. This thesis aims to provide a better understanding of the dynamic relationship between air quality and traffic.

Another scientific contribution is the development of traffic control algorithms using I2V communication to reduce traffic emissions. While some earlier studies aimed at the use of I2V communication to reduce traffic emissions, they focused mainly on traditional fixed-time signal controllers. In this thesis the use of I2V communication is studied in advanced traffic signal controllers such as actuated and adaptive controllers. The impact is evaluated not only in terms of traffic emissions, but also in term of local concentration levels.

1.5.2 Societal and Practical relevance

The two main societal objectives to which this thesis is expected to contribute are improving the quality of life and health as well as protecting the natural environment. In general, the use of the developed co-operative system will help to improve the air quality in urban areas and hence result in healthier and more socially friendly environment. Moreover, the implementation of the system in the future will help cities to meet the EU and national legislation on air quality.

The outcome of this thesis is relevant to road operators and traffic system suppliers who want to apply traffic management systems that focus on environmental aspects. The end product of the thesis provides a framework for environmentally friendly traffic management using communication between in-vehicle systems and traffic signals. The framework includes an indicator for the local air quality, which can be used to respond to high concentration levels at hot-spot locations. In this way, the framework identifies a solution to the local high concentration levels, and defines when this solution will be effective.

1.6 Thesis outline

Figure 1.2 offers a guide to reading the remainder of this thesis.

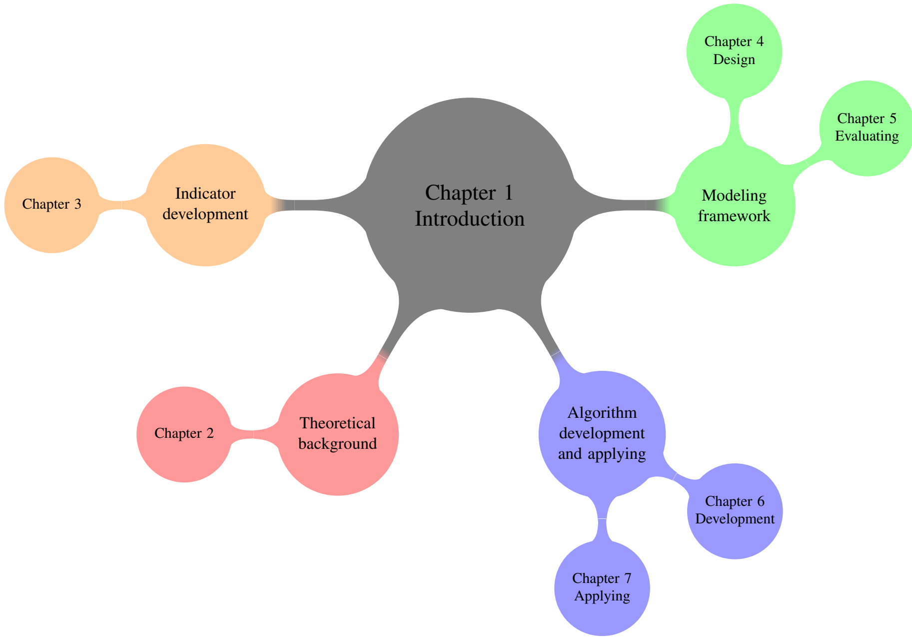


Figure 1.2: *Thesis outline*

Chapter 2 outlines the relevant theoretical topics related to this thesis. It discusses several examples of existing traffic measures aiming for the improvement of air quality. It also presents the concept of co-operative vehicle-infrastructure systems including recent developments in this area.

Chapter 3 presents the development of an indicator for local air quality. It explains the need for such an indicator and describes the steps taken for the development of the indicator.

Chapter 4 presents the design of the modeling framework. It includes a literature survey on traffic, emissions and dispersion models. Choices for models to be used are made according to the special requirements and level of detail needed in this thesis.

Chapter 5 evaluates the performance of the modeling framework. First, the calibration process for the traffic model is explained. Second, the validation process conducted for the emission model is presented. Third, hourly concentration results of NO_x from the dispersion model are compared with hourly concentration measurements at a monitoring station. Finally, a statistical analysis is conducted to assess the uncertainty of the results from the modeling framework.

Chapter 6 explains the development of an algorithm to influence traffic flow and change the behavior of drivers by using I2V communication. The chapter first explores the impact of different road-side and vehicle-side measures including: demand control, banning Heavy Duty Vehicles, speed restriction and Adaptive Cruise Control (ACC). Next, it presents a literature survey on systems using V2I or I2V communication to reduce traffic emissions. Finally, the algorithm is described assuming that drivers receive information about traffic signal status to avoid unnecessary accelerations and hard braking.

Chapter 7 presents and discusses the results of the algorithm. The chapter starts by a detailed description of the test site including the configuration of an actuated and an adaptive controller. The developed algorithm is implemented on top of the actuated and the adaptive controllers. First, the actuated controller is compared with the I2V actuated controller. Then, the adaptive controller is compared with the I2V adaptive controller. The results are presented in terms of average travel times and delay, emissions and hourly concentration levels of NO_x.

Chapter 8 gives concluding remarks and recommendations for future research.

Chapter 2

Theoretical background

This chapter outlines the relevant theoretical topics related to this thesis. Section 2.1 introduces the problem of air pollution defining its different sources. The most well known air pollutants are described in section 2.2. In the same section the pollutants to be considered in this thesis are selected. Section 2.3 focuses on traffic-related emissions. In section 2.4, several examples of existing traffic measures aimed at the improvement of air quality are discussed, in particular measures that use road-side and/or vehicle-side systems. The concept of co-operative systems is presented in section 2.4, including recent developments in this area. The chapter ends with a summary in section 2.5.

2.1 Introduction

Air pollution has become an increasingly serious problem due to its negative impacts on both public health and the environment. The World Health Organization (WHO) has reported that about 2.4 million people die every year from causes associated with air pollution. The problem of air pollution is more severe in urban areas where large amounts of population are vulnerable. The problem is aggravated by the urban geometry, where high-rise buildings lead to poor emission dispersion conditions. Therefore, great attention has been given to this problem by governments, local authorities, industry and scientists. For example in the USA, the Clean Air Act, formed in 1970, requires state and local governments to set minimum air quality standards called National Ambient Air Quality Standards (Mehata et al., 2003). In Europe, the EU directives 96/62/EC and 1999/30/EC, updated by directive 2008/50/EC have set limit values for the concentration of several air quality components (EU, 1996, 1999, 2008). Accordingly, plans of actions must be prepared by EU member states to improve the air quality in areas where the limit values are exceeded or expected to be exceeded in the near future.

There are two sources of air pollution, namely stationary and mobile. Examples of stationary sources are factories and industrial units. Mobile sources are various types of vehicles such as buses, cars and trucks. Ships are particularly significant mobile sources, especially in coastal areas (Saxe and Larsen, 2004). Emissions from industries have been reduced in many countries due to the enactment and enforcement of regulatory laws by governments. However, in many countries, traffic emissions have significantly increased due to the increased number of vehicles. Compared to polluting industries, vehicles can not simply be relocated to a remote area. Therefore, measures are needed to help reduce traffic emissions (Khare and Sharama, 2002).

2.2 Air pollutants

The most well known air pollutants together with their sources as well as their negative effects on human health and environment are presented in Table 2.1 (UNEP, 2006). According to the definition of different pollutants, the scope of the thesis has been determined. The selection of the pollutants was based on their potential health impacts and external costs. Moreover, attention was given to the EU limit values.

Table 2.1: *Air pollution sources and pollutants*

Pollutants	**Definition**	**Sources**	**Health effects**	**Environmental effects**
Carbon Monoxide (CO)	Colorless, odorless, tasteless, and toxic gas. Slightly soluble in the water	Incomplete combustion of fuels and vehicle exhausts	Has affinity for hemoglobin which decreases the percentage of oxygen carried by the blood	High level of exposure to CO can cause death and be harmful to plants
Oxide of Nitrogen NO_x (NO **and** NO_2)	NO: combination of nitrogen and oxygen at high temperature. NO_2 derived from NO (NO + O_2)	Natural emission sources and anthropogenic sources	Respiratory irritation and headache	Both NO and NO_2 cause damage to the ozone layer
Sulfur Dioxide (SO_2)	Colorless heavy gas	Volcanes, various industrial processes and burning of law quality coal and petroleum	Increases breathing rates and causes feeling of shortness of breath	Harm the plant
Volatile Organic Compounds ($VOCs$)	Hydrocarbons, halocarbon and oxygenates (organic compounds)	Hydrocarbons from gasoline evaporation and incomplete combustion oxygenates from vehicle exhausts	Some of the $VOCs$ are responsible for cancer	Indirect contributor to the formation of acidity
Ozone (O_3)	Molecule consisting of three oxygen atoms	Reaction of sunlight and NO_2	Irritation of lung, eyes and nose	Harm the plant
Lead (Pb)	Silver-gray soft metal	Vehicle emissions (leaded petrol)	Liver and kidney damage	Harm to plant and Animal
Particulate Matter ($PM_{2.5}$, PM_{10})	Tiny particle occur as fumes, smoke, dust and aerosols: PM_{10} (aerodynamic diameter $>$ 10 micrometers) $PM_{2.5}$ (aerodynamic diameter $>$ 2.5 micrometers)	Burning of fossil fuel in internal combustion engines, automobiles and power plants friction processes by tires on the road surface and brakes	Breathing problems	Corrosion of metals

The problem with regards to road traffic relate primarily to Nitrogen Oxides (NO_x) and Particulate Matter (PM) emissions. The emissions of NO_x refer to the sum of nitric oxide (NO) and nitrogen dioxide (NO_2), and occur primarily as NO. However, NO is very reactive and can interact with oxygen again and form NO_2. PM emissions are divided into coarse particles (aerodynamic diameter > 2.5 micrometers, PM_{10}) or fine particles (aerodynamic diameter < 2.5 micrometers, $PM_{2.5}$). Both NO_x and PM have severe health effects, where PM is considered as the most toxic pollutant. Health problems of PM are estimated to be continued even for PM concentrations below the EU limit values (Buringh and Opperhuizen, 2002).

In the Netherlands both NO_2 and PM_{10} have the most strict limit values (Velders and Diederen, 2009). For NO_2, the most important limit value is the annual average concentration which is 40 μgm^{-3} and had to be met by 2010. For PM_{10}, the annual average concentration is 40 μgm^{-3} that had to be achieved by 2005; and the daily average limit concentration is 50 μgm^{-3} which must not be exceeded more than 35 times in a year, and had to be met by 2005. In 2007, the limit values for both the annual average of NO_2 and the daily average of PM_{10} were exceeded along motorways and city streets in the Netherlands. The Dutch Government has agreed with the European Commission that concentrations must be below the limit values everywhere in the Netherlands by 2011 for PM_{10}, and by 2015 for NO_2. According to the National Air Quality Co-orporation Program (NSL), the EU limit values for NO_2 and PM_{10} can still be exceeded at specific locations by 2011 and 2015 (Beijk et al., 2010). Therefore, NO_2 and PM_{10} are very important to be considered in this thesis.

Emissions of CO_2 do not affect local air quality but climate change. CO_2 is a greenhouse gas and the transport sector is an important contributor to the emissions of CO_2 [1]. In the Netherlands, traffic was estimated to be responsible for one fifth of the greenhouse gas (approximately 18%) in 2010 (VROM, 2004). Recently the cabinet has agreed to send a road traffic emissions memorandum to the Dutch Parliament, stating that the EU fuel quality directive target of reducing CO_2 emissions from fuel combustion by 2020 will be applied. This means that CO_2 emissions from the entire motor fuel cycle must be reduced by 6% per energy unit compared to the 2010 level. Moreover, the interim targets of achieving 2% reduction by 2014 and 4% reduction by 2017 will be applied (VROM, 2010). Therefore, when evaluating ways for reducing environmental damage, CO_2 can not be ignored and hence will be considered in this thesis.

For SO_2, the National Emission Ceiling (NEC) forecasted that the limit values in the Netherlands will not be exceeded by 2010. The major part of SO_2 emissions is released from industry. In 2010, industrial sources were estimated to be responsible for 79% of the total SO_2 emissions in the Netherlands. Road traffic was estimated to be responsible for 18% of the total SO_2 emissions (VROM, 2004), which has been reduced due to the increased use of low sulphur and sulphur-free fuels (Panis et al., 2006). Reduction of SO_2 emissions must be achieved from maritime shipping, inland shipping and non-road mobile machinery (VROM, 2004). Accordingly, SO_2 will not be considered in this thesis.

Although CO is considered as a very toxic gas, it can hardly cause any negative impacts at low levels in open areas (Panis et al., 2006). Therefore, CO will be excluded.

The remaining pollutants i.e. O_3, Pb, and VOC (HC) will not be considered due to their minimal health effects compared to NO_x and PM_{10}. Ozone O_3 is a secondary pollutant result from the reaction between NO_x, VOC and the sun light. Smeet and Beck (2001)

[1] There are two other greenhouse gases emitted by traffic namely, the fluorocarbon $HFC - 134a$ (used in air-conditioning systems) and laughing gas N_20 (from exhaust system)

expected that only permanent and large-scale international measures will reduce ozone concentrations. On the other hand, lead (Pb) emission from road traffic has been reduced sharply due to the use of unleaded gasoline, where the industry and other stationary sources have become the major sources.

2.3 Traffic emissions

Traffic emissions are known to be the main source of deteriorating air quality in urban areas. Despite the fact that vehicle emissions have been subject to strict emission standards, traffic emissions continue to increase due to the increased number of vehicles. According to the data by ETC/ACC (2005), traffic emissions were responsible for about 42% of the total of NO_x emissions, 47% of the total of CO emissions and 18.4% of the total of PM emissions at the EU15 level. In the UK, areas with pollutant concentrations above certain thresholds have been declared as Air Quality Management Areas (AQMAs) and more than 90% of these areas were found to have been declared due to traffic emissions (van Breugel et al., 2005).

In order to quantify the amount of emissions from the transportation sector, it is important to define the vehicle processes associated with these emissions. There are two emission-producing processes namely, combustion emissions from the exhaust system and evaporation emissions from the fuel storage and delivery system (see Figure 2.1). Exhaust emissions are related to the operating modes of the vehicle i.e. start and hot stabilized modes. Start modes are defined as the first few minutes of operation after the engine has been switched on; while hot stabilized modes are all other operational modes. There are two types of starting modes, cold and hot which differ by the duration time between shutting off and restarting the engine. During the operating modes, the amount of emission depends on the fuel-air mixture and emission control equipment. For example, the emissions of VOC and PM are high during the cold start mode because the emission control systems are not providing full control and a richer fuel-air mixture is needed (i.e. higher proportion of fuel).

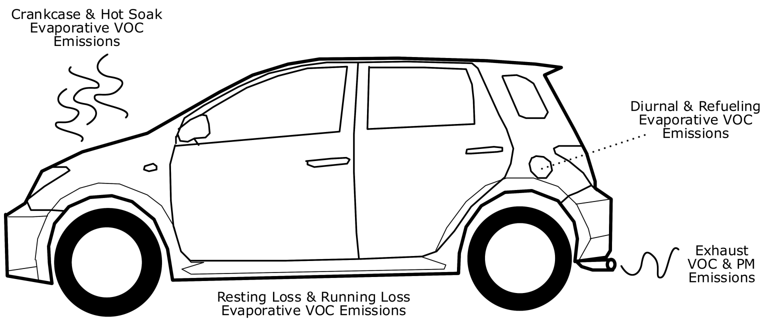


Figure 2.1: *Exhaust and evaporative emissions*

Normally, the combustion of oxygen and fuel (HC) produces CO and H_2O, but because of an incomplete combustion and the presence of N_2 in the air, HC, CO, O_2, CO_2, H_2O, and NO_x are produced. Moreover, the air-to-fuel (a/f) ratio is also important in determining the amount of emissions. It has been found that a rich fuel mixture (low a/f ratio and incomplete combustion) results in high emissions of CO and HC. On the other hand, a lean fuel mixture (high a/f ratio and complete combustion) results in high emissions of NOx and low emissions of CO and HC. Exhaust emissions are also related to vehicle activities. For example, a high power demand, such as during acceleration and while carrying heavy loads, requires a rich fuel mixture and hence emits a high amount of CO and HC emissions. On the other hand, driving at high speeds with low acceleration requires a lean fuel mixture and hence produces high amount of NOx emissions (Heywood, 1988).

Evaporation emissions consist of $VOCs$, where hydrocarbons can still be emitted into the air even if the vehicle is turned off. With the use of emission control technologies such as catalytic converter, evaporative emissions can account for a majority of the total VOC emissions. Evaporative emissions depend on the temperature, and can occur in several ways:

- Hot soak emissions: from the carburetor or fuel injector after the engine is turned off as the engine stays hot for some time after having been switched off.
- Diurnal emissions: from the breathing of the gasoline tank. It increases with the increase in the temperature.
- Running losses emissions: during operation, the hot engine and exhaust system can vaporize gasoline.
- Resting losses emissions: from vapor going through the evaporative emissions control system and from the vehicle fuel tanks.
- Refueling losses emission: from the gasoline vapor which escapes from the tank during the refueling process.
- Crankcase emissions: from imperfect crankcase ventilation valves (Mehata et al., 2003).

2.4 Road-side and vehicle-side measures

Although the implementation of the EU Directives have reduced emissions from major sources (i.e. industry and transport), pollutant concentrations are still exceeding the limits in some locations (hot-spots) and during specific times (pollution peaks). These exceedances occur due to the adverse topography (e.g., street canyon), weather conditions, but generally because of the intensity of certain activities (e.g., road transport or industrial activities). Figure 2.2 illustrates the formation of hot-spots in urban areas.

The regional background level represents the overall emissions activity within a region. This level is increased in urban areas due to local emissions resulting from human activities such as transport. As a result, limit values can be exceeded at hot-spots, especially during adverse meteorological conditions that hamper air dispersion.

There are two ways of addressing peak pollution periods:

- Measures on a regional scale when the problems are dominant on regional levels.
- Measures on a local scale when the contribution by local sources is dominant (Jones et al., 2005).

The focus in this thesis is on local scale measures, particularly measures that use road-side or vehicle-side systems to influence traffic flow and change drivers' behavior in real-time.

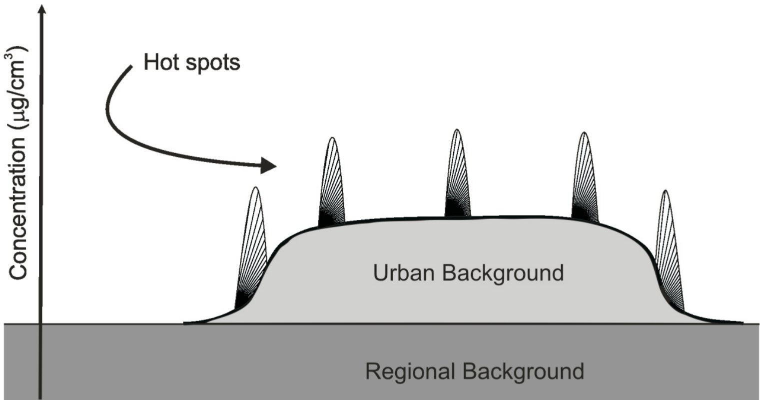


Figure 2.2: *Hot spot locations*

The objective is to combine the recent development on road-side and vehicle-side systems to see the potential of new measures which are based on co-operative systems. Examples of road-side and vehicle-side measures are discussed in the following subsections.

2.4.1 Road-side measures

1. *Low emission zones*

Low emissions zones are defined as areas which can only be entered by vehicles that meet certain EU standards. They can stimulate the use of cleaner vehicles. The traffic volume might not change but because a higher number of vehicles may have lower emissions, emissions may be reduced leading to a better air quality (Jones et al., 2005).

In Sweden, low emissions zones have been introduced to deal with air pollution problems especially with regard to NO_2 and PM_{10} emissions. The measure has been applied since 1996 in Stockholm, Göteborg and Malmö. From January 2001, the city of Lund was also included. Heavy-trucks and buses older than 8 years were forbidden to travel inside the defined zones. Accordingly, PM_{10} and NO_x emissions were reduced by about 40% and 10% respectively. Concentrations were also reduced by about 3% and 1.3% for PM_{10} and NO_x respectively. The reduction in concentration values was much lower than reduction in emissions due to the importance of the emissions from other road vehicles and other sources. Overall, the measure has been found to reduce the emission and concentration of different pollutants in all cities (van Breugel et al., 2005).

2. *Speed limit reduction with a trajectory-control system*

Traffic emissions are related to the speed of vehicles and speed variation (acceleration and deceleration). Maintaining a constant speed and reducing the speed variation will reduce the traffic emissions per kilometer. With regard to the average speed, PM_{10} emissions are highest at low speeds (below 40 kmh^{-1}) due to incomplete combustion. NO_x emissions, on the other hand, increase considerably at speeds higher than 100 kmh^{-1} due to higher combustion temperatures. The optimal speeds for PM_{10} and NO_x emissions are in the range of 60-100 kmh^{-1} (LAT, 2006). Concerning speed variation, traffic emissions are higher for traffic with large speed variation, than for traffic with less speed variation (Gense et al., 2001).

In the Netherlands, a pilot on the highway A13 was conducted in 2002 to strictly enforce a speed limit of 80 kmh^{-1}. The goal was to reduce the traffic-related emissions and the amount of noise. A trajectory-control system using speed violation cameras was installed every 3 km to make sure that speed limit was not exceeded. Measurements were carried out a year before and a year after the implementation of the measure in order to estimate the impacts of the measure on the emissions of NO_x and PM_{10}. The results were as follows:

- the speed variation and speed limit exceedances have been reduced leading to an estimated reduction of emission per vehicle of 15-25% for NO_x and 25-35% for PM_{10};
- air quality has improved during the westerly winds for NO_x and PM_{10} both for 200 and 50 meters distance;
- the noise pollution has reduced by 1,5 dB (A) at a distance of 150 meters;
- the local air quality has improved slightly due to the reduction in speed and speed variation, but mainly because of congestion relocation;
- collisions were reduced by 50% (van Breugel et al., 2005).

A recent study by Keuken et al. (2010) has evaluated the impact of 80 kmh^{-1} zones in Amsterdam and Rotterdam on both NO_x and PM_{10} emissions. The emissions were reduced by 5-30% for NO_x and 5-25% for PM_{10}. Therefore, the implementation of speed management with strict enforcement was found to be an effective measure for reducing traffic emissions on motorways.

2.4.2 Vehicle-side measures

Vehicle-side measures can be divided into Advance Driver Assistance Systems (ADAS) and Eco-driving solutions. ADAS are in-vehicle systems that assist the driver in performing one or more elements of the driving task. The goal of Eco-driving is to help drivers to obtain an efficient way of driving in order to save fuel consumption and reduce CO_2 emissions. The efficient way of driving is obtained through general advices giving to the driver such as: do not drive so fast, shift gear as soon as possible and use the correct tyre pressure. Some examples of ADAS and Eco-driving solutions are discussed in the following sub subsections.

2.4.2.1 Advance Driver Assistance Systems

1. *Adaptive Cruise Control*

Adaptive Cruise Control (ACC) is a system that uses a radar sensor to maintain a preset speed while adapting the speed to a slower predecessor. If a predecessor vehicle is moving at a lower speed, then the ACC controls throttle and brake to match the speed of the slower vehicle, otherwise the preset speed is resumed. ACC was primarily developed for driver comfort and safety enhancement. However, ACC can also have impact on traffic emissions and fuel consumption by smoothing traffic flow and homogenizing driver speeds. In (Bose et al., 2003; Ioannou and Stefanovic, 2005) a simulation of mixed traffic consisting of manual and ACC vehicles showed that the smooth response of ACC vehicles could reduce fuel consumption as well as the emitted pollutants. Bose and Ioannou (2000) showed that the presence of 10% Intelligent Cruise Control (ICC) vehicles can reduce total fuel consumption by 8.5%, and total emissions of CO_2 and NO_x by 8.1% and 18.4% respectively.

2. *Intelligent speed adaptation*

Intelligent Speed Adaptation (ISA) is a system that constantly monitors the local speed limit and the vehicle speed and implements an action when the vehicle is found to be exceeding the speed limit. The action can be in terms of advising the driver and/or governing maximum speed of the vehicle. Although ISA has been implemented to improve safety, it can also lead to a reduction in fuel consumption and vehicle emissions as it alleviates congestion by smoothing traffic flow. The system can be implemented with several methods depending on how the set speed is determined. These methods are: fixed (set speed by user), variable (by vehicle location) and dynamic (by time and location). The system can also be advisory (only warning), active support (system can change maximum speed, driver can override) and mandatory (system can change maximum speed, no driver override).

A simulation study by Servin et al. (2006) was performed to investigate the effect of ISA system on fuel consumption and vehicle emissions. A speed control strategy was developed which can change speed dynamically based on current traffic conditions. It was found that the ISA-equipped vehicle has a much smoother velocity trajectory with no difference in travel times compared to non-equipped vehicles. This resulted in a reduction of fuel consumption by 37%. Moreover, emissions were reduced for CO, HC and NO_x by 85%, 69% and 74% respectively with very little difference in overall travel time.

2.4.2.2 Eco-driving solutions

1. *Eco-driver assistance*

The Eco-driving assistance system includes energy-use indicator and gear shift indicator. The energy-use indicator is used to display information about the instantaneous and average fuel consumption to the driver using the on-board computer. The driver is thus informed when the vehicle is being operated in a fuel-efficiency manner. This has a direct effect on emissions since it improves the awareness of the driver about fuel efficient driving behavior. The energy-use indicator has been reported to reduce fuel consumption by 5% (ECODRIVING, 2010).

Figure 2.3: *Gear shift indicator (source: BMW)*

The gear shift indicator informs the driver when a gear shift is appropriate. Figure 2.3 illustrates an example of a gear shift indicator. The indicator displays a triangle pointing upwards if a gear shift to a higher gear is appropriate or downwards for a shift to a lower gear. The impact of the gear shift indicator on fuel consumption and CO_2 was investigated during a large measurement program using 28 passenger cars. The selected cars included petrol and diesel cars from the Euro 3 and Euro 4 categories. The fuel consumption was measured for an urban and a rural driving cycles which represent the average European Driver (CADC urban and CADC rural). The reductions were about 7 to 11% for petrol cars and 4 to 6% for diesel cars (Vermeulen, 2006).

2. *Stop and Start system*

The stop and start system automatically turns off the engine when the vehicle stops at a traffic light or in a traffic jam. The engine switches to standby mode when the driver brakes before the vehicle comes to a complete stop. The engine re-starts automatically when the driver releases the brake pedal. The system is used in hybrid electric vehicles, but also in some other vehicles.

The effect of the stop and start system on emissions is direct as emissions reduce during idling periods. The system is particularly important for vehicles that experience significant amount of waiting time at traffic lights in urban areas. However, the engine must stop for at least three seconds before fuel saving is realized because the start of the engine consumes an amount of fuel which is equal to three seconds idling. In addition to fuel saving, the system also enhances driver comfort and reduces noise level during standstill. In the Netherlands the percentage of idling in urban areas was estimated to be 14% for cars and 25% for trucks. The reduction in CO_2 due to the stop and start system was expected to be 3.7% in urban areas (Klunder et al., 2009)

2.5 Co-operative Systems

Co-operative systems are in-vehicle and road-side systems which can communicate wirelessly with each other leading to a better cooperation amongst drivers, vehicles and road-side infrastructure. Co-operative systems use two-way of communication including: Vehicle-to-Vehicle communication (V2V) and Vehicle-to-infrastructure (V2I or I2V) communication. Many types of information will be available about, for example, vehicles' location (i.e. floating vehicle data) and their surroundings (e.g. road conditions) as well as weather conditions. The availability of such information will allow both road operators and in-vehicle systems to benefit. For example, road operators can make better decisions in response to accidents and congestion. In-vehicle systems can provide better support to drivers by having more information about the surroundings (CVIS, 2010b).

The road-side and vehicle-side measures mentioned in the previous section can also be implemented in a co-operative manner. Some examples are described hereafter.

1. *Dynamic low emission zone*

Low emission zones have been applied in Sweden in a static manner i.e. access to the defined sensitive areas is denied at all times. However, the measure can also be flexible, such that the road-side unit can admit or deny access depending on traffic conditions and the air quality level inside the defined areas. For such measure, an indicator for the local air quality level is needed to decide when the measure should be activated. The negotiation starts between the vehicle and the road-side unit as soon as the vehicles enter the monitoring area around the defined areas. The vehicles send their data to be processed by the road-side unit which makes a decision as follows:

- Heavy Duty Vehicles (HDV) can be controlled according to the concentration levels inside the area;
- For Light Duty Vehicles (LDV), a recommended speed can be sent according to the individual vehicle characteristics.

2. *Co-operative Adaptive Cruise Control*

Co-operative Adaptive Cruise Control (CACC) is a further extension of ACC system. The CACC system uses V2V communication to exchange information with a predecessor vehicle. Accordingly, the ACC controller can response in a safer and smoother way. In (van Arem et al., 2006), a simulation study was conducted to investigate the impact of CACC on traffic flow characteristics. The system was found to have a positive impact on traffic throughput. The traffic flow improved especially in conditions with high-traffic volume and with higher penetration rate of CACC vehicles.

3. *Dynamic Eco-driving system*

The eco-driving systems discussed before are based on giving static advice to drivers. Barth and Boriboonsomsin (2009) proposed a dynamic eco-driving system which give dynamic advice to drivers based on traffic and weather conditions. The advices can be communicated to drivers in real-time from a traffic management center. The system tries to manage vehicles' speed and acceleration on motorway to reduce fuel consumption and vehicle emissions. The main goal of the system is to smooth traffic flow through advices giving to drivers to travel at specific speeds without affecting the overall travel time. However, real-time information about traffic conditions should be available. Such information can be obtained from loop detectors installed along the motorways. At a traffic management center, the information can be processed to calculate optimal set speed for individual vehicles. The system was found to reduce fuel consumption and CO_2 by 10-20% without affecting the overall travel time. The benefit can be higher for traffic with severe congestion.

Recently, co-operative systems have gathered a considerable interest through different European projects such as CVIS (CVIS, 2010a), SAFESPOT (SAFESPOT, 2010) and COOPERS (COOPERS, 2010). Comparable developments of co-operative system are also taking place in US through the IntelliDrive project (IntelliDrive, 2010) and in Japan notably the Advanced Safety Vehicle (ASV) project (NASVA, 2010). Many co-operative applications have been developed and demonstrated within the CVIS, SAFESPOT and COOPERS projects. The final results of the CVIS, SAFESPOT and COOPERS were demonstrated in the Amsterdam showcase, March 2010 (de Kievit and Op de peek, 2010). The applications were mainly developed for safety and efficiency objectives, and not specifically for environmental objectives. Some co-operative applications for environmental aspects are currently under development within a new European project, eCoMove started April 2010 (Vreeswijk et al., 2010).

2.6 Summary

Traffic emissions are the main source of air pollution in urban areas. In particular, traffic is responsible for the emissions of nitrogen oxides (NO_x), particulate matter (PM), volatile organic compounds (VOC) and carbon monoxide (CO), as well as the green house gas carbon dioxide (CO_2). From these pollutants only NO_x, PM_{10} and CO_2 were selected to be considered in this thesis. NO_x and PM_{10} were selected due to their severe health impacts and since they are the pollutants that regularly cause breaches of the EU limit values. CO_2 was considered due to its effects on global climate change.

To reduce traffic emissions various traffic measures can be implemented from road-side or vehicle-side. Examples of road-side measures are low emission zones and speed limit reduction. ADAS and Eco-driver solutions are examples of vehicle-side measures. Recently the use of co-operative systems have emerged as a potential candidate to improve traffic safety, efficiency and to reduce emissions. Various applications have been developed and tested within European projects such as CVIS and SAFESPOT. However, the focus in these projects was mainly on safety and efficiency aspects. Although the applications were not specifically developed for environmental objective, some of them were found to reduce fuel consumption as well as traffic emissions. More reductions can be achieved from co-operative system which specifically target environmental issues. The rest of this thesis will focus on developing and evaluating the impact of an environmentally friendly co-operative system on the environment.

Chapter 3

The development of an indicator for local air quality

This chapter presents the development of an indicator for local air quality to support decision making on short-term local traffic measures. The chapter begins with an introduction in section 3.1. Section 3.2 explains the need for an indicator for local air quality. The reference pattern method used in the development of the indicator is discussed in section 3.3. Section 3.4 describes the air quality data used for the indicator development along with the kerbside and the background monitoring stations. The steps taken to develop the indicator are explained in section 3.5. Finally, section 3.6 summarizes the contents of this chapter.

3.1 Introduction

Over the past years, traffic management has been used especially to improve traffic flow efficiency. However, with environmental concerns on the rise, traffic management can also be used to reduce the negative impacts of traffic on the environment. Traffic management may contribute to environmental objectives such as reducing noise and improving air quality. To improve air quality, locations with elevated levels of air pollutants are of major concern. Elevated levels of air pollutants can be caused by numerous sources and can be permanent or temporary. Permanent elevated levels are associated to ambient urban pollution and long-term air quality hot-spots, for which EU annual limit values have been implemented. Temporally elevated levels such as short-term pollution peaks are very high peak concentrations which occur for short periods of time. Short-term EU limit values (daily and hourly limits) have been implemented to deal with temporally elevated air pollutants. In the case of temporally elevated air pollutants, local short-term traffic measures such as speed adaptation can be used to reduce concentration levels (Jones et al., 2005). The short- and long-term EU limit values for NO_2 and PM_{10} are presented in Table 3.1.

Before implementing short-term local traffic measures, the local air quality needs to be measured to decide whether it is good or poor. There are two approaches for measuring local air quality, namely monitoring and modeling. Local air pollution monitoring has been started since the 1960's in many European cities. Monitoring data are important for defining the status of air quality in Europe and for policy needs. The data can also be compared with EU limit values to define areas which are exceeding the limits. Furthermore, monitoring data from local/hot spot stations can give a basis for assessing the high end of the population exposure to pollutants, since concentrations are highest near hot-spot locations. Generally two types of monitoring stations are installed: traffic or kerbside stations

Table 3.1: *Short- and long-term EU limit values for NO_2 and PM_{10}*

Pollutant	Short-term limit values	Long-term limit values
NO_2	Hourly limit value = 200 μgm^{-3} which must not be exceeded more than 18 times a year. It had to be met by 2010	Annual limit value = 40 μgm^{-3}. It had to be met by 2010
PM_{10}	24-hour limit value = 50 μgm^{-3} which must not be exceeded more than 35 times a year. It had to be met by 2005	Annual limit value = 40 μgm^{-3}. It had to be met by 2010

located near road-side, and background stations located in areas that are not significantly affected by any single source of emission (Sokhi and Yu, 2005).

The contribution of traffic to concentration levels at street level can be obtained by subtracting the time series of concentration measurements of a background station from that of a traffic station. Such time series are used in applications such as calculating emission and emission factors, and testing and validating dispersion models (Sokhi and Yu, 2005). However, the monitoring data do not give answers to questions such as: How is the air quality situation in areas where measurements are not taken? What are the main contributors to air quality and how much do they contribute? What are the most effective measures that can be implemented to reduce traffic emissions and improve local air quality?

Modeling is cheaper than monitoring especially for long periods or large scale areas. Modeling results can give an estimate of air quality situations for areas which are not covered by monitoring networks. However, models need to be evaluated in terms of accuracy before they can be used with confidence. Most importantly, modeling is useful for forecasting poor air quality situations. For the decision making on short-term measures, the use of forecasted data is better in order to avoid peaks in concentration levels instead of reacting to it once it occurs. Finally, modeling plays an important role in assessing the impact of various traffic measures, and hence decides which measure to be implemented for specific area.

Looking at the advantages and disadvantages of both approaches, it is clear that the most ideal method for assessing air quality is to combine measurements with modeling data. For example, measurement data can be used to validate dispersion models before they can be used with confidence. Another example is the run time integration of modeling with measurements to provide high time/space measurements resolution of both air pollutant concentrations and traffic emissions. This was used to design a system for the Beijing ITS-TAP project (Intelligent Transport System-Traffic Air Pollution) (Costabile and Allegrini, 2008). The same method of combining measurements with modeling results was used in the MESSAGE project in the UK (MESSAGE, 2010).

3.2 Needs for an indicator

If short-term traffic measures are considered to improve air quality, an indicator for local air quality is needed. Based on this indicator, it can be decided whether to activate a measure and when it might contribute to lower pollutant concentrations. Such an indicator can then be included in the framework of multi-objective traffic management systems. This will help to switch between different scenarios, for example, efficiency or environmental, especially in areas where the activation of environmental measures can negatively affect other objectives in other parts of the network.

In general, an environmental indicator can be based on emissions levels or concentration levels of air pollutants. However, concentration levels are more relevant for judging the actual air quality with respect to human health and when making a comparison to the EU limit values. Accordingly, short-term local measures should be related to concentration levels. The EU limit values can be used directly as indicator for local air quality. However, short- and long-term EU limit values send conflicting signals about the actual air quality. For example, in a certain area, while hourly concentrations always remain below the hourly limit, the yearly limit can be exceeded. The question is, therefore, how to judge the hourly concentrations measurements in relationship to the yearly limit. Since the annual EU limit value for both NO_2 and PM_{10} is stricter than the hourly EU limit value, it can be used to judge hourly measurements. However, both NO_2 and PM_{10} exhibit seasonal, daily and hourly variation, and hence an hourly concentration above the EU limit value might not be judged as poor if it can find adequate compensation at another moment in the year (Elshout, 2004).

3.3 Reference pattern method

Elshout (2004) has analyzed the conflict between short and long-term EU limit values and presented a solution method. The method is based on a reference pattern which has been developed from average concentrations of five years. The measurements were taken from an urban background station. Using statistical analysis, the method first establishes various patterns (daily, weekly, monthly) in the hourly concentration measurements. This leads to an average concentration pattern for each hour of the day, day of the week and month of the year. An example of such pattern for NO_2 is illustrated in Figure 3.1. The reference pattern is defined as the resulting pattern when the hourly concentrations are scaled in such a way that the yearly average of all average observations yields a concentration of 40 $\mu g m^{-3}$.

Statistically speaking, hourly concentrations above this reference pattern will contribute to exceedances of the limit value; it is unlikely that they will be adequately compensated by lower concentrations during other hours. Using this pattern, every hour a measured value can be checked to see if it fits into the pattern or contributes to the exceedances of the limit values. An example of the developed reference pattern, together with the observed values, is shown in Figure 3.2. In this Figure, the NO_2 concentrations scale is divided into three levels: poor, mediocre and adequate. If an hourly concentration is above 200 $\mu g m^{-3}$ (the EU hourly limit value), it is interpreted as poor. The reference pattern defines the border between the mediocre and the adequate level. The two arrows show that the

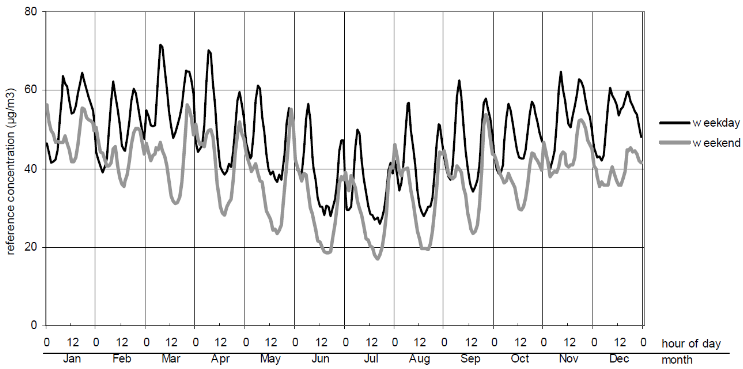


Figure 3.1: *Five-year average diurnal NO_2 concentration pattern, on weekdays and weekends, for each month of the year and with an urban background*

reference pattern is more strict on Saturday afternoon than on a weekday morning. The left arrow, which points to an hour with lower concentration than the right arrow, is judged as mediocre because statistically it is unlikely to be compensated by an hour with a lower concentration. On the other hand, the right arrow is judged as adequate.

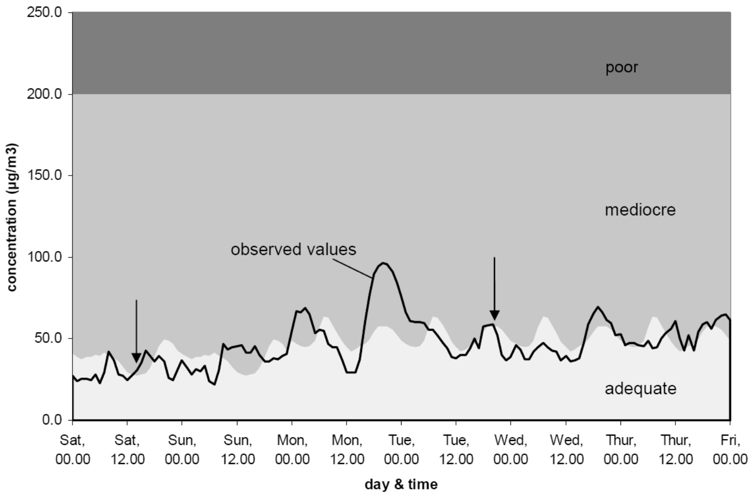


Figure 3.2: *Hourly NO_2 concentration interpreted using a reference pattern*

3.4 Data collection

The air quality data used for the development of the indicator was taken from a kerbside and an urban background monitoring stations. The kerbside station is located at the Bentinckplein intersection in Rotterdam, The Netherlands. See Figure 3.3.

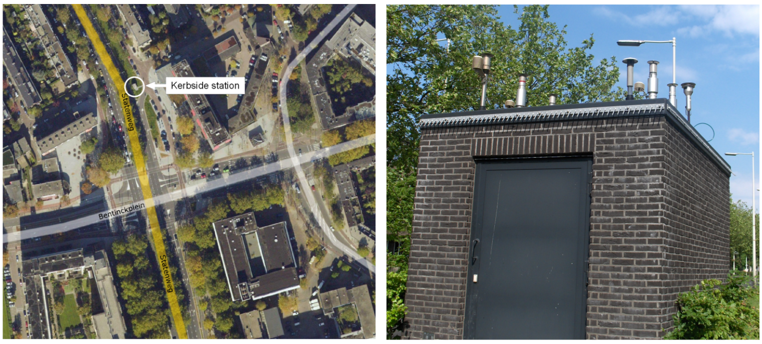


Figure 3.3: *The Bentinckplein intersection and the kerbside monitoring station*

The background station is located in the city of Schiedam about 4 km to the west from the kerbside station. Both the kerbside and the background stations are part of the regular regional air quality network in the Netherlands. Figure 3.4 illustrates both the kerbside and the background stations.

Figure 3.4: *The kerbside station, Rotterdam and the Background station, Schiedam*

Hourly concentration measurements for NO_2, NO and PM_{10} were available for the period of 2005-2008 at the two stations. The NO_x, concentration level was calculated using the following equation:

$$NO_x = NO * \frac{46}{30} + NO_2 \tag{3.1}$$

Equation 3.1 expresses NO_x in terms of NO_2. The right hand-side of the equation adds different pollutants expressed in $\mu g m^{-3}$. Therefore, one pollutant needs to be expressed into the molar weight of the other pollutant. NO_2 has a molar weight of 46 and NO of 30. To make the addition correct, NO is multiplied with the ratio of the molar weights of NO_2 and NO.

3.5 Development of the indicator

In this section the development of the indicator is explained. First, the main pollutant to be used as an indicator for traffic emission is selected. Next, the steps taken to develop the indicator are explained for NO_x and NO_2 as well as PM_{10}.

3.5.1 Selection of the main pollutant

Traffic is the major contributor of NO_x emissions in urban areas (Chaloulakou et al., 2008). Therefore, NO_x can be used as a main indicator for traffic emissions. However, the use of NO_x as a main indicator depends on the location. In a site affected by many other sources of emissions, NO_x will not be a reliable indicator for traffic emissions. To check if NO_x can be used as an indicator for traffic at Bentinckplein site, the data from the kerbside by time of day and day of week was plotted to see whether this follows known traffic variations. The result appears in Figure 3.5.

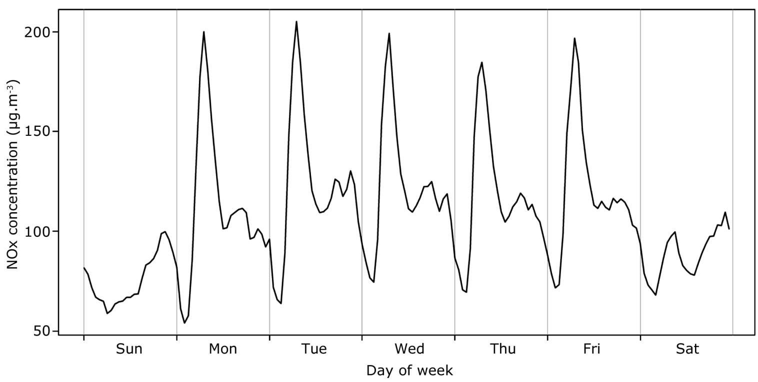


Figure 3.5: *NO_x concentration by Day of Week at the kerbside*

Figure 3.5 shows that the concentration of NO_x data follows the traffic variation, but the morning peak is much higher than the evening peak. This difference is caused by the condition of the atmosphere: in the early morning the atmosphere is stable, and the mixing layer is small. As the atmosphere warms up during the day the mixing layer expands, more turbulence occurs, wind might increase etc., resulting in more dispersion and lower concentrations. Also, early morning always shows a peak in energy demands because people wake up, switch on their heating, lights and start driving. This means that emissions are emitted in a small volume of air, showing a very steep rise.

Consequently, NO_x was used as the main pollutant in developing the indicator. However, NO_2 was also used to optimize the decisions for limit value compliance.

3.5.2 Indicator for Nitrogen Oxides, Nitrogen Dioxide

First, hourly NO_2 concentration measurements from the kerbside were compared against the previously developed reference pattern which was based on a regional background. Although the reference pattern allows for higher concentrations during rush-hour morning peaks, the kerbside measurements often appear to exceed the reference pattern. This means that the peaks are indeed traffic-related and hence a permanent measure could be implemented during the morning rush-hours. However, a permanent measure has two disadvantages: (1) it applies also on rainy and windy days when peaks do not occur and (2) it does not apply when peaks other than the rush hour occur. For the measure to be dynamic, it was decided that the measure should not be invoked more than 25 % of the time. This percentage is arbitrary, but it was reasoned that if a measure is needed more than 25 % of the time, a permanent measure could be warranted. A permanent measure will avoid the complicated environmental and IT infrastructure along with real-time decision-making systems. It was also decided that there should be a 90 % chance of three consecutive hours of exceedances; otherwise the system switches on and off.

Analyzing the air quality data for the year 2007, it was found that NO_x and NO_2 concentrations during the first quarter of the year (January to March) are much higher than in the rest of the year. Even when only looking at the winter season (October to March) a large difference was realized between the period of October to December, and January to March. Using these criteria, it was found that threshold values can be identified for roadside increments of NO_2 (ΔNO_2) and of NO_x (ΔNO_x) for different periods of the year. ΔNO_x is the difference between values at kerbside and background stations, which is a signal that NO_x increases due to the local traffic contribution.

$$\Delta NO_x(h_i) = C(NO_x(h_i))_k - C(NO_x(h_i))_b \tag{3.2}$$

where

$$\begin{aligned} CNO_x(h_i)_k &= NO_x \text{ concentration at kerbside station during hour } h_i \\ &\quad \text{of the day} \\ CNO_x(h_i)_b &= NO_x \text{ concentration at background station during hour } h_i \\ &\quad \text{of the day} \\ i &= 0, 1, .. 23 \end{aligned}$$

ΔNO_2 is the difference between values at kerbside station and the reference pattern, which is a signal that NO_2 concentrations are likely to contribute to a year average limit value exceedances.

$$\Delta NO_2(h_i) = C(NO_2(h_i))_k - C(NO_2(h_i))_r \tag{3.3}$$

The resulting threshold values for NO_x and NO_2 for different periods of the year are shown in Table 3.2.

The threshold values in Table 3.2 are based on a database of measured values. More accurate threshold values could have been obtained if a larger database was used. Moreover,

Table 3.2: *Threshold values for applying traffic measures to manage NO_2 peaks at the kerbside*

	Jan, Feb, Mar	April, May, June	July, Aug, Sept	Oct, Nov, Dec
ΔNO_x	20	10	10	10
ΔNO_2	25	10	10	10
Measure activation % of time	22 %	12 %	13%	16 %

to obtain more accurate results, threshold values can be decided for shorter periods, for example, per month.

These threshold values can be coupled with other real-time traffic and weather data used for operational decision making on environmental measures in the lower concentration ranges. If NO_2 concentrations exceed the hourly EU limit value of 200 μgm^{-3}, which is rare in Rotterdam, the measure should be invoked to avoid any further accumulation.

3.5.3 Indicator for Particulate Matter

Previous studies have shown that elevated PM_{10} concentrations in Rotterdam are always due to poor dispersion conditions and/or a high level of background concentration (Erbrink and Spoelstra, 2007). This suggests that the use of traffic measures will not significantly improve the situation. However, from a health perspective, the accumulation of PM_{10} traffic emissions during these conditions is undesirable. For this reason, the PM_{10} short-term EU limit value (a daily average concentration of 50 μgm^{-3}) was used. It was decided that if the 24-hour moving average PM_{10} concentration reaches 50 μgm^{-3}, the measure should be activated and remain in force until the hourly concentration drops below 35 μgm^{-3}. Even when the moving average remains high due to previously high concentrations, there is no need to maintain the measure once the actual hourly concentrations have dropped considerably. The maximum allowed level of 35 μgm^{-3} was selected arbitrarily because sufficient data was not available to carefully decide a reasonable stop indicator. If sufficient data is available, one could decide to trigger the measure at a lower 24-hour moving average concentration (e.g. 40 or 45 μgm^{-3}) if it could be shown that this moving average concentration would more likely continue to grow and exceed the threshold of 50 μgm^{-3} (e.g. 90 % of the time). A summary of the decision-making rules for the Rotterdam kerbside is presented in Table 3.3.

Table 3.3: *Summary of decision-making rules for the Rotterdam kerbside*

Step	Pollutant concentration $\mu g m^{-3}$	Description of Rule	Action if Answer is Yes
1	$CNO_2(h_i)_k > 200$	Exceeds short-term EU limit value?	Activate measure until concentrations drop
2	$CNO_2(h_i)_k > NO_2$ reference concentration by ΔNO_2	Hour likely to contribute to exceedances of year average limit value?	Check if there is a substantial traffic related component in the local air pollution
	$CNO_x(h_i)_k - CNO_x(h_i)_b$ by ΔNO_x	Tests for substantial traffic emissions (occurring as NO_x)?	Activate measure until concentrations drop
3	PM_{10} 24-hour moving average $> 50\ \mu g m^{-3}$	Exceeds short-term EU limit value?	Activate measure until hourly PM_{10} concentration drops $< 35\ \mu g m^{-3}$

3.6 Summary

Before implementing local short-term air quality measures, an indicator for the local air quality needs to be developed. This will help to determine when to activate the measures. In this chapter, a set of air quality rules was developed for a kerbside in the city of Rotterdam. The rules were based on statistical analysis of hourly measurements of NO, NO_2 and PM_{10} concentration levels. Threshold values for the road-side increments for NO_2 (ΔNO_2) and NO_x (ΔNO_x) were determined for different periods of the year (per three months).

The general methodology followed for the city of Rotterdam can be applied to other areas. The actual criteria are, of course, site specific and the following steps need to be taken: (1) Develop a reference pattern for the considered area, (2) Select a decision threshold for NO_2 (for different periods of year), (3) Choose the percentage of time that the measure might be invoked and (4) Select the minimum number of consecutive hours a measure is wanted. All these criteria are a function of statistical analysis of the available air quality data.

Chapter 4

Modeling framework

In this chapter the design of the modeling framework is presented. The chapter includes literature surveys on traffic, emissions and dispersion models. Choices for models to be used are made according to the special requirements and level of detail needed in this thesis. Section 4.1 introduces the concept of simulation models explaining their importance in assessing the impact of Intelligent Transportation Systems (ITS). Section 4.2 defines a number of different traffic modeling approaches, focusing on microscopic simulation models. Section 4.3 deals with traffic emission models and their various calculation methods. Dispersion modeling forms the subject matter of section 4.4. Finally a summary is given in section 4.5.

4.1 Introduction

A model is an abstraction of a system that exists and operates in time and space. Simulation is the manipulation of a model under different configurations in order to understand the interaction within the different parts of the system and the system as a whole (Bellinger, 2004). Recently simulation models have been increasingly used to model complex transport networks due to the availability of the required computing power. They are important tools in traffic engineering as they can be used to assess the impact of a system before the real implementation. However, as simulation models only give an approximate of the real system, their results will not give a perfect prediction of what will happen in the real world.

To evaluate the impact of a traffic measure on local air quality and to assess the effectiveness of the measure, a modeling framework is needed. For that traffic and environmental models are used. Traffic models are used to simulate the real traffic situation before and after the implementation of the measure. Environmental models including emission and dispersion models are used to simulate the effect of the measure on the emissions and the concentration of air pollutants. To increase the accuracy of the calculations, traffic and environmental models can be linked together. The link can be established at various spatial and temporal levels of vehicles aggregation (Boulter and McCare, 2007). The choices of the models should be made based on the required level of detail and the accuracy needed by the application, because no model can be the best for all situations. Figure 4.1 illustrates the interaction between the traffic, emission and dispersion models. The results from the traffic model are fed into the emission model to account for the amount of emissions released. The results from the emission model are used as inputs for the dispersion model, which calculates the traffic contribution to the concentration of air pollutants. The concentration of air pollutants are checked with a pre-determined limits. In the case of poor air quality, the measure is activated and the system gets feedback on the impacts of the measure on local air quality.

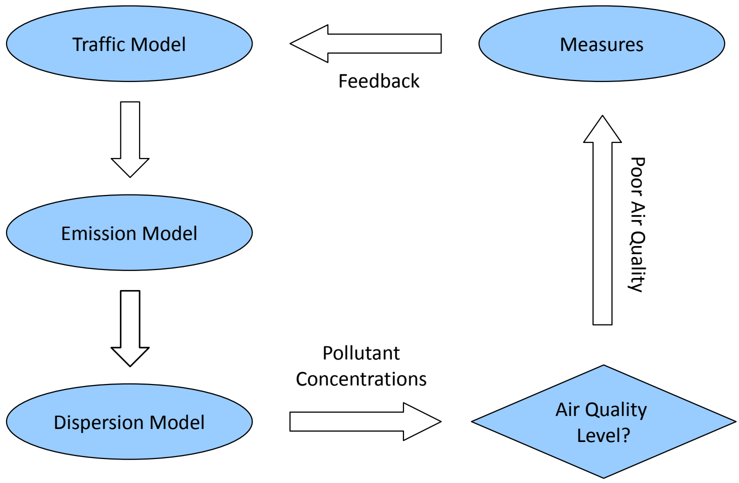


Figure 4.1: *Modeling framework*

Many different models are available for traffic, emission and dispersion modeling. For example, emission models can vary from instantaneous models that calculate emissions of a vehicle every second to models that calculate emissions based on average daily traffic flow. According to the level of detail of the emission model, the required inputs from the traffic model can range from aggregated traffic data (e.g. average speed) to the speed-time profiles of individual vehicles (Spence et al., 2008). A literature study of traffic modeling as well as emission and dispersion modeling has been carried out in order to identify the state of the art and to help designing the overall modeling framework.

4.2 Traffic Modeling

Traffic simulation models are computer programs that simulate the behavior of traffic over a user-defined transport network over time and space. Their main objective is to assess the network capacity and system performance using the relationships between traffic flow, speed and density. They can be divided into microscopic, macroscopic and mesoscopic simulation models. In microscopic simulation models, the movement of individual vehicles is considered. Macroscopic simulation models represent traffic as an aggregate flow to describe the relationships among traffic speed, flow and density. Mesoscopic simulation models deal with individual vehicles movements based on the macroscopic traffic relationships. Microscopic simulation models are better in representing the actual driver behavior since they consider the movement of individual vehicles. To accurately estimate traffic emissions, detailed information about vehicle operation and location is needed. Therefore, microscopic simulation models are often used in a connection with traffic emission models.

In general, microscopic simulation models predict the movement of individual vehicles in real time over a series of short time intervals. Models for driver behavior are used such as car-following, lane-changing and gap-acceptance models (Boulter and McCare, 2007). Car-following models describe how a vehicle reacts to a vehicle in front of it. Lane-changing models control the lateral movement of vehicles in multi-lane situations. Gap-acceptance models define the minimum distances to surrounding vehicles in the context of intersection and merging situations (Velez, 2006; Jones et al., 2004). To decide which microscopic simulation model is the most suitable for this thesis, a list of selection criteria has been set up. These include the following:

- the microscopic simulation model should be able to simulate an urban environment i.e. one or more intersections with the possibility to model the communication between vehicles and road-side units (e.g., traffic light);
- the model should be flexible in programming traffic signal control and could be linked to external signal state generator software;
- the model must be able to produce valid driving patterns to account for emission calculation;
- the model needs to be available (practical choice).

The most commonly used microscopic simulation models were reviewed keeping in mind the aforementioned list of criteria. The models reviewed include AIMSUN, PARAMICS and VISSIM. These are described in the following subsections.

4.2.1 AIMSUN

AIMSUN (Advanced Interactive Microscopic Simulator for Urban and Non-urban Network), was developed at the department of statistics and operational research, Universitat Poletecnica de Catalunya, Barcelona, Spain. It is a microscopic simulation model that can reproduce real traffic conditions of different networks (urban and non-urban). It is considered as combined discrete-continuous simulator, where some elements continuously change their states during the simulation time (e.g. vehicles), while other elements only change their state discretely at specific points (e.g. traffic signal).

The inputs to the AIMSUN model are the network description, traffic signal control plans, traffic demand and public transport demand. The network description includes information about network geometry, turning movements, layout of links and junctions and locations of detectors. Traffic signal plans define the signal stages and their duration, the priority definition for unsigned junctions, and information for ramp metering. The traffic demand can be specified as the traffic flow for the link, the turning proportion at junctions, and initial state of the network. The traffic demand can also be defined as Origin Destination (O/D) matrix that determines the number of trips from every origin to any destination. Finally, a public transport plan comprises the definition of bus lines and timetables for each line. The outputs from the simulation include statistical data, and data collected by the detectors as well as the continuous animated graphical representation of the network.

AIMSUN is integrated into GETRAM simulation environment (Generic Environment for Traffic Analysis and Modeling). GETRAM consists of a traffic network graphical editor (TEDI), a network database, a module for storing and API to interface to assignment models and other simulation models. Using the GETRAM extension (API) module, AIMSUN can communicate (i.e. interface) with external user-defined applications. AIMSUN has very detailed capabilities and can distinguish between different types of vehicles. It can also deal with a wide range of roadway types, model the impact of Variable Message Sign (VMS) and replicate any kind of traffic detector (Xiao et al., 2005; Velez, 2006).

Two environmental models are included in AIMSUN, namely fuel consumption and pollution emission models. These give results for different levels of aggregation i.e. entire network, each section and turning, and each route. The results from the pollution emission model include CO, NOx and HC emissions. All the information about AIMSUN was taken from the user manual of AIMSUN version 4.1 (TTS, 2002), which was available when this review was conducted.

4.2.2 PARAMICS

PARAMICS (PARAllel MICroscopic Simulation model) was developed in the late 1980s. It is a suite of high performance software tools where the movement and behaviors of individual vehicles can be modeled on urban and highway road networks. Since 1998 the model has been marketed by two companies Quadstone and SIAS as two models known as Q-PARAMICS and S-PARAMICS (Boulter and McCare, 2007). The focus here is on Q-PARAMICS version 5.1 which was available by the time this review was conducted.

Q-PARAMICS has the following modules:

1. *Modeler*: is the core simulation tool which provides network build, traffic simulation and visualization via graphical user interface (GUI). Moreover, it provides the users with a statistical output capability allowing them to study the performance of their networks.

2. *Analyzer*: is used for reporting output data and analyzing different set of results.

3. *Processor*: is a batch simulation tool used to run the simulation without visualizing the network and vehicles. This increases the simulation speed by making the statistical collection phase more efficient.

4. *Programmer*: is an Application Programming Interface (API) to simulate additional features and user defined algorithms.

5. *Estimator*: is the O/D matrix estimation tool.

6. *Viewer*: is the network visualization and demonstration tool.

7. *Designer*: is the 3D model-building tool used with *modeler* and *viewer*.

8. *Monitor*: is a pollution evaluation module which calculate emissions per vehicle level. It is based on emission inventories of UK. The results include emissions for CO, CO_2, NO_x, PM and fuel consumption. Monitor uses up to five variables to calculate pollution emissions including vehicle speed and acceleration, speed multiplied by acceleration, link gradient, and the time spent by the vehicle in the network. The emissions can be calculated using any combination of these variables.

PARAMICS was developed to be used under a Unix environment but can also be used with other operating systems such as Windows. In reality, there is no real limit to what can be modeled (number of links, nodes and zones) by the model. Therefore, PARAMICS is considered as a portable and scalable software which can be used to modeled different network sizes (QUADSTONE, 2005).

4.2.3 VISSIM

German for Traffic in Towns simulation (VISSIM) was developed at the University of Karlsruhe, Germany during the early 1970s. The model started to be commercially distributed by PTV Transworld AG in 1993 (Bloomberg and Dale, 2000). VISSIM is a microscopic/stochastic, time-step and behavior-based simulation model developed to model urban traffic and public transit operations. It is capable of simulating multi-modal traffic flows such as cars, trucks, buses, heavy rail, tram, bicyclist, and pedestrian. Each single entity is modeled as driver-vehicle-unit (DVU).

The model has two main components, namely traffic simulator and signal state generator (SSG). The traffic simulator model generates the traffic and allows the users to build their networks. The signal state generator receives the detector values from the traffic simulator and accordingly decides the signal status for the next time steps. With the SSG, users have the ability to define the signal control logic using the VAP (Vehicle Actuated Phasing) language. Moreover, the users can analyze the impacts of signal operations such as fixed time, actuated, adaptive, transit signal priority and ramp metering (Gomes et al., 2004).

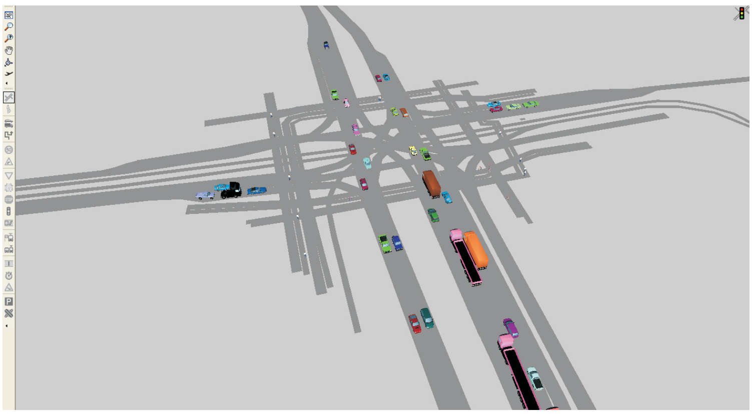


Figure 4.2: *VISSIM visualization*

In VISSIM, the traffic flow algorithms are based on a psycho-physical car-following model for longitudinal vehicle movement and a rule-based algorithm for lateral movement. The car-following model is based on the continued work of Wiedemann (Leutzbach and Wiedemann, 1986). There are four driving modes: free driving, approaching, following and breaking where the driver behaves differently in each mode. The acceleration in each mode is defined according to the vehicle speed, distance and speed difference between vehicles, and individual characteristics of the driver and the vehicle. On multi-lane links, a driver can decide whether to change the lane or not, depending on the routing requirements such as approaching an intersection (forced) or merging to a fast-moving lane. Before changing the lane, vehicles have to find an acceptable gap on the other lane.

The required input by the VISSIM include lane assignments and geometries, demands based on O/D matrices or flow rate and turning percentages, distribution of vehicle speeds, acceleration and deceleration and signal control timing plans. Many measures of effectiveness can be obtained as outputs such as total delay, stopped-time delay, stops, queue lengths, fuel emissions and fuel consumption (Xiao et al., 2005).

VISSIM has an optional emission module which requires an additional license. The emission module uses information per second about each vehicle type, position, speed and acceleration to calculate hot emissions and fuel consumption. Moreover, the emissions during cold start as well as during parking (evaporation emissions) are considered. Emission maps can be given per each vehicle type for different pollutants such as CO, CO_2, NO_x, PM, SO_2 and $VOCs$ (Boulter and McCare, 2007).

4.2.4 AIMSUN vs. PARAMICS vs. VISSIM

A functional evaluation of the three models was performed by Hidas (2005). The evaluation was based on the following version of the models: AIMSUN V4.2, PARAMICS V4.2 and VISSIM V3.7. In general, no model was considered as the best for all situations, but still there are some differences that can make one of the models less or more suitable for specific situations. Some of the differences are:

1. For bicycle, motorcycle, and pedestrian modeling, VISSIM has more realistic models than AIMSUN and PARAMICS.

2. The gap acceptance model in VISSIM has found to be more flexible and more detailed. This helps in modeling complex and unusual traffic situation in a more realistic way than in AIMSUN and PARAMICS.

3. VISSIM has more detailed network and traffic models allowing for the consideration of vehicle widths, lateral movement between the lanes, and modeling two-wheeled vehicles (motorcycles and cycles).

4. Compared to AIMSUN and PARAMICS, VISSIM is less suitable and convenient for simulating large networks with significant route choices options. However, VISSIM is more suitable for small-scale networks with complex geometry, and/or unusual difficult networks, traffic, and control conditions.

For intersection modeling, VISSIM is considered to have a better method for simulating traffic at intersections, because of the many modeling parameters for intersections that can be controlled by the user (Poska, 2002). Moreover, VISSIM has a high quality and more detailed traffic control model including user behavior at traffic signals. Furthermore, VISSIM has the ability to model adaptive signal control and link to external signal state generator software (VAP tool) (Hidas, 2005). Accordingly, VISSIM has been selected to be used in this thesis.

Although each microscopic traffic model has an internal emission module incorporated with it, these emission modules have not been used a lot in estimating emission. The results from these modules are not very reliable since the calculation is based on a relatively small database using speed-acceleration lookup table of emission factors.

4.3 Emission Modeling

Since 1970s, many studies have been conducted in Europe to estimate traffic emissions on both national and local basis, most often using traffic emission models (Spence et al., 2008). Traffic emission models are used due to the fact that measuring traffic emissions in real-time from the field is very expensive. Moreover, traffic emission models are used to forecast trends in future traffic emissions. Many factors influence emissions of individual vehicles including, for example: vehicle design characteristics, driving behavior, engine age and emission control components as well as driving modes (e.g., cold or hot) (Smit and McBroom, 2009). Traffic emission models vary in the way they consider all these factors and can be classified based on a combination of the following:

- the geographical scale of the application (i.e. micro-scale, meso-scale, macro-scale);
- the generic model type (e.g., aggregated emission factors, average speed);
- the nature of emission calculation approach (i.e. discrete, continuous).

Some examples of various generic types are defined in Table 4.1 (Boulter et al., 2002), together with their advantages and limitations. These are discussed in the next subsections (Boulter et al., 2002; Spence et al., 2008).

4.3.1 Aggregated emission factor models

Aggregated emission factor models use emission factors that are calculated from laboratory test on a number of vehicles using standardized driving cycles. Driving cycles are based on real-world measurements describing vehicle speed as a function of time. Emission factors are given in terms of the mass of pollutant emitted per vehicle and per unit distance (g/veh.km). Generally, emission factors models differentiate between urban roads, rural roads and motorways and do not take into account detailed vehicle operation. Therefore, aggregated emission factor models are more appropriate for large scale applications such as emission inventories.

4.3.2 Average speed models

Average speed models calculate average vehicle emissions over a trip as a function of average speed. The required input data is the trip-based average speed. Although, average speed models are more suitable for large scale applications, they have been used a lot for meso- and micro-scale applications, due to the fact that they have a long-established method and are easy to use. Moreover, the required input data is often available to the users. However, average speed models are not suitable for micro-scale applications due to the following limitations:

- for two different trips, although average speed can be the same, vehicles' operations (i.e. maximum speed, acceleration pattern) might be different and thus the level of emissions;
- for new vehicles equipped with after-treatment devices, the average speed is not a reliable indicator for emissions. This is due to the fact that for such vehicles, high amounts of emissions can be produced during very short sharp peaks that occur during gear changes and high acceleration;

- the function of the average speed does not reflect the real-world driving because it depends on the type of driving cycle used in the laboratory for the function development;
- with regard to dispersion modeling, average speed models lack detailed spatial information of the emission prediction. Berkowicz et al. (2006) found that the use of emission models that depend on average speed leads to a significant underestimation of street level pollution concentrations.

COPERT (Ntziachristos et al., 2009) is an example of an emission model that is based on aggregated emission factors and average speed. It is a European tool to calculate emissions from road transport. COPERT includes different calculation processes for exhaust and non-exhaust emissions.

4.3.3 Traffic situation models

Traffic situation models try to include the effect of both speed and cycle dynamics in the emission calculations. This is through the correlation of cycle average emission rates with various driving cycle parameters, which are referenced to specific traffic situations. The input data includes road type, speed limit and level of congestion. These should be provided by the user as a textual description, which might lead to conflict in interpretation.

An example of these models is the Handbook of emission factor factors (HBEFA) (HBEFA, 2010). The model has been used in Germany, Austria and Switzerland. The latest version of the model (3.1) is available since January, 2010. It provides emission factors for Passenger Cars (PC), Light Duty Vehicles (LDV), Heavy Duty Vehicles (HGV), urban buses, coaches and motor cycles. These are divided into different categories, for a wide variety of traffic situations.

4.3.4 Modal models

Modal emission models relate vehicle operation modes to the emissions produced during these modes. The emission rates during these operation modes are assumed to be fixed for a given vehicle and pollutant. Simple models use a small number of modes such as: steady-state, acceleration, deceleration and idling.

The Urban Road Pollution (UROPOL) model (Hassounah and Miller, 1995) is an example of a simple modal models. However, no recent information was available on this model.

Table 4.1: *Emission Models*

Generic Type	Definition	Examples	Advantages	Limitations
Aggregated emission factors	Emission factor calculated from laboratory test on a number of vehicles using a given driving cycle. A single emission factor is used to represent a particular type of a vehicle and a general type of driving	COPERT	Appropriate for large scale applications Relatively large number of measurements	Can not be used to determine emissions for situations which are not explicitly covered by the emission factors
Average speed	Calculate average vehicle emission over a trip as a function of average speed	COPERT	Suitable for large scale Relatively large number of measurements	Can not account for the variability in driving dynamics at a particular speed. With new vehicles average speed is not a reliable indicator for the high amount of emissions during short peaks
Traffic situation	Correlate cycle average emission rates with various driving cycle parameters, which are referenced to specific traffic situation	Handbook for emission factors (HBEFA)	Best for local applications (road links)	No universally accepted definitions for traffic situations
Modal (simple)	Relate vehicle operation modes (steady state, acceleration, deceleration and idling) to the emissions produced during these modes	UROPOL	Better than emission factor type as they reflect the effects of vehicle-operating modes, so high resolution is possible	Lack in the tool for forecasting vehicle activity modes
Instantaneous - speed based	Emission rates are calculated on a second-by-second basis from instantaneous speed & acceleration	MODEM	Can take into account the dynamics of driving cycles	Time lag and damping of the signal being sampled
Instantaneous - power based	Use description of the engine power requirement	PHEM	Take into account vehicle load and road gradients	Required information is expensive to collect
Instantaneous - statistical based	Calculate emissions using speed time profile of vehicles based on speed and acceleration	VERSIT+	Can estimate accuracy	Need very large database

4.3.5 Instantaneous models

Instantaneous models are a complex extension of modal models, in which emission rates are calculated on a second-by-second basis. A comprehensive review of instantaneous emission models was performed by Boulter et al. (2007). With instantaneous models, emissions can be calculated for any vehicle profile. Consequently, new emission factors can be obtained without extra laboratory tests. Moreover, the dynamics of the driving cycles can be taken into account. However, older generation of instantaneous models have the following problems:

- the required inputs are expensive and difficult to collect. They include detailed information about vehicle operation and location. However, with the use of microscopic simulation models, such information is becoming more and more available.
- continuous measurement of vehicles' emission in the lab with high accuracy is difficult. For example, the emissions signal was found to be delayed and smoothed during lab measurements, which make it difficult to assign emission rates to the correct vehicle operation. This has been solved in some recent instantaneous models.

Instantaneous models can be based on vehicle speed and acceleration, power engine demand and statistical analysis. These are discussed in the following paragraphs through a specific example.

MODEM (Joumard et al., 1995) is an instantaneous model based on speed and acceleration. The model was developed during the European Commission DRIVE program for urban areas with vehicle speeds up to 90 kmh^{-1}. An additional set of emission factors was added by TRL to account for higher speeds. The emissions are calculated as a function of vehicle speed and the product of the vehicle speed and acceleration. The model give results for fuel consumption as well as emissions of CO, HC, NO_x and CO_2. However, the model is considered outdated because the most recent class of vehicles included is Euro 1 (Boulter et al., 2007).

An example of instantaneous power-based model is the Passenger car and Heavy duty vehicle Emission Model (PHEM). The required inputs are a driving pattern defined by the user and a file describing the vehicle characteristics. PHEM calculates emissions based on the instantaneous engine power demand and engine speed. The model gives outputs for engine power, engine speed, fuel consumption and emissions of CO, CO_2, HC, NO_x and PM on second basis as well as average values for the whole driving pattern. PHEM has two parts, namely a heavy duty vehicles part and a passenger cars part. For passenger cars, the model has been adjusted to account for the problem with the delay of the emissions signal during measurements (Rexeis et al., 2005; Zallinger et al., 2005). PHEM has been linked to VISSIM as one toolbox. Hirschmann and Fellendorf (2010) used the toolbox to investigate the impact of different actuated signal control strategies on traffic emissions. Individual vehicle trajectories were obtained from VISSIM. PHEM calculates emissions for each vehicle per five seconds.

VERSIT+ is an instantaneous emission model with a solid statistical basis. The original version of the model was based on a multiple linear regression approach (Smit et al., 2007). The model was developed from a large theoretical and deterministic approach to a fully empirical and statistical framework. More than 153 actual speed-time profiles were used to apply 12,000 emission tests to a large number of vehicles. However, the recent updates to the model has shifted the model to an instantaneous model based on statistical analysis (Ligterink and de Lange, 2009). Default emission maps were developed as a function of the speed and the driving dynamics of a number of different vehicle categories. For the vehicle speed, three categories were defined: $v \leq 50\ kmh^{-1}$ (for urban), $50 \leq v \leq 80\ kmh^{-1}$ (for rural) and $v > 80\ kmh^{-1}$ (for motorway). Idling is taken into account defined as velocity less than 5 kmh^{-1} and acceleration less than 0.5 ms^{-2}. However, the vehicle fleet composition only represents the Dutch situation. The required input is the speed time profile for individual vehicles, which can be obtained from a microscopic simulation model or real world GPS data. To be able to calculate emissions for a traffic stream simulated with a microscopic simulation model, an aggregated version of VERSIT+ was developed (named as $VERSIT{+}^{micro}$). A coupling between $VERSIT{+}^{micro}$ and VISSIM was developed named as EnViVer (Ligterink et al., 2008). The input to EnViVer can be obtained from VISSIM as a data file containing information per second about individual vehicles, including vehicle type, vehicle number, speed and covered distance. Four vehicle categories are considered: light duty vehicles, heavy duty medium vehicles, heavy duty heavy vehicles and buses. For each vehicle the speed-time profile is used to calculate the emission. The emission of all traffic is obtained by aggregating the emissions of all vehicles.

4.3.6 Discussion on emission models

To select the most suitable emission model for this thesis, two important aspects should be considered. First, the model should be able to accurately calculate emissions on a micro-scale level. Second, the model must be able to evaluate the effect of traffic measures. With regard to the micro-scale applications, it is clear that models based on average speed are not suitable for such micro-scale applications. Models which consider speed-time profile of individual vehicles will give more accurate results. These are particularly instantaneous emission models.

To evaluate the effect of different traffic measures, the required emission model depends on how specific traffic measure influence individual vehicle behavior and traffic flow. For example, if the measure only affects the composition of the traffic flow and the total kilometers traveled, more aggregated models such as traffic situation models can be used. When the measure affects vehicle dynamics and engine efficiency, more detailed models can be used such as instantaneous emission models (Klunder et al., 2009).

Consequently, instantaneous emission models are considered to be the best for this thesis. In particular, the PHEM model and VERSIT+ model. The MODEM model is outdated and hence has not been considered. Other instantaneous power-based models such as the Comprehensive Modal Emissions Model (CMEM) model (Barth et al., 2001), which is used in US can also be considered. However, the focus was only on models that used in Europe. The PHEM model can be the best for evaluating eco-driving solutions such as gear-shift indicator as detailed information about engine power demand is considered in the model. The VERSIT+ model also consider emissions during idling periods and can be used to evaluate the effect of eco-driving solutions such as a Stop and Start system. Therefore, a more detailed model like PHEM might not be necessary. Furthermore, as PHEM considers only limited emission data based on specific vehicles, the results are much tuned towards these vehicles and can not represent other vehicle categories (Klunder et al., 2009).

Based on the information mentioned above the VERSIT+ model was selected for this thesis. In particular, the EnViVer model which can be used in a connection with VISSIM was selected.

4.4 Dispersion Modeling

Atmospheric dispersion models are used to predict the concentration of pollutants in the air that are emitted from different sources. They are very important tools in assessing the current and future air quality and hence help to design more efficient air pollution control management strategies. They can also be used to map the spatial distribution of air pollutants especially in areas, where monitoring stations are not installed. Dispersion models can be applied on a local basis as well as a regional and a national basis (Sokhi and Yu, 2005).

The basic concept behind air pollution modeling is the definition of a function F that predicts the concentration of pollutants in time and space from emissions and meteorological data. There are three approaches for defining F: deterministic (analytical or numerical), statistical and physical. These are summarized in Table 4.2, together with their examples, advantages and limitations (Khare and Sharama, 2002). A brief description of each approach with a model example is given in the following subsections.

4.4.1 Deterministic models

Using deterministic models, the concentrations of different pollutants can be estimated from an emission inventory and other variables (e.g, meteorological), by solving differential equations that relate the rate of change of pollutant concentration to the average wind and turbulent diffusion. In many cases a diffusion equation is used, which is derived from the mass conservation principle relating the change of the pollutant mass in time to pollutant's emission and diffusion and its flow through the surface (Khare and Sharama, 2002). Many deterministic models have been developed by the US EPA since the early 1970s. For example, HIWAY is a Gaussian dispersion model developed in 1975 (Zimmerman and Thompson, 1975). In this model, the highway emissions are treated as a series of finite line sources; where each lane is modeled as a straight finite line source with uniform rate. However, the model has been found to overestimate pollutant concentrations near the highway especially for stable atmospheric conditions and wind direction parallel to the road with low wind speeds. Different versions of the model have been developed including HIWAY-2, HIWAY-3 and HIWAY-4 (Khare and Sharama, 2002). Deterministic models can be divided into analytical and numerical models. These are discussed next.

Table 4.2: *Dispersion Model Approaches*

Approach	Examples	Advantages	Limitations
Deterministic	HIWAY	Most suitable for long term planning decisions	Over-prediction with parallel wind direction Gives inaccurate results with very low wind speed
Numerical	Computational fluid dynamics (CFD) models		Requires large amount of data
Analytical	CAR-FMI (Contaminants in the Air from a Road - Finish Meteorological Institute)	Gaussian models: Much experience achieved with them Easy to understand and require less computer running time	Due to the assumptions made for the construction of the models: For short time period ($\leq$ day), where steady-state assumptions are not met, give inaccurate results Can not account for sudden variations
Statistical	Methods: Regression models Multiple regression models	Take into consideration the unknown variation Allow all available data to be used in forecasting computations Have adaptive capabilities	Require long historical data sets to give accurate results Lack of physical interpretation Do not reflect the change in pollutant levels due to emission controls Site specific
Physical	Experiments carried out in wind tunnels and water channels	Best approach in case of: Complex air pollution situation When details are required	Expensive and difficult to set up

4.4.1.1 Analytical models

Analytical models calculate pollutant concentrations through analytical solutions of diffusion equation under simple assumptions (i.e. homogeneous and stationary conditions). They are Gaussian models that require less computer running time and easy to understand by the users.

CAR-FMI (Contaminants in the Air from a Road - Finish Meteorological Institute) model was developed by the Finish Meteorological Institute in 1995 as a road network dispersion model. It includes an emission model, a dispersion model and statistical analysis of the computed time series of concentrations. The dispersion equation is based on an analytic solution of the Gaussian diffusion equation for a finite line source model. A meteorological pre-processing model MPP-FMI is used with the model to evaluate the meteorological input data (Kukkonen et al., 2001). The model treats the road as a straight line of finite length. The hourly traffic volume is assumed to be constant and therefore the vehicular emissions can be simulated as a finite line source. The model can compute an hourly time-series of the pollutant dispersion for CO, NO, NO_2, NO_x, and $PM_{2.5}$ concentrations (Härkönen, 2002).

4.4.1.2 Numerical models

Numerical models describe the atmospheric dispersion process using numerical solutions of partial differential equations. They are able to deal with non-stationary, non-homogeneous conditions and complex configurations of the spatial domain (i.e. rough terrain).

Computational fluid dynamics (CFD) models are examples of advanced numerical models. CFD models have the advantage of representing buildings and vehicles in detail and hence they have been used for small-scale dispersion applications (street canyons). Moreover, they are capable of representing the traffic induced turbulence, which is very important in the case of low wind speed conditions. CFD models, however, are very difficult to use for operational applications since they need very extensive computing requirements (Sokhi and Yu, 2005).

4.4.2 Statistical models

Statistical models use statistical methods to calculate concentrations from meteorological and traffic data after forming a suitable relationship from empirical measurements of the concentrations. They are very useful for real-time, short-term assessment. Examples of statistical methods are regression, multiple regression, time series techniques and Artificial Neural Networks (ANN). They have some advantages since they require known input data with no assumptions. The most important feature of ANN is its adaptive nature. The network uses the learning by example technique instead of programming to solve the problem. Therefore, it is a very useful tool in the case that the problem is not understood or just a little is known about it. However, the availability of the real input data is important in order for the neural network to develop its own model and to calculate the required output (Khare and Sharama, 2002).

4.4.3 Physical models

Physical models simulate the real process of the atmospheric dispersion at a smaller scale. This can be done in the laboratory such as wind tunnel studies, where details are required about the complex air pollution situations. Physical models are mainly used as research tools (Khare and Sharama, 2002).

4.4.4 Discussion on dispersion modeling

Many mathematical models are used today to predict pollutant concentration near highways or roads. Different approaches are used for these models which can be broadly classified into deterministic and statistical approach as well as physical models. These models differ in complexity from simple Gaussian models to complex solutions of fluid dynamics equations. However, no model can be considered as the best for simulating all real-life conditions with different street configurations (Sokhi and Yu, 2005).

The main objective in this thesis is to evaluate the impact of a co-operative system on local air quality on a short-term (i.e. hourly basis). Considering the descriptions of the different approaches, the following observations can be made:

- deterministic models (i.e. Analytical) are, in general, un-suitable since they are more suitable for long term planning decision;
- although statistical models seem to be suitable (i.e. used for real-time, short-term assessment), they can not give information on how pollutant levels would respond to emission controls;
- numerical models seems to be the most promising approach and among them are the CFD models. However, CFD models require extensive computation and hence are too difficult to be used for real-time applications.

Consequently, a calculation approach was used based on dilution factors calculated for different wind directions using the WinMiskam CFD model (Eichhorn, 2010). A detailed description about this approach will be given in the next chapter.

4.5 Summary

Before implementing an environmentally friendly co-operative system in the real-world, one needs to assess and optimize the potential impacts of the system on the environment. For that a range of models needs to be considered. These include traffic, emission and dispersion models. In this chapter the modeling framework has been developed through the selection of the best models in relation to the special requirements of the thesis. For traffic modeling, the VISSIM microscopic model was selected because of its detailed traffic control model including user behavior at traffic signals. For emission modeling, the EnViVer model was selected due to the required level of detail (street level). For dispersion modeling, a calculation approach based on dilution factors calculated using the WinMiskam CFD model was selected according to real-time requirement.

Chapter 5

Evaluation of the modeling framework

In this chapter the modeling framework is evaluated. The evaluation is performed through a comparison of hourly concentration measurements of NO_x at a kerbside station with results from the modeling framework. Section 5.1 gives motivations for such an evaluation. Section 5.2 describes the test site together with the data collection process. A detailed description of the components of the modeling framework is presented in section 5.3. Section 5.4 explains the evaluation process for the modeling framework including traffic, emission and dispersion modeling. A discussion of the results is given in section 5.5. Section 5.6 summarizes the findings and concludes the chapter.

5.1 Motivation

To evaluate the potential impact of traffic emissions on local air quality and to assess the potential effectiveness of traffic measures, a modeling framework of traffic, emission and dispersion models is used. However, reliable results can only be expected when these models are well calibrated. Calibration is the process of adjusting model parameters to improve the ability of the model to reproduce the real conditions. For example, microscopic simulation models often come with a set of default parameters suggested by the model developers. However, the use of such default parameters may produce unreliable results (Park and Schneeberger, 2003). Accordingly, a calibration process is needed during which users must find the optimal set of parameter values for the model to best reproduce local traffic conditions (Dowling et al., 2004).

With regard to traffic emission models, a validation process is often conducted by the model developers. Validation is defined as the comparison of model results with independent real emission measurements to test the overall accuracy of the model. Smit et al. (2010) performed a review of various validation methods for traffic emission models. Most of the validation studies were found to be conducted for specific traffic situations during short time periods. Therefore, traffic emission models are considered to be partially validated.

For dispersion modeling, there is always uncertainty associated with the results. Uncertainty is defined as the discrepancy between a measured quantity and its true value, which can not be corrected by calculation or calibration (Idaho, 2010). The uncertainty in dispersion models can be caused by errors in the model physics and input data or due to stochastic process in the atmosphere. Given these uncertainties, it is vital to validate the performance of dispersion models to assess the extent to which it can be used with confidence. Unreliable results can lead to wrong decisions related to public-health and air quality. Currently there is no standard procedure for evaluating air quality models. However, statistical analysis can be used when comparing results from a dispersion model with real measurements to estimate the model uncertainty (Sokhi and Yu, 2005).

5.2 Site description and data collection

The test site is located at the Bentinckplein intersection in the city of Rotterdam, The Netherlands. The intersection has four legs with the main street (Statenweg) running north-south (from down town to the motorway), and the branch street (Bentinckplein) running east-west. The main street carries a heavy traffic volume of more than 45,000 vehicles per day. The site is not a typical street canyon with an average height of residential buildings of about 10 - 15 m. A kerbside monitoring station is located along the main street on the northeast side of the intersection. Buildings are located mainly to the North from the monitoring station. The monitoring station is located at a height of 2.5 m, and at a distance of 4.5 m from the center of the adjacent lane.

During the period from 12 September to 16 October, 2008, traffic volumes and average vehicle speed data were collected. The data was collected per 15 minutes for two classes of vehicles: shorter and longer than 3.5 m. The measurements were taken at two points on the main street at the southbound approach for two directions: Bent-Staten and Staten-Bent. See Figure 5.1.

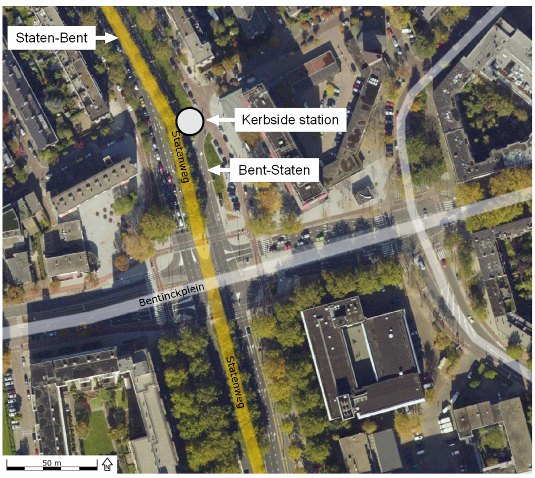


Figure 5.1: *The Bentinckplein intersection together with the kerbside station and the measurement points*

The background station is located in the city of Schiedam some 4 km to the west. The kerbside and the background stations are part of the regular regional air quality network and are equipped with the same instruments. For PM_{10} this includes a relatively fast responding (1 hour) TEOM-FDMS. FDMS stands for Filter Dynamics Measurement System, which is a self referencing airborne particulate monitor based on TEOM technology. The TEOM uses first principle physics to measure the mass of particles collected on a filter (Air-Monitors, 2010). Both the kerbside and the background station meet the criteria for such stations as spelled out in the EU guidelines (EU, 2008). Figure 5.2 illustrates both stations. Hourly concentration measurements for NO_2, NO and PM_{10} were available for the period of 2005-2008 at the two stations. For NO_x, concentration levels were calculated using equation 5.1.

$$NO_x = NO * \frac{46}{30} + NO_2 \tag{5.1}$$

The meteorological station is located at the Airport Rotterdam site (named as Zestienhoven) at a height of 10 m. The station is about 3 km from the kerbside station. See Figure 5.2. Both wind speed and wind direction are measured on an hourly basis.

Figure 5.2: *Locations of Kerbside (Bentinckplein), Background (Schiedam) and Meteorological (Zestienhoven) stations*

5.3 Description of the modeling framework

In this section, a detailed description of the components of the modeling framework is presented including traffic modeling, emission modeling and dispersion modeling.

5.3.1 Traffic modeling

A detailed description of drivers' behavior in VISSIM is given next, particularly the car-following behavior, the lane-changing behavior and turning movements at intersections (PTV, 2007).

Car-following behavior

The traffic flow model in VISSIM is defined as a discrete, stochastic, time step based, microscopic model with a driver-vehicle-unit (DVU) defined as a single entity. For longitudinal movements, VISSIM has a psycho-physical car-following model which takes into account the physical aspects and psychological restrictions of individual driver's ability.

The model is based on the continued work of Wiedemann (Wiedemann, 1974). Based on the car-following model a vehicle is assumed to be in one of four driving modes defined below:

- Free driving: a driver experiences no influence by vehicles in front, and will try to reach and maintain his/her individual desired speed.
- Approaching: a driver adapts his/her speed to a vehicle in front with lower speed. This is done by applying a deceleration so that the speed difference of the two vehicles will be zero at the moment the desired safety distance is reached.
- Following: a driver keeps the safety distance to the leading vehicle more or less constant. Accordingly, the speed difference between the two vehicles will oscillate around zero.
- Braking: a driver applies a medium to high deceleration rate if the safety distance falls below the desired safety distance.

The acceleration during each mode is described by a function of speed, speed difference, distance and the individual characteristics of the DVU. The DVU will switch from one mode to another as soon as it reaches a threshold which can be described as a combination of speed difference and distance. Figure 5.3 shows a faster DVU_j approaching a slower DVU_i. Driver j begins to decelerate until an individual threshold is reached. Driver j then decelerates below the current speed of DVU_i until other thresholds are reached and then accelerates again.

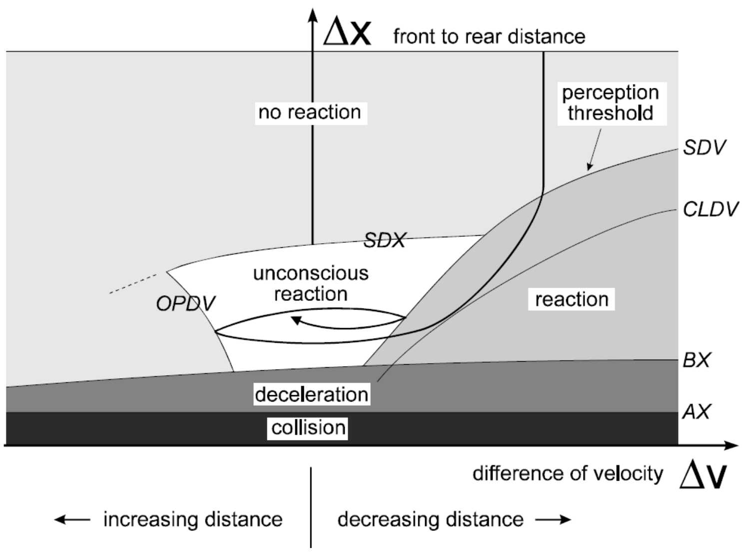


Figure 5.3: *Car-following model of Wiedemann, thresholds and one vehicle trajectory*

The thresholds in Figure 5.3 are defined as follows (PTV, 1998):

AX Desired distance between the front sides of two successive vehicles in a standing queue.

ABX Desired minimum following distance, which is a function of AX, safety distance and speed ($ABX = AX + (BX.v)$).

SDV Action point when a driver consciously observes that he/she approaches a slower vehicle. SDV increases with increasing speed differences.

OPDV Action point when a driver starts to decelerate after being traveling slower than a leading vehicle.

SDX Perception threshold to model the maximum following distance, which is about 1.5-2.5 times ABX.

Lane-change behavior

For lateral movements, VISSIM uses a rule-based algorithm. There are two kinds of lane-change: necessary and free lane-change. The necessary lane-change is required to reach the next connector of the vehicle's route if the current lane does not connect to the next link of the vehicle's route. The free lane-change is needed in the case that more room is available for a vehicle with higher speed. For both kinds of lane changes, VISSIM first tries to find a suitable gap (minimum headway) in the destination flow. This depends on the speed of the vehicle changing the lane and the trailing vehicle in the new lane.

For the necessary lane-changes, the maximum and the acceptable deceleration of the vehicle and the trailing vehicle on the new lane are used to control the lane-change. For free lane-change, VISSIM checks for the desired safety distance of the trailing vehicle on the new lane. This depends on the speed of the trailing vehicle and the vehicle that tries to change lane (PTV, 2007).

Turning movements at intersections

VISSIM controls the turning movements at intersections through priority rules and reduced speed areas, which are specified as input by the users. In this thesis, reduced speed areas were used to simulate turning movements at intersection. Therefore, only a description of reduced speed areas is given.

Reduced speed areas are used for curves to model vehicles' turning movement by assigning a new speed distribution to each vehicle class. Before reaching a reduced speed area, a faster vehicle will reduce its speed using a user-defined deceleration value to reach its new speed distribution at the beginning of the reduced speed area. For a slower vehicle no change in speed is applied unless the vehicle's speed is less than the speed distribution at the reduced speed area. After leaving the reduced speed area, each vehicle returns to its original desired speed. Both the characteristics of the DVU and the original desired speed determine the acceleration value at the end of the desired speed area.

5.3.2 Emission modeling

EnViVer is an interface between the VISSIM model and the aggregated version of the VERSIT+ emission model (i.e. $VERSIT{+}^{micro}$). $VERSIT{+}^{micro}$ is a statistical emission model to calculate real-world CO_2, NO_x and PM_{10} emissions of different vehicle categories. It calculates emissions based on speed-time profiles of individual vehicles simulated with a microscopic model. Four main vehicle categories are considered in $VERSIT{+}^{micro}$:

- Light Duty Vehicles (LDV) comprising passenger cars and commercial vehicles with a mass up to 3500 kg;

- Heavy Duty Medium Vehicles (HDMV) comprising smaller trucks with a mass $\geq$ 3.5 tonnes and 2 axes;
- Heavy Duty Heavy Vehicles (HDHV) comprising heavy trucks with a mass $\leq$ 2.5 tonnes and 3 or more axes;
- Buses comprising public transport buses and touring cars.

$VERSIT+^{micro}$ includes different emission models for urban areas and the combination of rural and highway areas. The main differences between these models are different in fleet compositions. Currently EnViVer is available as a commercial software tool operate under windows (Eijk et al., 2010). Figure 5.4 presents the EnViVer model interface.

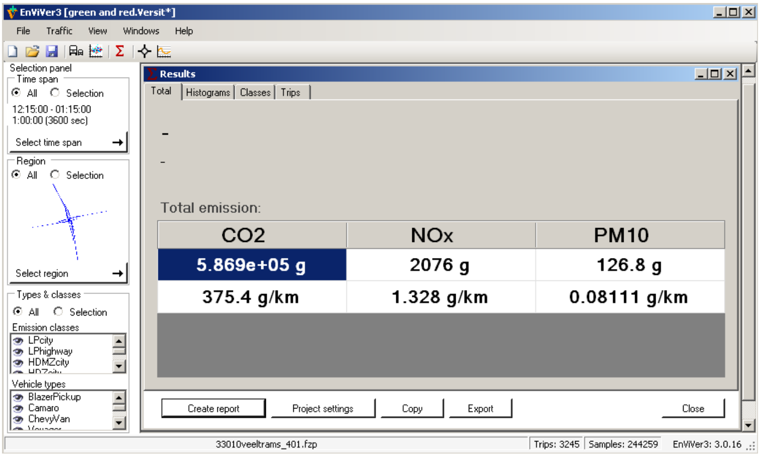


Figure 5.4: *EnViVer interface*

For emission calculations, EnViVer uses traffic data imported from VISSIM. These data include vehicle number, vehicle type, name of the vehicle type, simulation time and vehicle speed at the end of each simulation time step. Information about vehicles x-y coordinates is used to create plots of the calculated emissions in the network. Vehicle types defined in VISSIM are linked to the vehicle emission classes in EnViVer. Based on the instantaneous speed and acceleration from the speed-time profile, emissions are calculated for each individual vehicle.

To calculate emissions, EnViVer uses default emission maps from VERSIT+ on a more aggregated level. These emission maps were developed from a large data set of measurements for each emission component and for every vehicle category. The emissions are described in gs^{-1} as a function of the instant speed and acceleration. Figure 5.5 illustrates an example of such an emission map. It shows the linear relationship between the instantaneous emissions and the vehicle speed and acceleration. A linear relationship was used to fit the emission map on emission measurement data from different sources and belonging to different vehicles from the same vehicle class. For each trip, the emissions are calculated in gkm^{-1}. Three categories are defined for the vehicle speed: $v \leq 50\ kmh^{-1}$ (for urban), $50 \leq v \leq 80\ kmh^{-1}$ (for rural) and $v > 80\ kmh^{-1}$ (for motorway). Idling is taken into account defined as speed less than 5 kmh^{-1} and acceleration less than 0.5 ms^{-2} (Ligterink and de Lange, 2009).

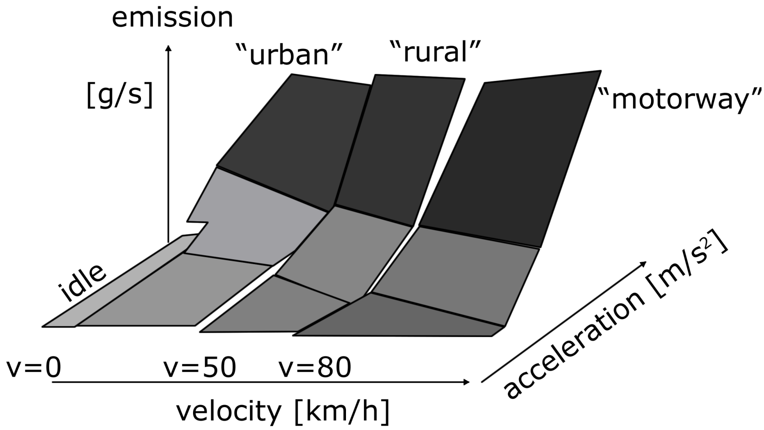


Figure 5.5: *An example of an emission map in VERSIT+ for one vehicle class*

5.3.3 Dispersion modeling

For dispersion modeling, a calculation approach was used based on dilution factors calculated for different wind directions using the the WinMiskam CFD model (Eichhorn, 2010). The concentration is estimated at the location of the kerbside monitoring station. It depends on the distance and the dispersion condition between the emission source and the kerbside station. Therefore, the concentration is defined as the emissions multiplied by the dilution. The dilution for the Bentinckplein situation was studied with the WinMiskam calculations for different wind directions. The calculations were performed for a reference wind speed and the dilution factors were corrected for the difference between the actual and the reference wind speed. The reference wind speed at Zestienhoven station was equal to 8.4 ms^{-1}.

The hourly total concentration level C (in μgm^{-3}) is calculated as the sum of the background concentration C_b and the concentration contribution from traffic (ΔC):

$$C = C_b + \Delta C \tag{5.2}$$

The contribution from emissions by traffic is calculated by a dilution factor (θ) using the following equation:

$$\Delta C = E * \theta * \frac{U_{Ref}}{U} \tag{5.3}$$

where

$$\begin{aligned} E &= \text{the total emissions from traffic in } \mu gs^{-1}m^{-1} \\ \theta &= \text{the dilution factor in } sm^{-2} \\ U_{Ref} &= \text{the reference wind speed in } ms^{-1} \\ U &= \text{the actual wind speed in } ms^{-1} \end{aligned}$$

It is assumed that only traffic on the main street (Statenweg) contributes to the concentrations at the kerbside monitoring station. Moreover, vehicle induced turbulence was not taken into account during the CFD-simulations. The advantage of this calculation approach is that the results can be obtained in real-time, which make it suitable for operational applications. However, the calculations are highly sensitive to low wind speeds (i.e. 1 ms^{-1}). Therefore, all wind speeds lower than 2.5 ms^{-1} are set to 2.5 ms^{-1}. The value of 2.5 ms^{-1} was taken from the literature below which the linear relation between dilution and wind speed was found to be weak.

5.4 Evaluation of the modeling framework

5.4.1 Traffic modeling

The VISSIM network of the Bentinckplein intersection was obtained from the Rotterdam traffic department, dS+V. As can be seen from Figure 5.6, the intersection has four legs with the main street (Statenweg) running north-south and the branch street (Bentinckplein) running east-west. Public transportation lines for buses and trams are included together with pedestrian and cyclist crossing facilities. The number of approaching lanes is two on the main street and one on the branch street. All approaching roads are widened to three lanes before the stop line to support left and right turns as well as the through direction.

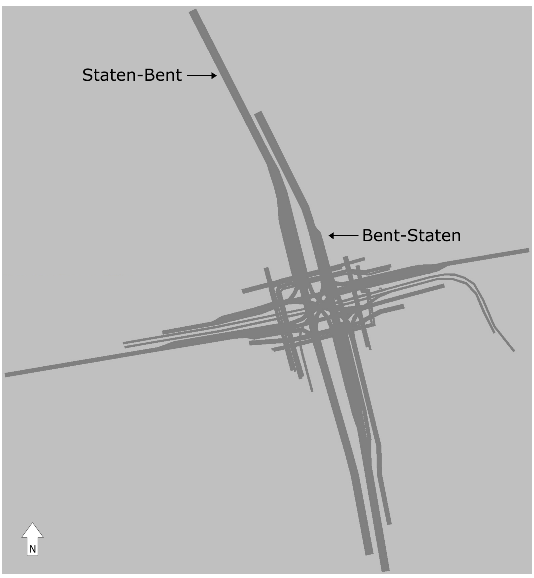
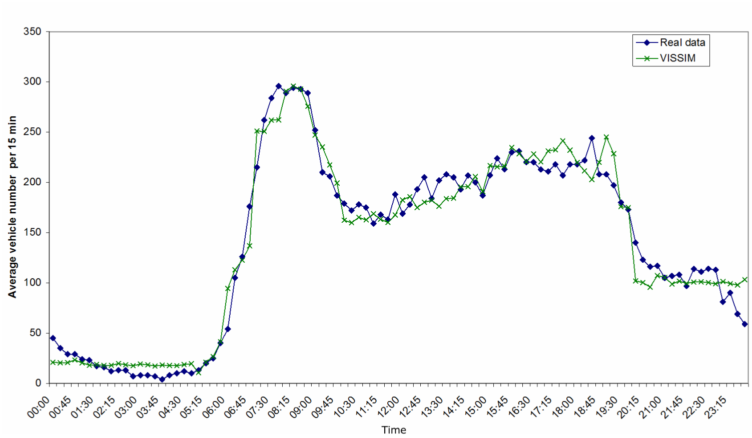


Figure 5.6: *The VISSIM network of the Bentinckplein intersection and the measurements points*

The traffic demand was a representation of the evening peak hour only. To obtain a traffic demand representing the whole day, O/D matrices needed to be generated. For this purpose, hourly traffic volumes recorded during green times on the 15^{th} of September, 2008 were obtained from the Rotterdam dS+V. O/D matrices were generated for five hours for periods between 0:00-5:00 and 20:00-24:00. For the period between 10:00-15:00 O/D matrices were generated for one hour. To simulate the morning and evening peak hours, O/D matrices for periods 5:00-10:00 and 15:00-20:00 were generated per 15 minutes. Since traffic volumes during green times were only available on an hourly basis, ratios from data collected on the main street were used to generate 15-minute O/D matrices.

Reduced speed areas were applied at left and right turns with a speed distribution of 25-30 kmh^{-1} and acceleration of 2 ms^{-2} for LDVs. For HDVs and buses a speed distribution of 20-25 kmh^{-1} with acceleration of 1 ms^{-2} was applied.

The first runs using the default parameters showed differences between real world measurements and simulation results. Therefore, additional efforts to adjust calibration parameters were needed. The results from VISSIM for both traffic volumes and average speed (using 8 runs with different random seeds) compared with real measurements are presented in Figure 5.7 and 5.8 respectively.



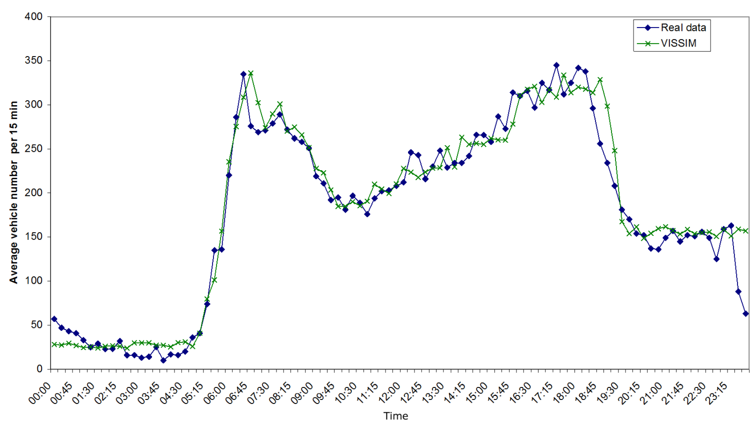
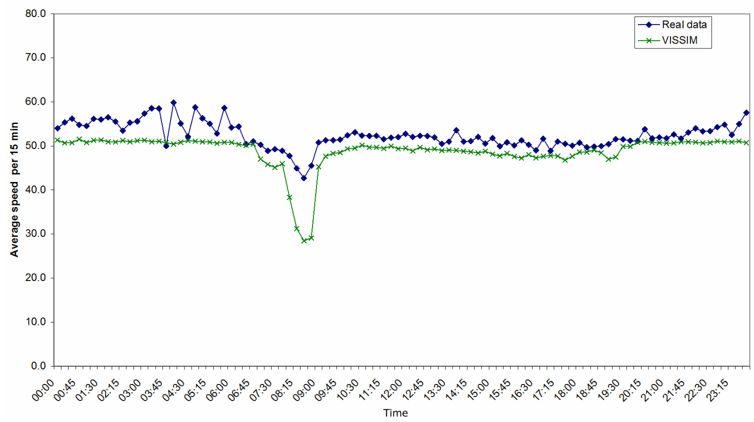


Figure 5.7: *Traffic volume, VISSIM results vs. real measurements: Staten-Bent (up), Bent-Staten (down)*



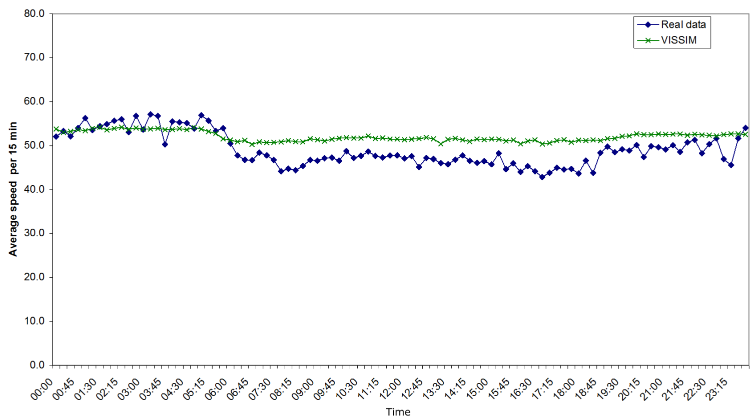


Figure 5.8: *Average speeds, VISSIM results vs. real measurements: Staten-Bent (up), Bent-Staten (down)*

For traffic volume, the Geoffrey E. Havers (GEH) statistic test (Dowling et al., 2004) was used to compare hourly volumes. The GEH is calculated as:

$$GEH = \sqrt{\frac{(E-V)^2}{(E+V)/2}} \tag{5.4}$$

where

E = the hourly volume by the model

V = the real hourly volume

The GEH was first introduced by Geoff Harvers to compare two different values of traffic volume on a link. It was used because it overcomes the inability of either the absolute difference or the relative difference to cope over a wide range of flows (Vliet, 2002). If the GEH value is less than 5 the hourly estimated and real-world traffic volumes can be considered a good fit. The GEH value was less than 5 for all the hours except for the last hour in the Bent-Staten direction. Accordingly, the results for the traffic volumes were considered to be acceptable.

Regarding the average speeds, vehicles for the Bent-Staten direction seemed to travel at a constant speed in simulation, while in reality the speed actually dropped between 6:00 and 19:00. For the Staten-Bent direction, the vehicle speed in VISSIM was generally lower and dropped more frequently during the morning peak.

The average speed was used as the main calibration variable because speeds of vehicles are a good reflection of driving behavior parameters. For urban areas, speed is considered to be a good measure of effectiveness (MOE) which reflects the level of service of the study area (Dowling et al., 2004). Furthermore, when calibrating for emissions calculation, one should ensure the consistency between parameters produced by the microscopic traffic model and those needed for the emissions calculation by the emission model (Spence et al., 2008). The input to EnViVer consists of speed-time profiles for individual vehicles.

The calibration parameters in VISSIM can be divided into car-following parameters, lane-change parameters, simulation resolution and desired speed distribution. These are described in Table 5.1 together with their default values.

Table 5.1: *Calibration parameters in VISSIM*

	Parameters	**Description**	**Default**
Car following parameters	Maximum look ahead	Maximum distance a vehicle can see forward and react to other vehicles	250 meters
	Number of observed vehicles	Number of preceding vehicles a vehicle can see. Affect how well vehicles in the network can predict other vehicles movement and react	2 vehicles
	Average standstill distance	Average desired distance between stopped vehicles	2 meters
	Additive part of safety distance Multiple part of safety distance	Both affect saturation follow rate and define the number of vehicles that can free flow through VISSIM during one hour. See equations 5.5 and 5.6	2 3
Lane change parameters	Waiting time before diffusion	Maximum time a vehicle can wait at emergency stop for gap to change lane before it is removed	60 seconds
	Minimum headway	Minimum distance to the vehicle in front for lane change in standstill condition	0.5 meters
	Maximum deceleration	The fastest a vehicle can slow down or stop	-4 ms^{-2}
	Reduction rate	Used to reduce the max deceleration with increasing distance to emergency stop	100 meters
	Accepted deceleration	A deceleration with which a vehicle can slow down without any dangerous, its value is smaller than maximum deceleration and bigger than minimum deceleration	-1 ms^{-2}
Others	Simulation resolution	Number of times a vehicle's position will be calculated within one simulation second	10 steps/ sim.sec
	Desired speed distribution	Define the desired speed for a vehicle type when entering the VISSIM network. Affect both capacity and travel time	48-58 kmh^{-1}

To reduce the scope of the calibration process, some calibration parameters in VISSIM were excluded. For example, parameters for lane-change behavior were excluded because of the short links before and after the intersection. In the case of a standstill situation both lanes were full and hence there were fewer possibilities for lane changes. To test this, multiple runs were performed for different values of lane-change parameters. These were found to have no impact on vehicles speeds. From the car-following parameters, only those parameters that have an impact on speed results in the two directions were selected. These included average standstill distance, the additive part of safety distance and the multiple part of safety distance. Simulation resolution was excluded because a specific value (i.e. 10 time steps/sim.sec) was needed to generate the input for the emission model. Finally, the desired speed distribution was selected. Equations 5.5 and 5.6 define the relation between average standstill distance, the additive part of safety distance and the multiple part of safety distance parameters.

$$d = ax + bx \tag{5.5}$$

$$bx = (bx_{add} + bx_{mult} * z) * \sqrt{v} \tag{5.6}$$

where

$$\begin{aligned} d &= \text{distance between two vehicles} \\ ax &= \text{standstill distance} \\ bx_{add} &= \text{additive part of safety distance} \\ bx_{mult} &= \text{multiple part of safety distance} \\ v &= \text{the vehicle speed in } ms^{-1} \\ z &= \text{a value of range 0-1, normally distributed around 0.5 with} \\ & \quad \text{a standard deviation of 0.15} \end{aligned}$$

The calibration strategy recommended by Dowling et al. (2004) was followed. This included the following steps: first calibrate capacity parameters, then route choice parameters and finally calibrate the overall model performance. In each step, parameters that affect the simulation on a global basis are adjusted first and then those which have an impact on a local basis (i.e. link-specific parameters). First the desired speed distribution was calibrated, then both the additive and multiple part of safety distance and finally the average standstill distance. To evaluate the quality of the simulation, the Sum of Squared Error (SSE) was used between collected vehicle speeds and those obtained from multiple runs of VISSIM. The SSE is recommended for calibration as it is most sensitive to large volume errors. It is calculated as follows:

$$SSE = \sum_{i=1}^{N} (v_i^c - v_i^s)^2 \tag{5.7}$$

where

$$
\begin{aligned}
i &= \text{1, 2, 3 to N each represents a 15 minute time interval} \\
N &= \text{96, which is the total number of intervals per 24 hours} \\
v_i^c &= \text{average vehicle speed at interval i collected from the field} \\
v_i^s &= \text{average vehicle speed at interval i simulated by VISSIM}
\end{aligned}
$$

The golden section method was used as a searching algorithm for the optimal parameter value (Dowling et al., 2004). The calibration parameters together with some of the applied values and their corresponding results of the SSE are presented in Table 5.2 and 5.3 for the two directions: Staten-Bent and Bent-Staten.

Table 5.2: *Calibration parameters and their SSE for Staten-Bent direction*

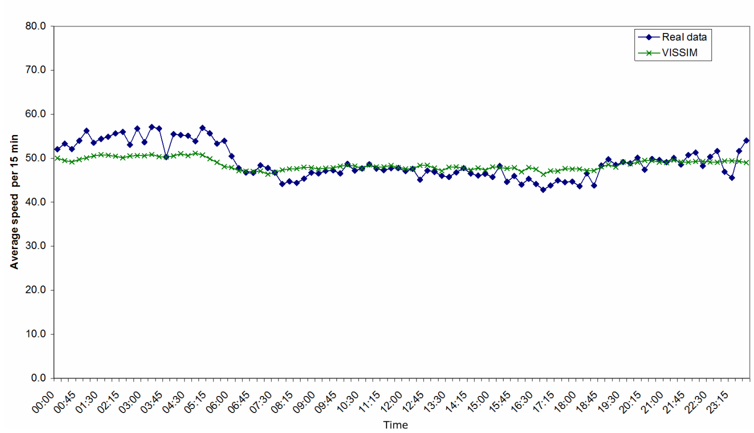
Parameters	Default	SSE	Value1	SSE	Value2	SSE	Value3	SSE
Desired speed distribution	LD:45-60 HD:45-50	2118	LD:45-55 HD:40-45	2901	LD:45-65 HD:45-55	1758	LD:55-65 HD:50-55	756
Additive part of safety distance	2	756	1.5	622	1.69	594	1.8	681
Multiple part of safety distance	3	594	2.69	477	2.8	457	2.75	460
Average standstill	2	457	1	450	1.6	378	1.47	375

Table 5.3: *Calibration parameters and their SSE for Bent-Staten direction*

Parameters	Default	SSE	Value1	SSE	Value2	SSE	Value3	SSE
Desired speed distribution	LD:45-60 HD:45-50	1664	LD:45-55 HD:40-45	1071	LD:45-65 HD:45-55	1643	LD:55-65 HD:50-55	8143
Additive part of safety distance	2	1071	1.5	817	1.69	778	1.8	790
Multiple part of safety distance	3	778	2.69	790	2.8	792	2.75	796
Average standstill	2	792	1	783	1.6	783	1.47	787

For the desired speed distribution, it is clear that when increasing desired speed distribution, the SSE decreases in the direction of Staten-Bent and increases in the direction of Bent-Staten. This means that vehicles have different speed distributions for the two directions, which is logical as vehicles coming from the direction of the motorway might have a higher speed than those coming from inside the city. Accordingly, value 3 of the desired speed distribution was used for the Staten-Bent direction, and value 1 for the Bent-Staten direction. The range of the other parameters was narrowed using multiple random runs to evaluate their effect on the results. The selected values for additive and multiple part of safety distance were 1.69 and 2.8 respectively. Finally, for average standstill 1.47 meters was selected.

The results from multiple runs using calibrated parameters compared with real measurements are presented in Figure 5.9. These were much better than those obtained using default parameters.



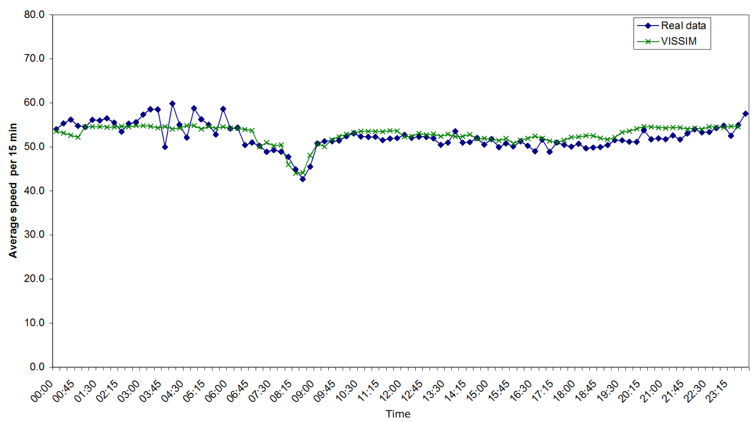


Figure 5.9: *Average speeds, VISSIM results (calibrated parameters) vs. real measurements: Staten-Bent (up), Bent-Staten (down)*

5.4.2 Emission modeling

When the EnViVer/$VERSIT+^{micro}$ model was developed on the basis of the VERSIT+ model, two main simplifications were made. First, only four aggregated vehicle categories were defined namely, light duty vehicles, heavy-duty medium vehicles, heavy-duty heavy vehicles and buses. Second, for each category, a fleet composition was made for the urban and rural/highway environment, which was based on an average Dutch fleet composition. Model developers at TNO validated $VERSIT^{+micro}$ by comparing its results with the more detailed VERSIT+ model. They evaluated EnViVer for both urban and rural/highway areas for the four vehicle categories and the results from EnViVer were consistent with the calculations of the VERSIT+ model (Ligterink et al., 2008). Therefore, EnViVer was considered valid especially for the Dutch environment.

The VERSIT+ model was evaluated by the model developers at TNO. They compared the model predictions with average experimentally measured emissions for a number of vehicles and different real world driving patterns. In addition, detailed VERSIT+ results were compared with results from other micro-scale emission models such as the Passenger and Heavy duty vehicle Emission Model (PHEM). The comparison showed a good correspondence of the VERSIT+ results with both the experimental and the PHEM results (Benz, 2010). Figure 5.10 shows a comparison between fleet average results from the VERSIT+ model with average experimentally measured emissions for fuel consumption (FC), NO_x, PM_{10} and CO_2.

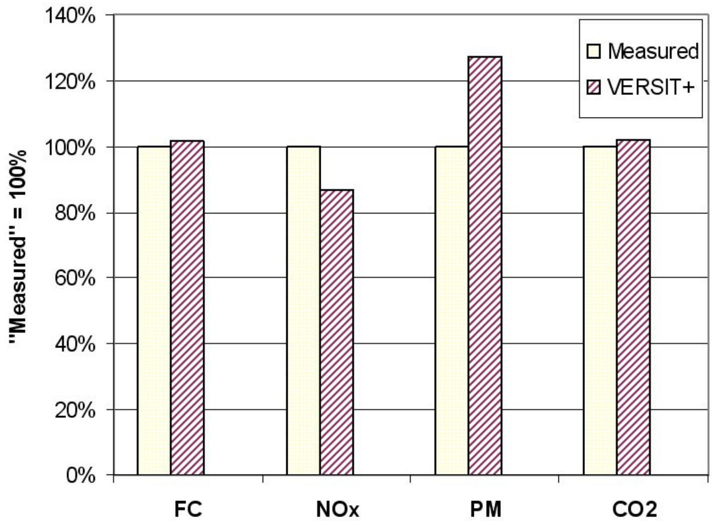


Figure 5.10: *Comparison of results from the VERSIT+ model with average experimentally measured emissions for a number of vehicles and different real driving patterns*

5.4.3 Dispersion modeling

To compare the modeling results with the real measurement at the kerbside station, the total concentration was considered (i.e. traffic contribution + background). First the hourly traffic contribution of NO_x was calculated using the modeling framework. This was then added to the hourly background concentration.

The following hours were excluded from the calculation:

- hours during the weekend days;
- hours during the autumn holiday in the Netherlands (13^{th} to 17^{th} of October);
- hours during days with traffic volume differing more than 10% from the reference day i.e. 15^{th} of September, 2008;
- hours for which data was missing due to malfunctioning of monitoring devices.

The NO_x monitors operate under an accepted Dutch quality assurance system and meet the European uncertainty requirements i.e. 15% (EU, 2008). The uncertainty in the NO_x measurements was established as $< 11\%$ (Spoelstra, 2007) and has been further reduced following the recommendations made during the assessment. The Bentinckplein site is part of the national quality assurance program and permanently monitored by two different organizations in parallel.

The uncertainty in the modeling results is associated with the uncertainty in the input data (e.g., traffic volume, meteorological data and background concentrations) and the dispersion parameters. The uncertainty in traffic data is in the order of 15% considering the original difference between VISSIM results and traffic volumes on 15$^{\text{th}}$ of September as well as the differences between 15$^{\text{th}}$ of September and the other days during the study period. Meteorological data including wind speed and direction were recorded outside the city and not at the street level. The same holds for background concentration measurements that are expected to be influenced by traffic emissions from the A20 motorway in the case of strong wind coming from the North. The linear regression analysis of the total modeled vs. total measured concentration of NO_x at Bentinckplein is presented for all wind directions in Figure 5.11.

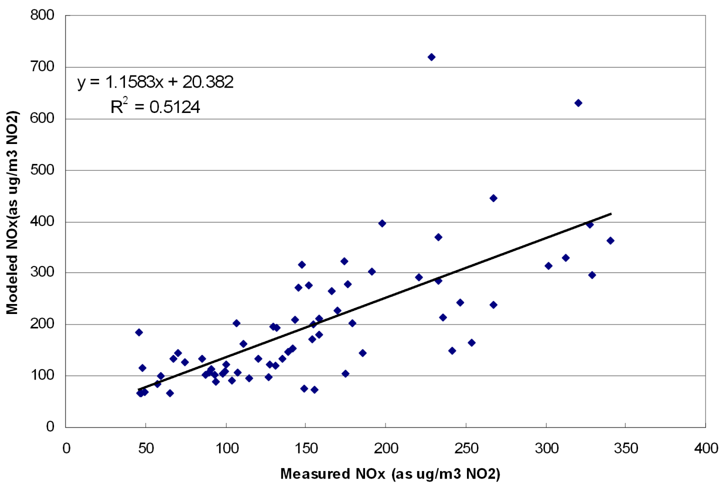


Figure 5.11: *Scatter plots of modeled and measured total NO_x concentrations at the kerbside station*

In general, the model overestimates the measured concentrations. However, the R^2 of 0.5 is reasonable taking into account that background concentrations as well as wind speed and directions were measured outside the city. To obtain more information about the model performance, two statistical parameters including the index of agreement (IA) and fractional bias (FB) were calculated. The IA is a measure of the correlation coefficient of the modeled and the measured time series of the concentrations. It was used because its sensitive to differences between observed and estimated means, as well as to certain changes in proportionality (Willmott, 1981). However, the FB is a measure of the agreement of the mean concentrations (Kukkonen et al., 2001). It was selected because its symmetrical and bounded between -2 (extreme under-prediction) and +2 (extreme over-prediction).

Equations 5.8 and 5.9 defined the calculation of IA and FB.

$$IA = 1 - \frac{\overline{(C_{modeled} - C_{measured})^2}}{(|C_{modeled} - \overline{C}_{measured}| + |C_{measured} - \overline{C}_{modeled}|)^2} \tag{5.8}$$

$$FB = \frac{2(\overline{C_{modeled}} - \overline{C_{measured}})}{\overline{C_{modeled}} + \overline{C_{measured}}} \tag{5.9}$$

The resulting values were 0.75 for IA and 0.25 for FB. For IA, a value of unity means a perfect agreement between measured and modeled concentrations. The value of 0.75 indicates a fair agreement between the measured and the modeled concentrations. The positive value of the FB (0.25) confirms that the model overestimates the measured concentrations by +25%.

The performance of the simulation framework was studied with regard to the wind speed and direction. Both wind speed and direction play an important role in determining the dilution and distribution characteristics of the modeled concentrations (Sokhi et al., 2008). The results are presented in Figure 5.12 and 5.13 for wind speed and direction respectively.

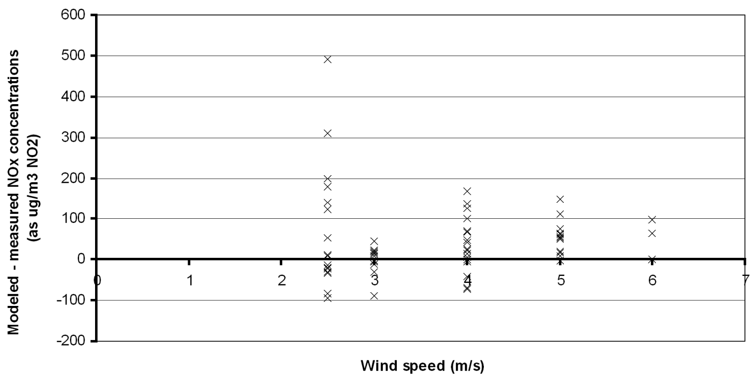


Figure 5.12: *Differences between modeled and measured hourly NO_x concentrations as a function of wind speed*

The highest over-estimation occurred during low wind speed i.e. 2.5 ms^{-1}. These are the lower wind speeds which have been replaced by 2.5 ms^{-1}. This indicates that the threshold wind speed of 2.5 ms^{-1} is not suitable for Bentinckplein and a further investigation is needed to decide the most suitable one. For the other wind speeds the differences between the modeled and the measured concentrations remain in the range of ± 100 $\mu g m^{-3}$.

Concerning wind directions, the over-estimation occurred mainly during wind direction of 20°, 30° and 40° i.e. when the wind is blowing from the direction of the kerbside station. Note that the main street runs in an angle of 330°. This means parallel wind directions are in the range of 300° to 20° and 120° to 180°; while perpendicular wind directions are in the range of 30° to 90° and 210° to 270°. The model also over-estimates the measured concentrations for parallel wind directions (e.g., 160° and 170°). For perpendicular wind directions, the model tends to slightly under-estimate the measured concentrations (e.g., 60° and 70°).

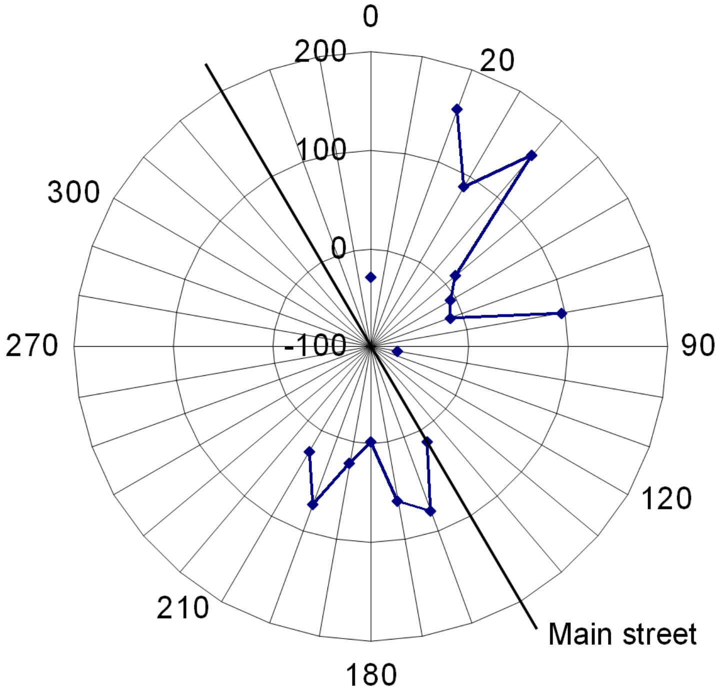


Figure 5.13: *Differences between modeled and measured hourly NO_x concentrations as a function of wind direction*

5.5 Discussion

5.5.1 Traffic modeling

The calibration process focused only on the vehicles' average speeds. Further improvement of the representation of the drivers' behavior especially for emission calculation, would require adjusting also the desired acceleration distribution in VISSIM. This requires detailed empirical data (e.g., data collected by a camera), which was not available in this study. Hirschmann and Fellendorf (2010) calibrated the acceleration using data from GPS equipped vehicles. It was found that the simulated accelerations in VISSIM are higher (max 3.5 ms^{-2}) than the observed one (max 2 ms^{-2}).

Another important issue to consider is the percentage of HDVs. Data collected from the field should not only differentiate between LDVs and HDVs, but further differentiate between different types of HDVs category (i.e. heavy duty medium and heavy duty heavy vehicles).

5.5.2 Emission modeling

The acceleration and the number of HDVs have a significant impact on the accuracy of the emission calculations. The vehicles' acceleration is considered to be the highest contributing factor for emissions at intersections. It is one of the parameters used by EnViVer for the emission calculations. HDVs are a major contributor to emissions because they produce as much as 10 times more emissions per kilometer compared to LDVs. The NO_x emission factors for HDVs obtained from EnViVer were in the range of 13 - 14 gkm^{-1}. These are less than the standard emission factor used for congested cities in the Netherlands for the year 2008 (which is 15.17 gkm^{-1}). In this study, the emissions dataset for 2009 in EnViVer was used, because the dataset for 2008 was not available.

The use of the higher default acceleration in VISSIM model is expected to lead to higher emissions than in reality, which is a possible explanation why the model over-estimates the measured concentrations. However, the use of the emissions dataset from the year 2009 instead of the year 2008 might underestimate the emissions as the calculation is performed assuming a somewhat newer car park. Since the differences in average emissions are small, this is not expected to affect the calculation significantly.

5.5.3 Dispersion modeling

The simple calculation used for the hourly NO_x concentrations is expected to be very useful for practical and real-time applications. When used to obtain an estimated level of air quality inside busy streets, it can be used as a basis to invoke traffic measures for mitigating traffic emissions. However, it is not expected to provide highly accurate results. To improve the accuracy, a dedicated background station for the study area is needed. Moreover, meteorological data including wind speed and direction must be measured on the roof of the considered street. In real world situations, a dedicated background station can not be installed for every intersection in the city. Therefore, for practical implementation, one needs to rely on one or two background stations installed around the city.

The results obtained from the modeling framework are fairly acceptable taken into account the practical set up applied in this study. In (Keuken et al., 2010), dedicated background samplers were used at distance of more than 250 m from the motorways. The results values for R^2 were in the range of 0.6 to 0.8 for NO_x. With respect to the IA, the value of 0.75 was considered to be acceptable in (Kukkonen et al., 2001) using the CAR-FMI model.

5.6 Summary

In this chapter the modeling framework was evaluated. For traffic modeling, the VISSIM microscopic model was used after calibrating the vehicles' average speeds. For emission modeling, the EnViVer model was used, considering that the model is valid especially for the Dutch environment. The total hourly concentration measurements of NO_x at a kerbside station were compared with the hourly concentration results from the modeling framework. Statistical analysis was used to estimate the uncertainty of the modeling framework.

The results indicate that the modeling framework over-estimates the measured concentration with FB = + 25%. The R^2 of the regression analysis was 0.5 with an IA = 0.75. In general the results were considered acceptable, taking into account the experimental set up, in which background concentrations as well as meteorological data were measured outside the city. For an ideal experimental test set-up, dedicated stations for background concentration and meteorological data nearby the considered street are needed.

The main reasons for the differences between the measured and modeled concentrations are the inaccuracy in traffic flow and emissions estimates as well as the inaccuracy in measured concentrations and meteorological data (Kukkonen et al., 2001). The information about local topography and surrounding building is also important. This was taken into account when calculating dilution factors for different wind directions using the Win-Miskam CFD model. It is important to mention that the study period was not too long, where for proper validation, one needs to consider long-term periods under different road topography and traffic conditions.

Chapter 6

The development of the algorithm

This chapter presents the development of the algorithm to reduce traffic emissions and improve local air quality in urban areas. The algorithm uses Infrastructure-to-Vehicle (I2V) communication to influence the traffic flow and driver behavior in real-time. Section 6.1 gives an introduction about the different types of traffic signal controllers. Section 6.2 investigates the impact of different traffic measures on local emissions. Section 6.3 reviews examples from the literature on the use of V2I or I2V communication to reduce traffic emissions. The development of the algorithm is described in section 6.4. Section 6.5 summarizes the chapter.

6.1 Introduction

To reduce traffic emissions in urban areas, special attention needs to be paid to vehicular traffic at intersections. Traffic-related characteristics such as deceleration, idling and acceleration, which increase traffic emissions, occur frequently at intersections (Pandian et al., 2009). In general, traffic signal controllers are categorized into fixed-time, actuated and adaptive controllers. For fixed-time controllers, historical data are used by engineers to develop a fixed signal timing plan. Actuated controllers use detectors to sense approaching vehicles and decide whether to extend or terminate the current green phase according to the demand on the active green phase. Adaptive controllers, in addition to the use of detectors, use a traffic model to select the optimal decision based on objectives that take into account the demand on the entire intersection (van Katwijk, 2008).

Fixed-time controllers are relatively cheap to construct compared to actuated and adaptive controllers, because they do not require the installation of detectors. However, they can not react to sudden changes in traffic conditions. Furthermore, fixed time plans can suffer from aging problems if they have not been updated for many years (Hounsell and McDonald, 2001). In the case of actuated controllers, detectors are used to measure the gap between approaching vehicles. A green phase is terminated if the measured gap is larger than a pre-defined threshold. The main drawback of actuated controllers is that traffic on other approaches is not considered which causes “a tunnel vision” problem. Adaptive controllers use a traffic model to select the optimal decision based on current objectives. Traffic demand on all approaches is considered in the decision making. However, current adaptive controllers do not consider environmental aspects explicitly. Adaptive controllers, as other traffic signal controllers, focus mainly on improving traffic throughput and reducing delays. Although this can also help in reducing traffic emissions, recent studies have proved that this is not always the case. Chen and Yu (2007) found that the implementation of an exclusive lane for buses improved traffic operation but increased the overall emissions. Generally, adaptive controllers use a travel time model to perform optimization based on the evolution of the queues in the network. The current travel time models do not consider vehicle characteristics, because traditional detection devices only detect vehicle presence, volumes and sometime speeds and vehicle length.

6.2 The impact of road-side and vehicle-side measures

In this section, the impact of different traffic measures on local emissions is evaluated. The evaluation is conducted using the VISSIM microscopic traffic model and the EnViVer emission model. The measures included are traffic demand control, banning Heavy Duty Vehicles (HDVs), speed restriction and Adaptive Cruise Control (ACC). These are assumed to be either implemented from the road-side (i.e. demand control, banning HDVs and speed restriction) or the vehicle-side (i.e. ACC). The objective is to explore the potential impact of different traffic measures on emissions. First, the theory behind the selected measures is discussed. Then, a description of the experimental set up is provided. Finally, the results are presented and concluding remarks are made.

6.2.1 Theoretical background

In order to develop a measure to improve air quality, it is necessary to understand which traffic parameters are important in the context of air quality and how to include them in the development of the measure. In general, traffic emissions increase with an increase in traffic volume, the number of heavy vehicles, the amount of acceleration and deceleration and in the cases of very high or very low speeds (Wilmink and Op de Beek, 2007). Therefore, traffic measures should focus on four aspects: reducing traffic volume, reducing the number of heavy vehicles, avoiding acceleration and deceleration and optimizing speed. Each of the selected measures focuses on one of the four aspects: demand control reduces the total number of vehicles, banning HDVs reduces the number of HDVs, speed restriction limits the maximum vehicle speed and ACC decreases the amount of acceleration and deceleration.

To reduce traffic emissions at hot-spot locations, the total number of vehicles can be reduced by means of traffic re-routing. When implementing such a measure, it is important to ensure that spare capacity is available in the network. In the HEAVEN project (HEAVEN, 2010), the implementation of re-routing through streets closure in Rome has worsened the situation as spare capacity was hardly available in the urban network.

Heavy duty vehicles are known to be the major sources of NO_x and PM_{10} pollutants. Access control measures have been implemented in countries like Sweden and the UK (van Breugel et al., 2005). The measures have been used in a static manner, prohibiting access to sensitive areas (e.g., city centers) by heavy trucks and old buses at all times. The results showed a large reduction in PM_{10} emissions and less in terms of NO_x emissions.

Speed is an important factor in vehicular emissions. From a safety point of view, lowering speed limits in urban areas is known to have significant benefits on road safety (Anderson et al., 1997). The impact of a speed limit on the environment depends on the impact the speed limit has on driver behavior and may be different for different pollutants. Int Panis et al. (2006) found that the introduction of 30 kmh^{-1} zones in urban areas had no significant impact on NO_x and CO_2 but may reduce PM emissions from diesel vehicles.

Adaptive Cruise Control was originally designed to enhance driver comfort on motorways. Several studies have shown that ACC also affects traffic flow and road safety by reducing the percentage of very short headway times (van Driel, 2007). Moreover, ACC can also have an impact on traffic emissions and fuel consumption by smoothing traffic flow and homogenizing driver speeds. Simulation of mixed traffic consisting of manual and ACC vehicles showed that the smooth response of ACC vehicles can reduce fuel consumption as well as the emitted pollutants (Bose et al., 2003; Ioannou and Stefanovic, 2005).

6.2.2 Experimental set up

In order to evaluate the effect of the traffic measures under consideration, a morning peak hour of the Bentinckplein network was simulated. For each scenario, 10 runs of VISSIM using different random seeds were conducted. Ten runs per scenario were considered sufficient after also conducting 20 runs, which showed that the average and the standard deviation of the emissions of each run stabilized between 5 - 10 runs and did not change after 10 runs. A rectangular node, of length 170 m and width 132 m, was drawn around the intersection. From within this node traffic parameters in VISSIM were extracted for each measure including the number of vehicles as well as the delay and number of stops per vehicle. Furthermore, the average speed on the main road was obtained.

The reference scenario included the morning peak hour between 07:00 to 08:00. The fleet composition consisted of 93% light duty vehicles and 7% heavy duty vehicles. The speed distribution was 45-55 kmh^{-1} for LDVs and 40-45 kmh^{-1} for HDVs. Before the peak hour started, 15 minutes O/D matrix was loaded for warming up the simulation.

Demand control was implemented by reducing the total demand by 20%. The reduction affects both LDVs and HDVs equally by multiplying the O/D matrices by 0.8. The demand for buses and trams was unchanged.

Banning HDVs was implemented by replacing each HDV by 1.5 LDV to maintain an equivalent cargo capacity. Thus, the total demand was increased by a factor of 1.035.

The original speed limit on the main road was 50 kmh^{-1}. However, during the morning peak hour the average speed on the main road was 43.9 kmh^{-1}. A speed limit of 30 kmh^{-1} was introduced on both the main and cross roads. This was done by applying a speed distribution of 25-30 kmh^{-1} in VISSIM for all vehicle types including buses.

The ACC was implemented using the Application Programming Interface (API) in VISSIM. For each simulation time step, all relevant information about the vehicle state was extracted including the speed, acceleration, position of host and predecessor vehicles. This information was then used to calculate the desired acceleration of the ACC vehicles and sent back to VISSIM to update the state of ACC vehicles. The ACC algorithm as described in (van Driel, 2007) was used. The desired acceleration is preliminarily calculated for both free-driving and car-following conditions. The desired acceleration is set to the minimum of these two values. The desired acceleration is bounded between the maximum acceleration and deceleration rate.

$$a_{des} = \begin{cases} a_{max} & \text{if } a_{des} > a_{max} \\ d_{max} & \text{if } a_{des} < d_{max} \\ a_{des} & \text{otherwise} \end{cases} \tag{6.1}$$

The desired acceleration (a_{des}) is determined as:

$$a_{des} = min(a_{i,free}, a_{i,follow}) \tag{6.2}$$

$a_{i,free}$ is the acceleration for free-driving condition, which is determined as:

$$a_{i,free} = k * (v_0 - v_i) \tag{6.3}$$

$a_{i,follow}$ is the acceleration for car-following condition, which is determined as:

$$a_{i,follow} = k_d * (d_i - d_{i,desired}) + k_v * (v_{i-1} - v_i) \tag{6.4}$$

The desired distance headway ($d_{i,desired}$) is determined as:

$$d_{i,desired} = d_0 + h_w * v_i \tag{6.5}$$

Where a_{max} denotes maximum acceleration, d_{max} maximum deceleration, v_0 desired distance, d_0 safety margin, h_w desired headway and k, k_d and k_v are gain parameters. The value for each parameter was set as follows: a_{max} = 3 ms^{-2}, d_{max} = -5 ms^{-2}, v_0 = 55 kmh^{-1}, d_0 = 3.0 m, h_w = 1.5 $sec.$, k = 0.4, k_d = 0.3 and k_v = 1.2. The ACC penetration rate was set to 40 %.

6.2.3 Results and discussion

The impacts of all the measures on both total emissions and emissions per vehicle types appear in Table 6.1. In addition, number of vehicles, average speed on the main road as well as delay and number of stops per vehicle are also given. The results and discussion from each measure are presented next.

Table 6.1: *Total emission change and change per vehicle type due to the traffic measures*

Measure		Emission Parameters			Traffic Parameters			
		CO_2	NO_x	PM_{10}	Number of veh.	Aver. speed	Delay/ veh.	Stop/ veh.
Reference scenario	Total	100%	100%	100%	3367	43.9	25.3	0.5
	LDV	65.8%	42.3%	59.9%	2927	44.2	24.3	0.4
	HDV	32.6%	54.5%	36.7%	218	39.9	24.6	0.4
	Bus	1.6%	3.2%	3.4%	10	34.2	19.2	0.5
Demand control	Total	-23.3%	-24.6%	-23.4%	-18.5%	+6.5%	+2.4%	+22.6%
	LDV	-22.8%	-21.9%	-22%	-19.5%	+6.5%	+3.4%	+25.1%
	HDV	-27.5%	-28.4%	-27.9%	-22.8%	+4.8%	+3.9%	+19%
Banning HDVs	Total	-25.8%	-50%	-30.9%	+3.7%	+1.6%	-2.7%	+4.9%
	LDV	+10.3%	+10.2%	+9.3%	+11.7%	+0.9%	-2.6%	+5.5%
	HDV	-100%	-100%	-100%	-100%	-100%	-100%	-100%
Speed restriction	Total	-16.1%	-13.4%	+19.6%	-0.1%	-32.8%	-3.9%	-0.7%
	LDV	-16.7%	-16.8%	+15.9%	-0.2%	-33.1%	-5%	-1.4%
	HDV	-15.9%	-12.4%	+25.7%	-0.5%	-28.2%	-7.9%	-3.6%
ACC	Total	-7.9%	-8.7%	-1.1%	+0.01%	-1.5%	-8.4%	+138%
	LDV	-8.1%	-11.3%	-1.4%	-0.05%	-1.5%	-9.4%	+149%
	HDV	-7.8%	-7.0%	+0.4%	-1.2%	-1.2%	-7.3%	+274%

1. Reference scenario

For the reference scenario the percentage contributions from LDVs and HDVs for each pollutant are given. The average speed on the main road was 43.9 kmh^{-1}. The total number of vehicles was 3367 vehicles, the total delay per vehicle was 25.3 second and the total number of stops per vehicle was 0.5.

2. Traffic demand control

The results show that a reduction of the demand by 20% leads to a reduction of the total emission by 23%. The reduction in emission is larger than the reduction in demand, indicating that there is an additional reduction in emission because of the reduction of speed varaition in terms of accelaration and deceleration. Focusing on the reduction per vehicle type, almost the same reduction 23% was obtained per pollutant for LDVs. However, for HDVs the reduction was more than 23% for all pollutants (CO_2: 27.5%, NO_x: 28.4% and PM_{10}: 27.7%), because HDVs have a significant effect on total emissions as they produce as much as 10 times more emissions per kilometre compared to LDVs. For the traffic parameters, the reduction for the traffic volume was about 18.5%. The total delay and number of stops per vehicle increased by 2.4% and 22.2% respectively. Although the relative change in the number of stops might seem large, absolute changes were marginal (i.e. 0.58 for total, 0.55 for LDVs and 0.53 for HDVs). The delay and number of stops per vehicle increased due to the change in the operation of the actuated controller where more green was given to trams and buses. Delay of buses and trams was reduced by 43.2% and 40.5%, while the number of stops was reduced by 27.7% and 21%.

3. Banning heavy duty vehicles

The replacement of each HDV by 1.5 LDV results in a total reduction of 25.8% for CO_2, 50% for NO_x and 30.9% for PM_{10} emissions. Although the contribution from HDVs was reduced by 100% for all the pollutants, an increase of about 10% was realized from LDVs for CO_2, NO_x and PM_{10}. This is due to the increased demand of LDVs which replaced the HDVs in the network. Although the number of vehicles was increased by 3.7%, total average speed on the main road was increased by 1.6%. Total delay per vehicle was reduced by 2.7%, total number of stops per vehicle was increased by 4.9%.

4. Speed restriction

Applying a speed limit of 30 kmh^{-1} (distribution 25-30 kmh^{-1}) was found to reduce both CO_2 and NO_x by 16.1% and 13.4% respectively. However, PM_{10} significantly increased by 19.6%. The changes per vehicle type were as follows: for LDVs, both CO_2 and NO_x were reduced by 16.7%; the same hold for HDVs, where CO_2 and NO_x were reduced by 15.9% and 12.4%. However, PM_{10} increased for both LDVs (15.9%) and HDVs (25.7%). The increase in PM_{10} can be explained by the reduction in average speed as PM_{10} emissions are very sensitive to vehicles' speed. The total delay and the number of stops per vehicle were reduced by 3.9% and 0.7% respectively.

5. Adaptive cruise control

Equipping 40% of vehicles with ACC leads to a reduction of about 8% for both CO_2 and NO_x, and about 1.1% for PM_{10}. The reduction was larger for LDVs than for HDVs, which can be explained by the fact that only LDVs were equipped with ACC. The fact that also the emissions of HDVs decrease as well, indicate that HDVs profit from the smoothening impact of the LDVs equipped with ACC. Velocity-acceleration distribution plots from EnViVer showed that the amount of acceleration and deceleration was reduced in the ACC scenario, which explains the reduction in CO_2 and NO_x emissions. PM_{10} emissions are not sensitive to vehicle dynamics and hence the reduction of PM_{10} is very small. Although the delay per vehicle was reduced by 8.4%, the number of stops was increased by 138%. The increase in the number of stops can be explained by the way VISSIM counts stops: a stop is counted if the speed of a vehicle at the end of the previous time step was larger than zero and at the end of the current time step the speed is zero. However, the increase in the number of stops does not mean an increase in emissions because the total delay per vehicle has decreased. This indicates that there are many vehicles that were not delayed at all or delayed less.

6.2.4 Concluding remarks

After reviewing the change of the total emission per each measure, the following was concluded:

- The best measures with regard to a reduction in all pollutants are measures that reduce traffic demand, either total traffic volume or the number of heavy vehicles. Such measures can be applied at local areas (hot-spots) to help reduce the number of EU limit value violations.
- Heavy Duty Vehicles have a strong impact on both NO_x and PM_{10} emissions. The reduction in the case of banning HDVs for NO_x and PM_{10} was larger than

that obtained by reducing the total demand by 20%, taking into account that HDVs accounted for only 7% of the total demand and each HDV was replaced by 1.5 LDVs.
- Traffic measures to reduce emissions should focus not only on affecting one of the four considered aspects (i.e. traffic volume, number of HDVs, speed and traffic dynamics). While some pollutants are sensitive to one aspect (i.e. PM_{10} for speed), others are not and can be negatively affected.
- The different measures studied have shown to have different types of impact. For example, reducing total demand has reduced the amount of acceleration and deceleration; while banning HDVs has increased the average speed.

6.3 Using V2I/I2V communication to reduce traffic emissions

In this section, examples from the literature are presented on the use of V2I or I2V communication to reduce traffic emissions. The examples include both modeling studies and real-world tests. First the examples are presented and then a discussion is given.

6.3.1 Adaptive traffic control using V2I communication

A modeling study of an adaptive traffic signal controller based on V2I communication was conducted by Gradinescu et al. (2007). The study aimed to investigate the impact of the adaptive controller on traffic emissions and fuel consumption. Using V2I communication, the controller receives the information from all approaching vehicles and determines how crowded the intersection is. Two important traffic metrics are used namely, control delay and queue length. Control delay is calculated as the difference between estimated travel times with and without the presence of a traffic signal. Queue length is calculated directly from the information received from approaching vehicles. Accordingly, both the cycle length and the green time splits for each phase are determined. Green times are extended until a maximum pedestrian waiting time is reached.

A simulation framework was developed including both a traffic simulation model and data communication model. The traffic simulation model is based on the Wiedemann model used in VISSIM. The data communication model deals with delivery of messages between nodes. Furthermore, a module to calculate fuel consumption and pollutant emissions was developed. The module considers the relation between fuel consumption, emission, speed and acceleration of vehicles.

A test site in Bucharest was modeled to study the effect of the proposed adaptive traffic signal. The site consists of a single intersection of two streets (luliu Maniu and Vasile Milea) in downtown Bucharest. The simulation results showed that the proposed adaptive controller performs better than the existing fixed-time signal controller. Traffic emissions were reduced by 6.5% for CO_2, 3.7% for CO, 8.9% for HC and 3.2% for NO_x.

6.3.2 Advance driver information

An advanced driver information system was proposed by Wu et al. (2008). The system is an in-vehicle advisory device based on receiving real-time Traffic Signal Status (TSS) information from signal controllers using I2V communication. First, when a traffic signal turns to green, it sends information about time-to-red (TTR) to all approaching vehicles. Then, the in-vehicle advisory system compares the TTR with an estimated time-to-travel to an intersection. If a driver is expected not to pass through the intersection before the end of green, an alert will be issued to prepare to stop. The driver is assumed to smoothly decelerate (using a deceleration rate of -0.45 ms^{-2}) until a crawl speed (i.e. 8.1 kmh^{-1}) and maintain this speed till he/she applies a maximum deceleration to stop.

the PARAMICS microscopic simulation model was used together with the CMEM emission model to quantify the energy and emission benefits of the in-vehicle advisory system. A network of two successive signalized intersections was modeled. The intersections were controlled using a two-phased fixed-timing signal control. Different levels of volume-to-capacity (v/c) ratios were modeled. Assuming a penetration rate of 100%, both fuel consumption and CO_2 emissions were found to decrease by 1-12% and 1-14% respectively. The benefits decrease when the v/c ratio exceeds 0.8 (Wu et al., 2010).

6.3.3 SKY project

The SKY project (Start ITS from Kanagawa Yokohama) was a field operation test conducted by Nissan in Yokohama, Japan. Started in October, 2006 the project continued for two and half years till March, 2009. The main goal was to test the use of I2V communication to help reducing accidents and ease congestion. However, fuel consumption was also expected to improve. The test site consists of two intersecting main roads: one of two kilometers running east-west and another of one kilometer running north-south. Each of the two intersecting main roads contains multiple intersections.

Standard traffic signals and road beacons were installed in the test roads. To help reducing accidents, time lapses between crossing pedestrian and changes in traffic signals were optimized. The main objective was to ensure pedestrian safety by giving them the right-of-way. However, when no pedestrian is present, traffic signals were switched to green if a request was received from a vehicle through V2I communication. To help reducing congestion, advices on Eco routing guidance were provided to drivers according to real-time information about vehicles location and speed. Both travel times and CO_2 emissions were reduced by 20% and 17% respectively (Fukushima, 2008).

6.3.4 TRAVOLUTION project

TRAVOLUTION (Traffic and Evolution) is a German project that started in spring 2006 and ended in June 2008. The project was funded by the state of Bavaria and carried out by the University of Munich (department of traffic engineering and control), GEVAS software GmbH and AUDI AG in the operation with the city of Ingolstadt. The project addressed four main objectives: improving traffic flow, enhancing safety, reducing travel time and traffic emissions. To achieve these objectives, two approaches were followed through two sub-projects. The first sub-project includes an on-line optimization of network wide traffic signal control using evolutionary algorithms. The second sub-project considers the use I2V communication to inform drivers about remaining green times. Only the second sub-project is described next.

Three intersections were equipped with road-side units including WLAN hot-spots. Traffic signals were able to communicate with equipped vehicles in the range of 200-300 meters around the intersections. Moreover, software components were installed at the signal controllers in order to calculate the following green time intervals. The on-board devices recommend an optimal driving speed for drivers to pass the next intersection without stopping. A reduction of travel times by 5% was realised by the drivers (Braun et al., 2008).

6.3.5 Discussion

According to the presented examples, it is possible to reduce traffic emissions by using V2I or I2V communication. First, V2I communication can be used to send detailed information about vehicle characteristics such as vehicle type, weight/load and direction. This information can be used by traffic signal controllers to optimize the green times settings for different approaches. Second, I2V communication is used to send information about the remaining green time to avoid unnecessary braking and acceleration. Based on these findings, the algorithm will be developed in the next section.

6.4 Development of the algorithm

The algorithm is developed using I2V communication to inform drivers about the traffic signal status. If drivers receive information in advance, for example, about the remaining green time, they may start decelerating earlier and hence reduce idling time at the intersection. In an ideal case, a vehicle might even avoid stopping and return to normal accelerating when the signal switches to green. Figure 6.1 illustrates two trajectories of a vehicle with and without receiving information about the remaining green time. The two trajectories are illustrated together with a schematic diagram of expected CO_2 emissions and fuel consumption during cruising, decelerating and idling.

The optimal trajectory for different vehicles can be determined according to the powertrain of individual vehicles. For hybrid vehicles, one could prefer to let a vehicle drive normally because hard braking can be used to charge the vehicle's battery and idling has zero emission (i.e. engine is shut down).

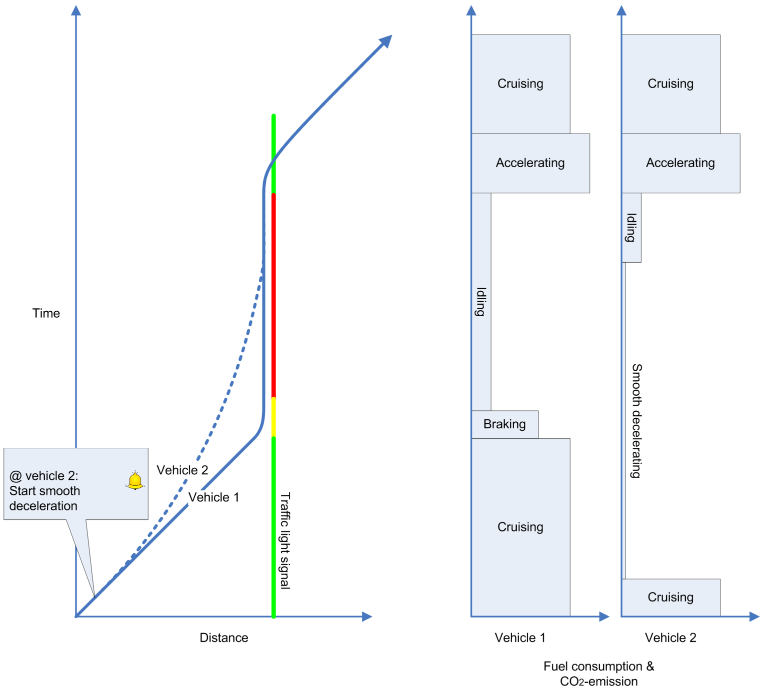


Figure 6.1: *Trajectories for a vehicle with/without receiving information about remaining green time*

The CO_2 emissions and fuel consumption during smooth deceleration depend on the engine revolutions per minute (rpm). If the engine rpm is larger than a specific value during vehicle deceleration with released throttle, modern vehicles will not inject fuel and consequently there will be no emissions and fuel consumption. The specific rpm value depends on the vehicle type (i.e. around 800 rpm).

6.4.1 Description of the algorithm

Drivers are assumed to receive information about the status of the signal at 300 m from the intersection. If the signal is red, drivers are assumed to smoothly decelerate (using a deceleration rate of -0.45 ms^{-1}) to the stop line or the end of the queue. The goal is to reduce idling times and number of stops. If the signal is green, drivers are assumed to smoothly decelerate if their travel time to the intersection is greater than the maximum green. Otherwise, no actions are taken and drivers will follow the normal VISSIM behavior.

Figure 6.2 illustrates the flow chart of the developed algorithm, which is evaluated every time step. For each vehicle, the algorithm is applied if the distance to the traffic signal (D_{sig}) is less than 300 m. Two conditions are considered separately namely, a leading and a following vehicle. These are discussed next in detail.

Leading vehicle

First, the minimum distance, the smooth distance and the travel time to the stop line are

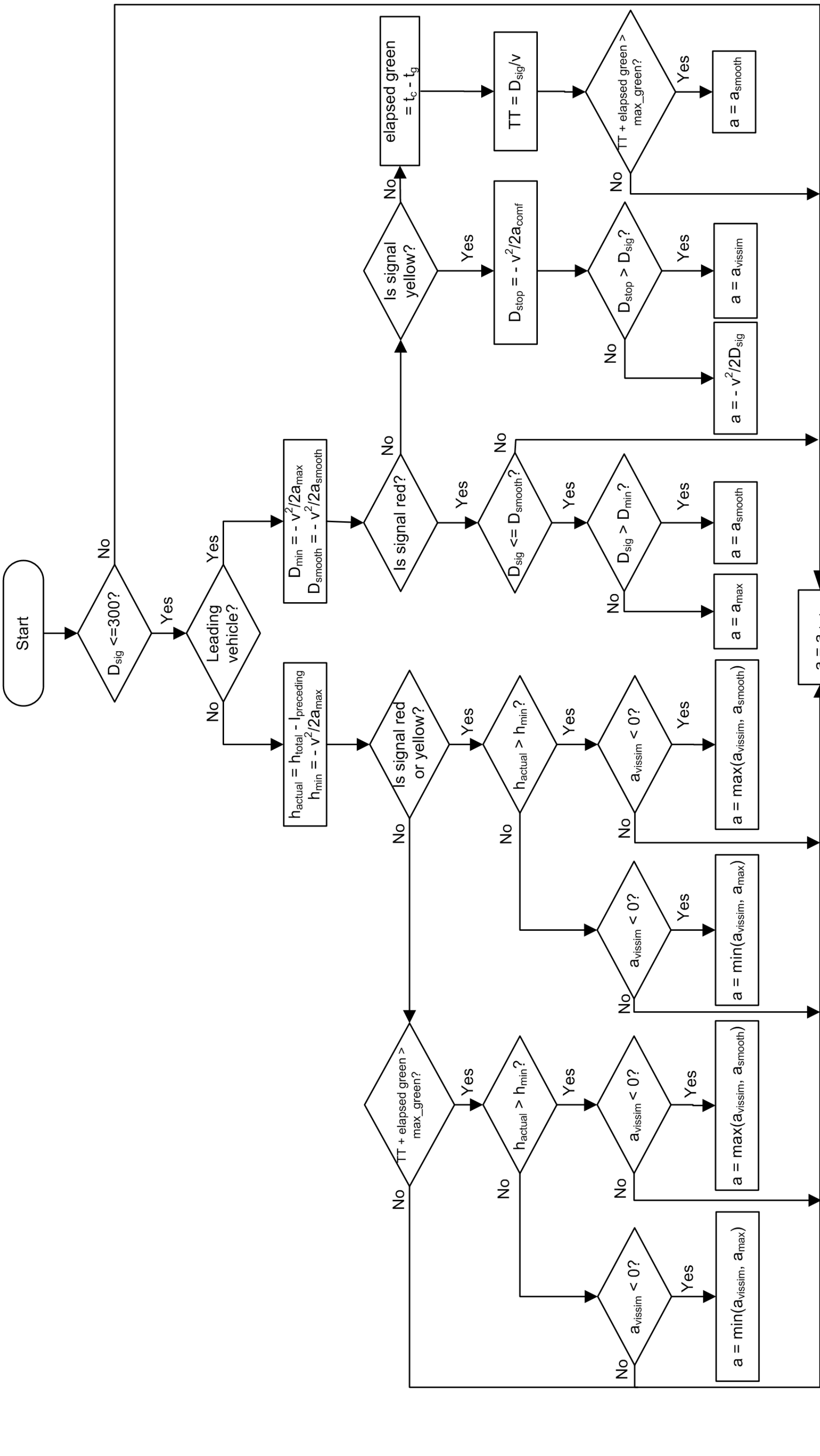


Figure 6.2: *A flow chart for the developed algorithm*

determined. The minimum distance to the stop line, after which a driver has to apply maximum deceleration to be able to stop, is determined as:

$$D_{min} = -\frac{v^2}{2a_{max}} \tag{6.6}$$

where

D_{min} = minimum distance to the stop line in m
v = current vehicle speed in ms^{-1}
a_{max} = maximum deceleration, set to -5 ms^{-1}

The smooth distance, which is required by a driver to arrived to a complete stop using the smooth deceleration is determined as:

$$D_{smooth} = -\frac{v^2}{2a_{smooth}} \tag{6.7}$$

where

D_{smooth} = smooth distance in m
a_{smooth} = smooth deceleration, set to -0.45 ms^{-1}

The travel time to the stop line is determined as:

$$TT = \frac{D_{sig}}{v} \tag{6.8}$$

where

TT = estimated travel time to the stop line in $sec.$
D_{sig} = distance to the stop line in m

If the signal is red and the distance to the stop line is less than the smooth distance, the leading vehicle will smoothly decelerate until the minimum distance is reached. After that the maximum deceleration is applied to stop.

If the signal is yellow, the leading vehicle will determine whether it can stop using a comfortable deceleration of -2 ms^{-1}. If the vehicle can not stop, it will continue using the normal VISSIM behavior; otherwise a new stopping deceleration is calculated to stop by the stop line.

If the signal is green, the elapsed green time is determined as the difference between the current simulation time (t_c) and the simulation time when the current green phase has started (t_g). If the travel time plus the elapsed green time is greater than the maximum green (i.e. 40 seconds), the leading vehicle will smoothly decelerate.

Following vehicle

The behavior of a following vehicle is determined according to the signal status and the behavior of the preceding vehicle. First both the actual and the minimum headways to the preceding vehicle are determined using equations 6.9 and 6.10.

$$h_{actual} = h_{total} - l_{preceding} \tag{6.9}$$

where

h_{actual} = distance between the front bumper of a vehicle and the rear bumper of the preceding vehicle in m

h_{total} = distance between the front bumper of a vehicle and the front bumper of the preceding vehicle in m

$l_{preceding}$ = length of the preceding vehicle in m

Figure 6.3 illustrates the total and the actual headways between two vehicles.

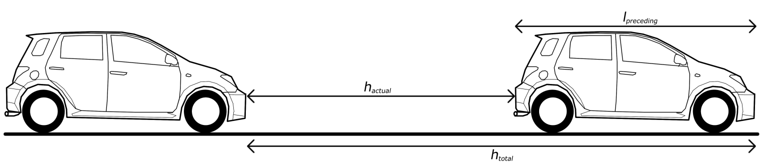


Figure 6.3: *Total and actual headways between two vehicles*

$$h_{min} = -\frac{v^2}{2a_{max}} \tag{6.10}$$

where

h_{min} = minimum headway to the preceding vehicle in m

The behavior of the preceding vehicle is determined by checking the desired acceleration for the next time step calculated by VISSIM for the following vehicle (i.e. a_{vissim}). An action is taken only if a_{vissim} is smaller than zero; otherwise the following vehicle follows the normal VISSIM behavior.

If the signal is red or yellow, the acceleration of the following vehicle is dependent on the actual headway to the preceding vehicle. For headways larger than the minimum headway, the maximum of a_{vissim} and a_{smooth} is taken. For headways smaller than the minimum headway the minimum of a_{vissim} and a_{max} is taken (See Figure 6.2).

If the signal is green, the same logic used during red and yellow times is applied after comparing the travel time plus the elapsed green with the maximum green (See Figure 6.2).

6.5 Summary

In this chapter, an algorithm was developed to reduce traffic emissions at signalized intersections using I2V communication. First, the impact on local traffic emissions was studied for different measures including: traffic demand control, banning HDVs, speed restriction and Adaptive Cruise Control (ACC). The measures were assumed to be either implemented from the road-side (i.e. demand control, banning HDVs and speed restriction) or the vehicle-side (i.e. ACC). The best measures with regard to a reduction in all pollutants were found to be measures that reduce traffic demand, either total traffic volume or the number of heavy vehicles. In the case of ACC, both CO_2 and NO_x emissions were reduced by 8% when only 40% of vehicles were equipped. This indicates the importance of in-vehicle systems since there is a level of detail involved in optimizing driving styles which can only be achieved through in-vehicle systems. It is expetced that measures which use both road-side and vehicle-side systems, through I2V and V2I communications, will result in larger reductions in terms of traffic emissions. Moreover, by using both road-side and vehicle-side systems, more detailed information can be obtained about vehicle characteristics and the surroundings, and hence more accurate recommendations from the road-side can be sent to drivers.

To develop the algorithm, some examples from the literature were reviewed on the use of V2I/I2V communication to reduce traffic emissions in urban areas. The algorithm was developed assuming that drivers receive information about traffic signal status at 300 m from the intersections. During red phases, drivers were assumed to smoothly decelerate to reduce idling times and number of stops. During green phases, drivers were assumed to smoothly decelerate if they know in advance that they can not pass through the intersection before the end of green.

Chapter 7

Results and discussions

In the previous chapter, an algorithm was developed that uses I2V communication between a traffic signal and vehicles to enable vehicles to anticipate the traffic signal status. In this chapter the developed algorithm is implemented on top of an actuated and an adaptive controller. First, a description of the actuated and the adaptive controllers is given in section 7.1. Section 7.2 explains the experimental set up defining the traffic data extracted from VISSIM. Section 7.3 presents the results of a comparison of the actuated controller with the I2V actuated controller and the adaptive controller with the I2V adaptive controller. Finally, the chapter is summarized in section 7.4.

7.1 Description of the controllers

In this section a description of the controllers is presented. First, a general description of the Bentinckplein intersection is provided, including the physical layout as well as the route choice and traffic demand. Next, the configuration of the actuated and the adaptive controllers is explained. Finally, the two controllers when using I2V communication is described.

7.1.1 General description

The Bentinckplein intersection is located in the city of Rotterdam, The Netherlands. The intersection has four legs with the main street (Statenweg) running north-south and the branch street (Bentinckplein) running east-west. Public Transportation (PT) lines for buses and trams are included together with pedestrian and cyclist crossing facilities. The number of approaching lanes is two on the main street and one on the branch street. All approaching roads are widened to three lanes before the stop line to support left and right turns as well as the through directions.

The route choice is based on hourly origin destination (O/D) matrices obtained from vehicles intensities recorded during green times. The O/D matrices were generated using traffic counts collected per 15 minutes on the main street. The measurements were taken on the southbound approach for two directions (i.e. Staten-Bent and Bent-Staten). Ratios of the collected traffic counts per 15 minute were used to generate 15 minute O/D matrices.

The network traffic demand is a representation of the morning peak hour (7:00 to 8:00). The O/D matrix for the morning peak hour is shown in Table 7.1.

Table 7.1: *O/D matrix (in $veh.h^{-1}$) for the morning peak hour (7:00 to 8:00)*

Zones	1	2	3	4
1	0	41	998	8
2	88	0	256	144
3	1076	249	0	95
4	13	115	152	0

Figure 7.1 illustrates the VISSIM network of the Bentinckplein intersection along with the two directions for the collected data and the O/D zones.

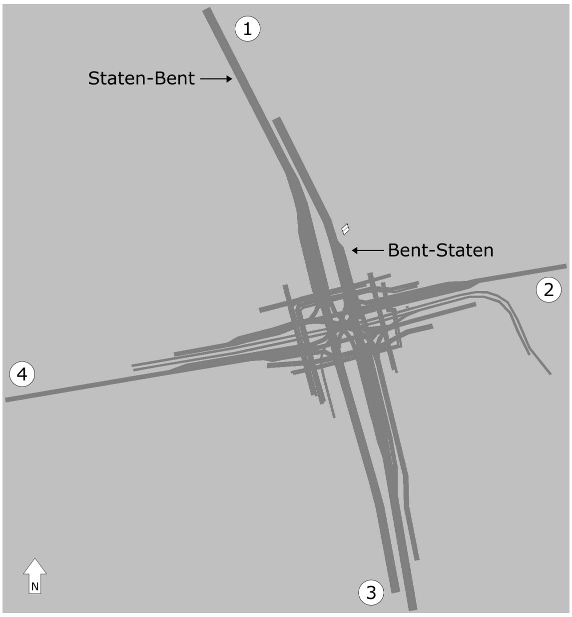


Figure 7.1: *VISSIM network of the Bentinckplein intersection: locations of the measurement points (Staten-Bent and Bent-Staten) and the O/D zones*

7.1.2 Actuated controller

The signal actuated controller consists of two controllers, denoted by SC11111 and SC33-010. The signal controller SC11111 is responsible for the WisselVRI configuration (switch for Trams) and includes two signal groups. The signal controller SC33010 is responsible for the whole intersection and has 39 signal groups numbered as follows:

- 1 to 12 for motorized traffic (12 signal groups);
- 22 to 24 and 26 to 28 for cyclists (6 signal groups);
- 30 to 38 for pedestrian (9 signal groups);
- 42 to 46 and 48 for PT (6 signal groups);
- 82 to 84 and 86 to 88 for opposite cyclists directions (6 signal groups).

Figure 7.2 shows the position of the signal groups. Note that for the main signal groups on the main street (i.e. $fc05$ and $fc11$), there are two signal heads included for each

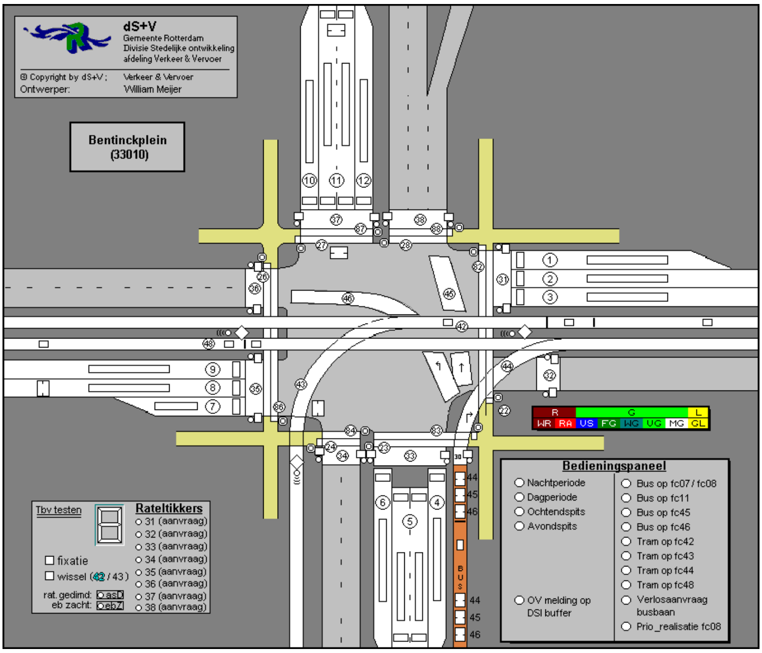


Figure 7.2: *Signal groups at Bentinckplein intersection*

signal group due to the two lanes. On the main street, there are two directions for each pedestrian and cyclists crossing: feeding and following directions. For the branch street, the two directions are included only for pedestrian. The bus lines are on signal groups: $fc07$, $fc11$, $fc45$ and $fc46$; while tram lines are on signal groups: $fc42$, $fc43$, $fc44$ and $fc48$. The bus lines on signal groups $fc45$ and $fc46$ share a special PT lane with the tram line on signal group $fc44$.

Actuated controllers use detectors to sense approaching vehicles and accordingly decide which signal groups can get green. The sequence in which signal groups get green is specified in the so-called block structure (see module structure). A block is defined as a collection of signal groups that can be green simultaneously. If a block is in an active state, all signal groups of that block are allowed to become green. The decision of whether to extend/terminate the current green phase is based on the gap measurement between vehicles using inductive loop detectors installed in the asphalt. If the gap between vehicles is larger than a predefined threshold, the green time is terminated; otherwise the green time is extended till a maximum green is reached. Pedestrians are detected if the push button was used. Cyclists are detected using detectors and/or push buttons.

The VISSIM network in Figure 7.3 presents the configuration of the detectors at Bentinckplein. Using these detectors at approaching lanes, green, yellow and red times are defined accordingly. The guaranteed green, yellow and red for different signal groups are listed in Table 7.2. The specific configuration of the Bentinckplein controllers is described next. All information is derived from (Meijer, 2008).

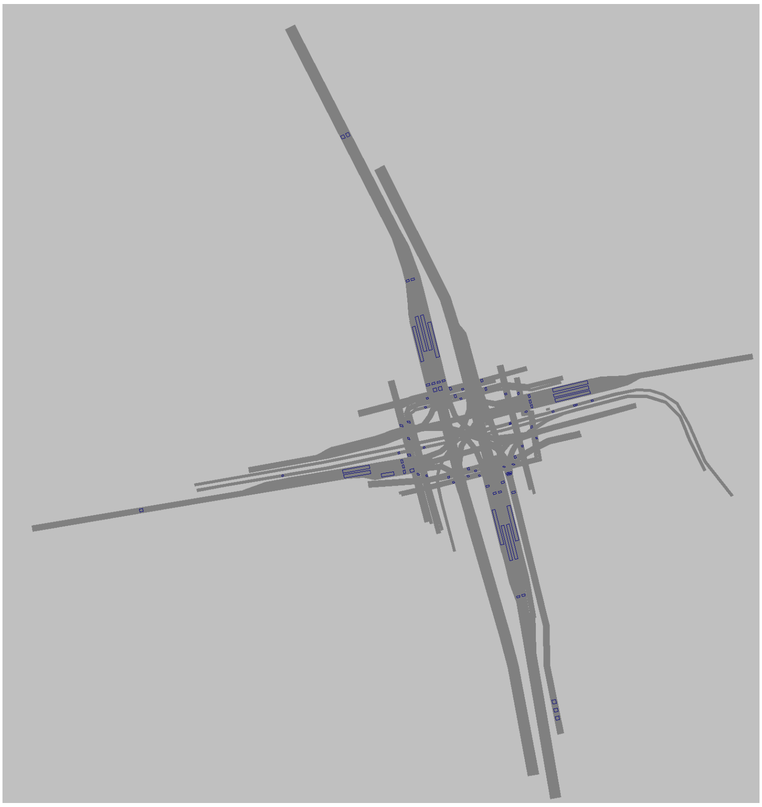


Figure 7.3: *VISSIM network of Bentinckplein, Detectors (in blue)*

Green time extension

The maximum green times for the motorized signal groups are defined for four periods during the day: the night hours (20:00 - 6:00), the morning rush hours (6:00-10:00), the day time hours (10:00-15:00) and the evening rush hours (15:00-20:00). For the cyclists, only one default maximum green is applied for the complete 24 hours, which is set to 15 sec. The controller does not apply green time extension if the travel time between the farthest upstream detector and stop line is greater than the maximum green time.

Module structure

The basic module structure at Bentinckplein consists of six blocks, two of which specifically control public transportation lines. See the structure in Figure 7.4. The six blocks from the basic module structure are described next.

Block 1 controls the main signal groups (i.e. $fc05$ and $fc11$) on the main street. The pedestrians have right-of-way on the green start if the push button is used. Cyclists also receive green with the parallel directions of pedestrians in case the push button is used and if there is no conflict with the PT signal groups. The right turn vehicles on signal groups $fc04$ and $fc10$ can optionally receive green instead of the parallel cyclists and pedestrians under the cover of the main signal groups. Block 2 serves the right turns vehicles on signal groups $fc1$ and $fc07$ and the left turns vehicles on signal groups $fc06$ and $fc12$. Block 3

Table 7.2: *Guarantee green, yellow and red times in 0.1 sec for different signal groups*

	Signal groups	Guarantee green	Guarantee yellow	Guarantee red
Motorized	1	40	30	20
	2	40	30	20
	3	40	30	20
	4	40	30	20
	5	40	40	20
	6	40	30	20
	7	40	30	20
	8	40	30	20
	9	40	30	20
	10	40	30	20
	11	40	40	20
	12	40	30	20
Cyclists	22	40	30	10
	23	40	30	10
	24	40	30	10
	26	40	30	10
	27	40	30	10
	28	40	30	10
Pedestrian	30	40	30	10
	31	40	30	10
	32	40	30	10
	33	40	30	10
	34	40	30	10
	35	40	30	10
	36	40	30	10
	37	40	30	10
	38	40	30	10
PT	42	40	40	10
	43	40	40	10
	44	40	40	10
	45	40	40	10
	46	40	40	10
	48	40	40	10
Cyclists	82	40	30	10
	83	40	30	10
	84	40	30	10
	86	40	30	10
	87	40	30	10
	88	40	30	10

gives green for the main signal groups on the branch street (i.e. $fc02$ and $fc08$) together with the parallel pedestrian and cyclists. Note that trams on signal groups $fc42$ and $fc48$ also get green during this period. The right turn vehicles on signal group $fc07$ optionally receive green instead of the parallel cyclists and pedestrians under the cover of the main signal groups. Block 4 again serves the right turns vehicles on signal groups $fc04$ and $fc10$ and the left turns vehicles on signal groups $fc03$ and $fc09$. Block 5 controls green to the tram on signal group $fc43$. Finally, block 6 gives green to the tram on signal group $fc44$ and both buses on signal groups $fc45$ and $fc46$.

At the start all signal groups remain inactive except signal group $fc30$ for pedestrians crossing the special PT lane for signal groups $fc44$, $fc45$ and $fc46$. The signal group $fc30$ has a fixed request during each cycle, where it remains green until the bus arrives. All pedestrians have a green wave to their follow directions. Cyclists have a traffic dependent detector to their follow directions.

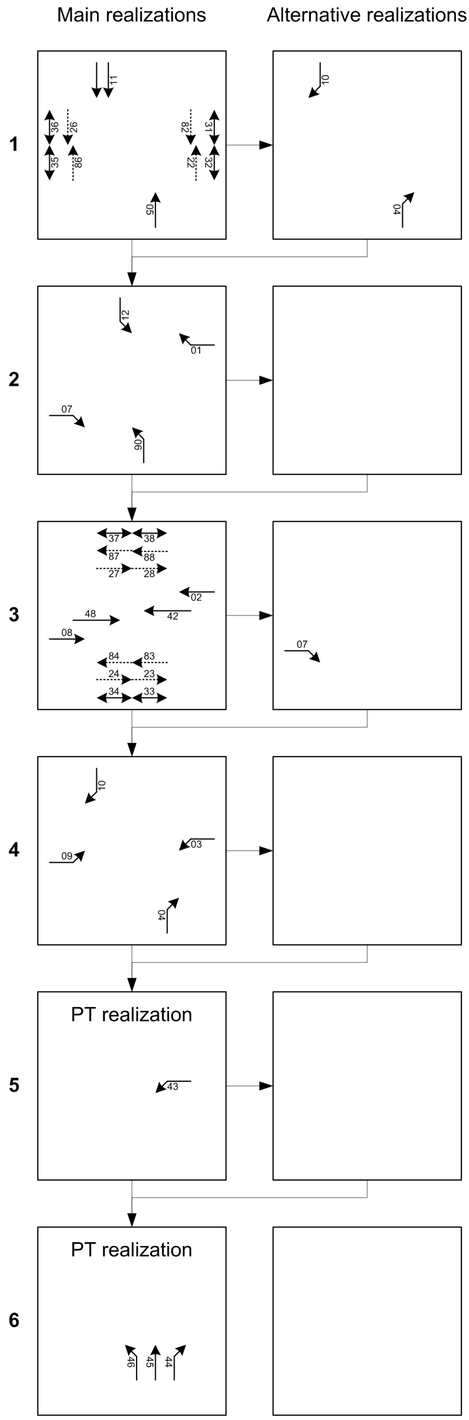


Figure 7.4: *Basic Module structure*

Public transportation

Buses and trams are treated using three priority options defined as follows:

- priority 1: all conflict signal groups can be terminated;
- priority 2: keep the signal green if a bus or tram has arrived;
- priority 3: skip the standard sequence of block structure and give green to PT.

The priority options for the PT lines are presented in Table 7.3. According to these priority options the PT lines can be served between the regular blocks. In the case of no priority, the PT lines will be served at the end of each cycle. The green waves for pedestrians and cyclists can not be terminated. Moreover, the PT lines can not terminate green times for the main signal groups (i.e. $fc05$ and $fc11$) before a minimum 30 seconds of green time has been passed. Finally, the PT lines are not allowed to terminate green time for other signal groups if an adjustable maximum waiting time has been exceeded. This maximum waiting time can be set for each signal group, for example it has been set to 90 seconds for cyclists and to 120 seconds for motorized signal groups.

Table 7.3: *Priority options for different PT lines*

Public Transportation	Given priority
Tram on fc48	23
Tram on fc44	123
Tram on fc43	23
Tram on fc42	23
Bus on fc46	123
Bus on fc45	123
Bus on fc07	23
Bus on fc11	123

7.1.3 Adaptive controller

The main limitation of actuated controllers is that the decision whether to extend or terminate the active green phase is based only on the traffic condition on the current active approach. Adaptive controllers, on the other hand, consider the traffic condition on the whole intersection using a traffic model to evaluate a set of possible control decisions and select an optimal decision based on the current objectives. A look-ahead adaptive controller, in addition to the regular adaptive controller, performs a long term analysis using information from further upstream. Such information can be obtained, in real world, through installation of more detectors.

In this thesis, the look-ahead adaptive controller developed by (van Katwijk, 2008) was used. The main features of this controller compared to the actuated controller are:

- the entire intersection is taken into account and not only the currently active green phase;
- the decision is based on a long term planning i.e. look into the next 120 seconds;
- have a variable/flexible (not fixed) sequence of green times for different signal groups.

The same signal groups and blocks defined in the actuated controller are used by the adaptive controller. Moreover, the guaranteed green, yellow and red for different signal groups have the same values listed in Table 7.2.

Green time extension

The adaptive controller decides to extend or terminate the current green time of traffic signals taken into account the overall travel time of traffic on the entire intersection area for a specified planning horizon. The intersection area is defined as the intersection itself including the approaching roads, typically some 200-300 m. The objective of the adaptive controller is to find an optimal sequence of green time decisions so that the travel time over the entire planning horizon is minimized. The main features of the adaptive controller are described next.

Similar to actuated control, the adaptive controller assumes that traffic signals are grouped into fixed blocks, each block defined as a set of signal groups that can safely receive green simultaneously. Time is represented by discrete time steps of equal length. The optimization horizon defines the time ahead considered in the optimization, typically 120 s. The decision variables define the blocks receiving green during each time step in the optimization horizon. Typically, the solution space of the decision variables is restricted by conditions such as the minimal green time, priority for blocks containing signal groups serving trams and buses and the maximum waiting time for each signal group.

In order to minimize the overall travel time of the traffic on the entire intersection over the optimization horizon, a function is needed that calculated the travel time for each block. The travel time per vehicle is defined as the time difference between the arrival time instant of a vehicle at the intersection area and the time instant the vehicle leaves the intersection area. The travel time is estimated per signal group for a given block being in the same state (green/red) for a given number of time steps, given the current positions of the vehicles in the intersection area. If the signal groups are red, then evidently all vehicles present at and approaching the corresponding signals can not leave, thus adding extra delay to the travel time. If the signal groups are green, then vehicles are assumed to pass the intersection and leave the intersection area. The travel time functions, the details of which can be found in van Katwijk (2008), allow for the computation of the overall travel time for each feasible combination of decision variables.

The algorithm to find which blocks need to receive green in which time steps in order to minimize the total travel time on the intersection area is called every time step. It uses a dynamic programming principle, for further details see van Katwijk (2008).

Public transportation

Compared to the actuated controller, the look-ahead adaptive controller applies full priority to all PT signal groups. All trams and bus lines can terminate all conflicting signal groups even before a minimum 30 seconds of green time is experienced by the main groups $fc05$ and $fc11$. In the case of the actuated controller, not all PT signal groups are given full priority; for example trams on signal groups $fc42$, $fc43$ and $fc48$ can not terminate all conflict signal groups (see Table 7.3). Moreover, due to the long term planning feature of the look-ahead adaptive controller, the arrival of the PT lines can be anticipated and hence faster responses can be given to them. This will reduce travel times for PT lines on the special PT lane.

7.1.4 Actuated/adaptive controller with I2V communication

In the case of the actuated/adaptive controller with I2V communication, vehicles are assumed to receive information about the status of the traffic signal at 300 m from the stop line. If the signal is red, drivers are assumed to smoothly decelerate (using a deceleration rate of -0.45 ms^{-1}) until the stop line or the end of the queue. If the signal is green, drivers are assumed to smoothly decelerate if their travel time to the intersection is greater than the maximum green. Otherwise, no actions are taken and drivers will follow their normal behavior.

7.2 Experimental set up

The impacts of the actuated and adaptive controller with I2V communication are studied for the Bentinckplein intersection using the microscopic simulation model VISSIM as a basis. This section describes the experimental set up used for both the actuated and the adaptive controllers as well as the actuated/adaptive controller when using I2V communication.

7.2.1 Actuated controller

The model set up for the actuated controller is shown in Figure 7.5. The logic of the actuated controller is implemented in the external signal controller. The external signal controller uses information about loop detection and decides the sequences and duration of red, yellow and green.

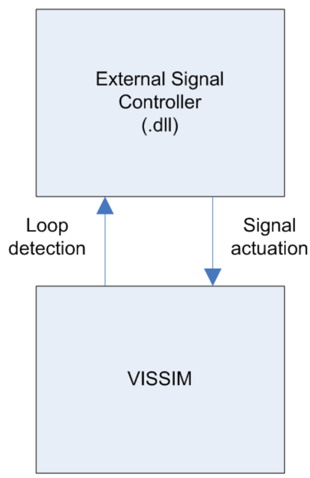


Figure 7.5: *Actuated controller*

The data exchanged between VISSIM and the external signal controller are:

- Loop detection,
- Signal actuation (i.e. sequences and duration of red, yellow and green).

7.2.2 Adaptive controller

The model set up of the look-ahead adaptive controller is illustrated in Figure 7.6. Additional to the set up of the actuated controller, the COM interface and the ITS modeler are used. The COM interface is used to get information about individual vehicles, while the ITS modeler is used to implement the algorithm of the look-ahead adaptive controller.

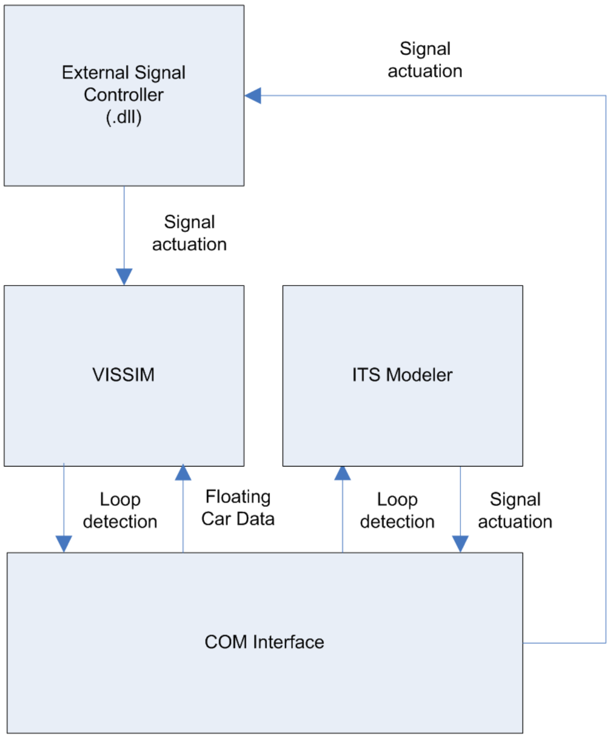


Figure 7.6: *Look-ahead adaptive controller*

The ITS modeler was developed at TNO as a modeling environment to simulate intelligent road-side and vehicles systems and the interaction between them. The users can define their own algorithms, which represent the ITS system, to control the behavior of drivers and vehicles. In this way, ITS modeler can be used to evaluate and assess the impacts of new ITS systems (Versteegt et al., 2005).

The COM interface and external signal controller are communicating through shared memory. The data exchanged between VISSIM and the COM interface are:

- Loop detection,
- Floating Car Data (i.e. vehicles position and distance).

The data exchanged between the COM interface and ITS modeler are:

- Loop detection,
- Floating Car Data (i.e. vehicles position and distance),
- Signal actuation (i.e. sequences and duration of red, yellow and green).

The loop detection information is transferred from VISSIM to the ITS modeler through the COM interface. It is used used by the ITS modeler for the computation of the signal actuation. The signal actuation is sent to VISSIM through the COM interface and the external signal controller. The external signal controller is used to input the signal actuation (decided at the ITS modeler) to VISSIM.

7.2.3 Actuated/adaptive controller with I2V communication

In the case of actuated/adaptive controller with I2V communication, the External Driver Model (EDM) in VISSIM is used to change the behavior of vehicles. The EDM is an interface provided by VISSIM for the users to control vehicles' movement in the network and override VISSIM decisions. For each simulation time step, VISSIM provides the current state of each vehicle and the EDM does its own computation about it and passes the updated state of the vehicle back to VISSIM. Different EDMs can be implemented for different vehicle types in VISSIM. If a vehicle type in VISSIM is assigned to use the EDM, VISSIM calls the functions in the DriverModel.DLL to decide about the acceleration/deceleration for all vehicles of that vehicle type. In this thesis, a 100% penetration rate is assumed, where all vehicle types are assigned to the EDM except buses. The same DriverModel.DLL is assigned to both LDVs and HDVs.

The model set up for the I2V actuated controller and the I2V adaptive controller is shown in Figure 7.7 and Figure 7.8, respectively.

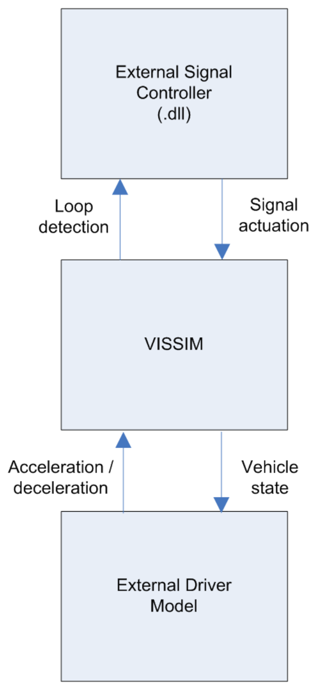


Figure 7.7: *I2V actuated controller*

The data exchanged from VISSIM to the EDM are:

- Gross distance to the preceding vehicle (i.e. front end to front end distance),
- Length of the preceding vehicle,
- Distance to the traffic signal,
- Current state of the traffic signal (i.e. red, yellow and green),
- Simulation time when signal changed to the current state,
- Current simulation time,
- Current vehicle speed,
- Desired acceleration in the next time step.

All the data provided by VISSIM is used by the EDM to calculate the acceleration/deceleration for individual vehicles.

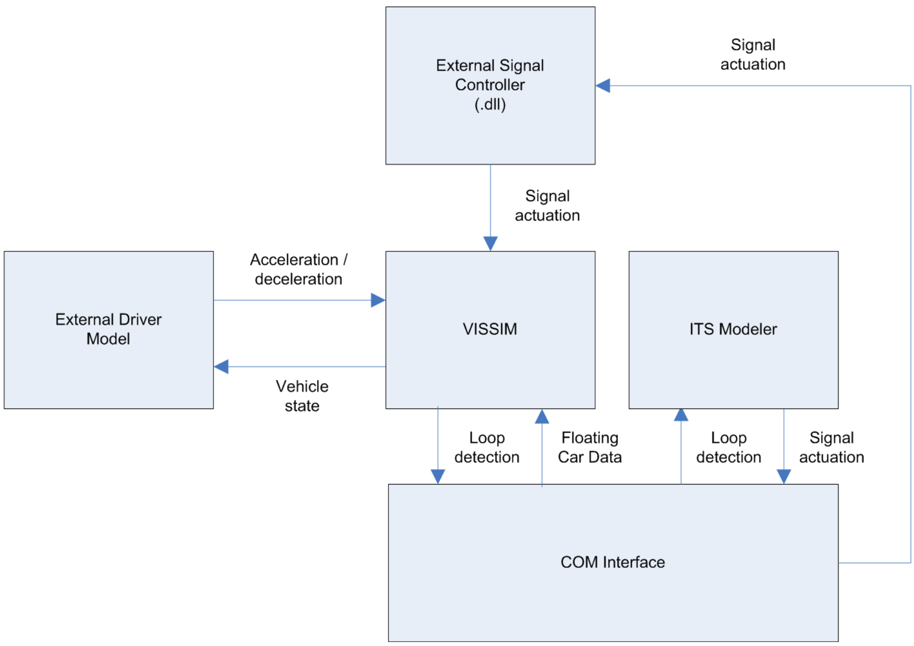


Figure 7.8: *I2V adaptive controller*

7.2.4 Output data

The following VISSIM outputs were extracted:

Travel times were calculated between measurements points placed for different signal groups. For each signal group, two measurement points were placed: one up stream before the stop line and the other is down stream after passing the intersection. The location of the measurement points before the stop line was about 150 m for the main street and about 100 m for the branch street. The average travel time (including waiting time) is calculated as the time between a vehicle crosses the first measurement point to crossing the second measurement point.

The average delay per vehicle (in seconds) is calculated using the same measurements points used in the calculation of the travel times. The delay is computed for every vehicle by subtracting the theoretical (ideal) travel time from the real travel time. The theoretical time is the time that would be reached if there were no other vehicles and no signal controls or other stop in the network. It is calculated assuming that vehicles are traveling at their desired speed.

Vehicle records were extracted for the calculation of emissions using the EnViVer model. For each vehicle, the following parameters were recorded: vehicle number, vehicle type, vehicle type name, total distance traveled, vehicle speed and x,y coordinates.

To check the number of vehicles during the simulations, traffic volume per hour on the main street was extracted and used for the dispersion model's calculation. This includes both LDVs and HDVs at the Staten-Bent and the Bent-Staten directions (see Figure 7.1).

For each scenario 10 stochastically independent runs of VISSIM were conducted. For each output variable, the average value was calculated for these 10 runs. To compare the results from the different scenarios, the paired t-test was used. The paired t-test is a statistical technique used to compare means of two samples. It is often used to compare before-after situations, which was the case in this experiment. Before calculating the paired t-test, a hypothesis needs to be set up. In this experiment, a null hypothesis was used, which assumes that the mean of two paired samples are equal. Moreover, a two-sided significance level of 5% was selected. Accordingly, only if the p-value associated with t is less than 0.05, the differences are considered to be significant (i.e. reject the null hypothesis).

7.3 Results and discussion

In this section the results are presented and discussed. First, the actuated controller is compared with the I2V actuated controller. Then, the adaptive controller is compared with the I2V adaptive controller. The results are presented in terms of average travel times and delay, emissions and concentration levels of NO_x. A comparison between the actuated and the adaptive controller was not conducted since the baseline situation is not the same. For example, the PT lines are treated differently. Moreover, information about vehicles from upstream is not available to the actuated controller.

7.3.1 Actuated vs. I2V actuated controller

Average travel time and delay

The results of the average outcomes over all simulation runs are presented in Table 7.4. In general, both average travel times and delay remain the same for all signal groups. This indicates that smoothing the deceleration of vehicles approaching the intersection does not affect traffic efficiency. Using the paired t-test, the only significant change was found for the PT line on signal group $fc45$, where the average travel time and the delay per vehicle were increased in the case of the I2V actuated controller. This may be explained by the fact that the main signal groups on the main street get more green due to the smooth deceleration of approaching vehicles. All insignificant changes are shown between brackets in Table 7.4. The final column of Table 7.4 displays the traffic volume per signal group in $vehh^{-1}$, which was the same for the actuated and the I2V actuated controller.

Table 7.4: *Average travel time and delay: actuated vs. I2V actuated controller*

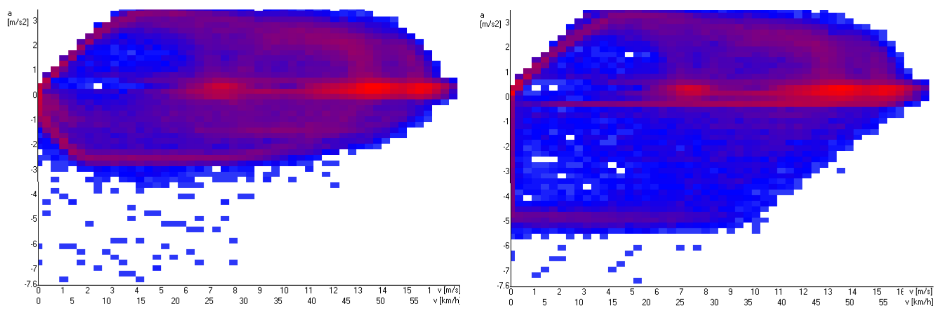
		Actuated controller		I2V actuated controller		Change %		
	Signal groups	**Average travel time (s)**	**Average delay time (s)**	**Average travel time (s)**	**Average delay time (s)**	**Average travel time (s)**	**Average delay time (s)**	**No of vehicles (veh)**
Motorized	1	49.5	33.8	48.9	33.2	(-1.3%)	(-1.7%)	85.5
	2	54.3	37.4	53.4	36.6	(-1.4%)	(-2.1%)	139.3
	3	75.3	52.6	73.2	50.3	(-2.8%)	(-3.9%)	248.2
	4	55.8	38.4	57.6	40.1	(+3.3%)	(+4.6%)	239.2
	5	52.5	34.4	50.8	32.8	(-3.1%)	(-4.9%)	1069.8
	6	75.7	50.9	75.4	50.6	(-0.3%)	(-0.5%)	90.3
	7	61.2	42.9	59.8	41.5	(-2.3%)	(-3.4%)	152.8
	8	53.6	39.6	53.2	39.2	(-0.8%)	(-1.1%)	112.1
	9	77.4	58	73.4	54.1	(-5.1%)	(6.8%)	13
	10	67.4	44.8	61.3	38.7	(-9.1%)	(-13.7%)	7.5
	11	57.1	36.6	57.1	36.4	(-0.2%)	(-0.2%)	979.8
	12	75.7	53.1	79.1	56.5	(+4.5%)	(+6.3%)	39
Cyclists	22	39.3	35.6	41.1	37.3	(+4.3%)	(+4.8%)	16.3
	23	3.8	0.6	4.1	0.9	(+6.1%)	(40.3%)	58.3
	24	48.9	40.9	47.2	39.2	(-3.3%)	(-3.9%)	58.2
	26	23.5	19.2	22.1	17.8	(-5.9%)	(-7.3%)	16.2
	27	39.2	35.7	38.2	34.7	(-2.3%)	(-2.6%)	21.1
	28	6.2	2.1	6.1	2.1	(-0.6%)	(-0.9%)	21.1
Pedestrian	30,1	17.2	0.9	16.9	0.6	(-1.9%)	(-35.7%)	16
	30,2	14.2	1.3	15.2	2.3	(-6.6%)	(+71.6%)	73.4
	31,1	34.1	17.9	37.5	21.3	(+10.2%)	(+19.2%)	74.9
	31,2	31.8	23.1	30.7	21.9	(-3.4%)	(-4.7%)	15.7
	32,1	54.2	32.8	60.9	39.5	(+12.4%)	(+20.7%)	16
	32,2	49	7.5	48.3	5.7	(-1.4%)	(-23.7%)	73.9
	33,1	15.2	11.2	14.9	10.9	(-1.7%)	(-2.7%)	16.1
	33,2	20.2	7.5	18.5	5.7	(-8.8%)	(-23.7%)	73.5
	34,1	63.8	39	62.3	37.5	(-2.4%)	(-3.9%)	73.4
	34,2	53.8	36.6	51.1	33.9	(-5.0%)	(-7.4%)	16.1
	35,1	39	16.2	37.5	14.7	(-4.0%)	(-9.6%)	74.7
	35,2	22.9	12.7	23.5	13.2	(+2.2%)	(+4%)	50.8
	36,1	23.2	13.4	25.3	15.5	(+9.3%)	(+15.9%)	50.9
	36,2	29	12.3	29.6	12.8	(+1.8%)	(+4.5%)	74.5
	37,1	30.5	16.1	31.5	16.8	(+2.3%)	(+0.4%)	75.1
	37,2	22.1	6.9	22.5	7.4	(+1.8%)	(+1.8%)	50.3
	38,1	51.6	29.3	51.6	29.4	(+0.1%)	(+0.3%)	50.1
	38,2	27.5	11.6	28.2	12.3	(+2.5%)	(+6%)	75.4
PT	42	51.9	18.3	52.1	18.4	(+0.2%)	(+0.6%)	3
	43	52.1	18.4	52.3	18.5	(+0.2%)	(+0.5%)	3
	44	38.4	22.1	35.7	19.4	(-7.0%)	(-12.2%)	4
	45	30.5	15.8	39.4	24.7	+29.3	+56.3%	4
	46	32	14.5	36	18.4	(+12.4%)	(+27%)	4
	48	19.7	6.9	15.6	2.2	(-23.7%)	(-67.8%)	2
Cyclists	82	36.9	33.4	34.7	31.1	(-5.9%)	(-6.6%)	40.5
	83	43.4	35.5	42.8	34.9	(-1.2%)	(-1.6%)	98.8
	84	6.7	1.4	6.7	1.3	(-1.4%)	(-6.3%)	99
	86	22.3	16.6	23.9	18.4	(+7.8%)	(+10.4%)	20.9
	87	3.6	0.2	3.6	0.3	(0%)	(+8.7%)	16.1
	88	37.4	28.6	33.3	24.5	(-11.1%)	(-14.5%)	16.1

Emissions

Table 7.5 shows the resulting emissions for the actuated controller and the I2V actuated controller. The I2V actuated controller reduces total traffic emissions as well as emissions per LDVs and HDVs for all pollutants (about 7% for both CO_2 and NO_x and 4% for PM_{10}). Using the paired t-test, all the reductions were found to be significant. In order to check whether the reduction in emissions was caused by smoother vehicle's trajectories with less deceleration, a comparison was made for the acceleration as function of speed for both scenarios. The comparison appears in Figure 7.9, which confirms the decrease of the deceleration between -1 and -3 ms^{-2} in the case of the I2V actuated controller. However, emissions from buses were increased by about 5% for both CO_2 and NO_x, and by 3% for PM_{10}. This is partially due to the increase in travel times for the bus on signal group 45 (see Table 7.4). Looking at the individual bus trajectories in EnViVer, more emissions were realized from buses on motorized signal groups i.e. $fc07$ and $fc11$. This can be explained by the fact that buses on motorized signal groups are interrupted by vehicles which smoothly decelerate.

Table 7.5: *Traffic emissions: actuated vs. I2V actuated controller*

Scenario/Pollutants		**Emission Parameters**		
		CO_2 (g)	NO_x (g)	PM_{10} (g)
Actuated controller	Total	537325.1	1936.1	102.4
	LDV	363745.7	815.6	62.6
	HDV	164440.6	1017.6	36.1
	Bus	9143.7	66.8	3.6
I2V actuated controller	Total	-7.4%	-7.7%	-3.9%
	LDV	-6.7%	-8.2%	-4.4%
	HDV	-9.5%	-8.1%	-3.7%
	Bus	+5.7%	+5.8%	+3.4%



(a) (b)

Figure 7.9: *Speed-acceleration plot: actuated (a) vs. I2V actuated controller (b)*

Air quality

The concentration contribution from traffic (ΔC) is calculated by a dilution factor (θ) using the following equation:

$$\Delta C = E * \theta * \frac{U_{Ref}}{U} \tag{7.1}$$

where

$$
\begin{aligned}
E &= \text{the total emissions from traffic in } \mu g s^{-1} m^{-1} \\
\theta &= \text{the dilution factor in } s m^{-2} \\
U_{Ref} &= \text{the reference wind speed in } m s^{-1} \\
U &= \text{the actual wind speed in } m s^{-1}
\end{aligned}
$$

The value for each parameter was set as follows: U = 4 ms^{-1}, U_{Ref} = 8.4 ms^{-1}, (θ) = 0.000214286, for wind direction of 60°.

Table 7.6 compared the air quality results for the actuated controller and the I2V actuated controller. The I2V actuated controller reduces NO_x concentration by 8%. The main reason for this is the reduction in the emissions factor of both LDVs and HDVs.

Table 7.6: *Concentration levels of NO_x: actuated vs. I2V actuated controller*

	No of vehicles (veh.)		Emissions factors (gkm^{-1})		NO_x concentration (μgm^{-3})
	LDVs	HDVs	LDVs	HDVs	
Actuated controller	2042.8	146.9	0.798167	13.64475	0.4544
I2V actuated controller	2041.7	146.3	0.732856	12.5723	0.4169
Change %	-0.05%	+0.06%	-8.1%	-7.8%	-8.2%

7.3.2 Adaptive vs. I2V adaptive controller

Average travel time and delay

Generally, the average travel time and average delay per vehicle remain almost the same for all signal groups (see Table 7.7). The final column of Table 7.7 displays the traffic volume per signal group in $vehh^{-1}$, which was the same for the adaptive and the I2V adaptive controller. Using the paired t-test, the only significant changes were realized for motorized signal group $fc06$ and pedestrian signal group $fc33, 1$.

Emissions

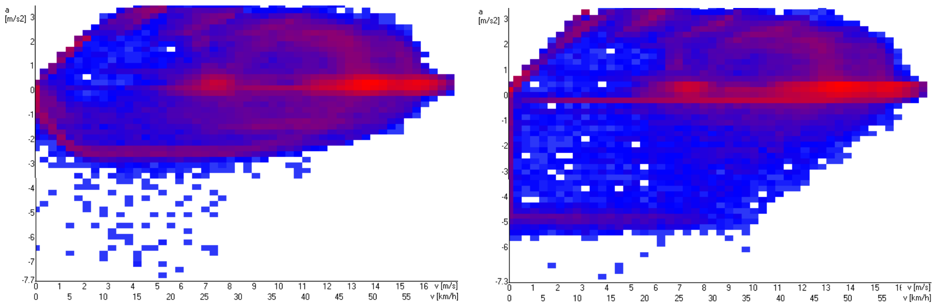
Table 7.8 shows that the I2V adaptive controller reduces total traffic emissions as well as emissions per LDVs and HDVs for all pollutants. Using the paired t-test, all the changes were found to be significant except for buses. Again, the reduction was mainly due to the smoother trajectories of the vehicles, where less decelerations between -1 and -3 ms^{-2} were realized in the case of the I2V adaptive controller. Figure 7.10 compares the acceleration as a function of speed for the adaptive and the I2V adaptive controller.

Table 7.7: *Average travel time and delay: adaptive vs. I2V adaptive controller*

		Actuated controller		I2V actuated controller		Change %		
	Signal groups	**Average travel time (s)**	**Average delay time (s)**	**Average travel time (s)**	**Average delay time (s)**	**Average travel time (s)**	**Average delay time (s)**	**No of vehicles (veh)**
Motorized	1	53.2	37.5	53.1	37.5	(-0.1%)	(-0.1%)	85.8
	2	46.5	29.7	46.1	29.2	(-0.9%)	(-1.5%)	139.1
	3	81	58.3	81.3	58.5	(+0.3%)	(+0.3%)	248.3
	4	33.2	15.8	33.7	16.3	(+1.5%)	(+3.2%)	244.1
	5	28.5	10.5	28.5	10.5	(0%)	(-0.1%)	1057.2
	6	64.3	39.5	61.2	36.4	-4.7%	(-7.8%)	92.6
	7	48.8	30.4	48.7	30.3	(-0.3%)	(-0.6%)	152.8
	8	48.9	34.9	50.4	36.4	(+2.9%)	(-3.9%)	112.3
	9	101.5	82.1	101.3	81.9	(-0.2%)	(-0.2%)	13.6
	10	42.5	20	49.4	26.8	(+16.2%)	(+34.2%)	7.6
	11	32.9	12.4	32.6	11.9	(-1.1%)	(-3.1%)	976.1
	12	86.5	63.8	88.1	65.4	(+1.8%)	(+2.3%)	40.6
Cyclists	22	17.1	13.4	17.6	13.9	(+2.8%)	(-0.6%)	15.9
	23	13.6	10.4	13.2	9.9	(-2.9%)	(-3.5%)	63.9
	24	46.6	38.6	50.1	42.1	(-2.6%)	(+9.2%)	64.1
	26	12.8	8.5	13.3	8.9	(+3.7%)	(+5.6%)	16.1
	27	28.4	24.9	26.6	23.1	(-6.2%)	(+0.5%)	20.4
	28	14.3	10.2	12.5	8.4	(-12.6%)	(-17.6%)	20.5
Pedestrian	30,1	22.3	5.9	22.1	5.6	(-1%)	(-4.2%)	14.1
	30,2	16.7	3.6	17.4	4.3	(+4.2%)	(+19.3%)	72.7
	31,1	22.2	5.9	22.6	6.3	(+1.7%)	(+6.4%)	72.8
	31,2	15.4	6.7	15.8	7.2	(+3.1%)	(+6.7%)	14
	32,1	36.9	15.4	35.9	14.5	(-2.6%)	(+6%)	13.9
	32,2	35.7	9.1	36.7	10.2	(+2.9%)	(+11.6%)	72.9
	33,1	24.3	20.2	31.3	27.2	+28.6%	+34.4%	14.2
	33,2	47.4	34.4	42.9	29.9	(-9.4%)	(-12.9%)	73
	34,1	62.4	37.3	62.7	37.7	(+0.6%)	(+1%)	73.4
	34,2	70.3	53	68.3	51.1	(-2.8%)	(-3.6%)	14.1
	35,1	30.2	7.2	30	7.4	(-0.4%)	(-1.5%)	75.4
	35,2	18.2	7.9	18.9	8.9	(+4.4%)	(+10.2%)	51.3
	36,1	15.9	6.4	16.7	7.1	(+4.7%)	(+11.2%)	51.2
	36,2	23.6	6.9	24.2	7.4	(+2.3%)	(+7.5%)	75.4
	37,1	32.7	18	33.8	19.1	(+3.3%)	(+5.8%)	75.5
	37,2	43.2	27.9	44.4	29.1	(+2.6%)	(+4%)	50.6
	38,1	53.4	27.9	54.6	29.1	(+2.2%)	(+4%)	51
	38,2	44.6	31.6	45.8	12.3	(+2.6%)	(+3.7%)	75.4
PT	42	48.7	13.6	47.9	13.1	(-1.2%)	(+4.5%)	3
	43	48.5	13.7	47.8	13.1	(-1.3%)	(-4.4%)	3
	44	16.8	0.6	16.7	0.4	(-0.9%)	(-27.2%)	4
	45	17.9	3.3	18.5	3.8	(+2.8)	(+16.1%)	4
	46	20.4	2.7	20.8	3.1	(+2.0%)	(+15%)	4
	48	13.3	0.3	13.1	0.2	(-0.9%)	(-39.3%)	2
Cyclists	82	16.1	12.5	16.7	13.1	(+3.4%)	(+4.5%)	39.9
	83	36.4	28.4	37.6	29.6	(+3.2%)	(+4.2%)	98.5
	84	19.1	13.7	21.9	16.6	(+15%)	(+20.7%)	98.8
	86	12.6	7	11.7	6.1	(-7.1%)	(-12.5%)	20.5
	87	8.8	5.4	6.4	3.1	(-26.2%)	(-42.5%)	16.2
	88	39.4	30.7	38.7	29.9	(-1.8%)	(-2.4%)	16.2

Table 7.8: *Traffic emissions: adaptive vs. I2V adaptive controller*

Scenario/Pollutants		**Emission Parameters**		
		CO_2 (g)	NO_x (g)	PM_{10} (g)
Adaptive controller	Total	452406.3	1580.6	89.9
	LDV	31290.7	700.1	55.0
	HDV	132246.5	827.3	31.7
	Bus	7252.1	53.2	3.1
I2V adaptive controller	Total	-6.4%	-7.3%	-2.4%
	LDV	-5.8%	-7.4%	-3.1%
	HDV	-8.2%	-7.6%	-1.9%
	Bus	(+0.9%)	(+0.9%)	(+3.5%)



(a) (b)

Figure 7.10: *Speed-acceleration plot: adaptive (a) vs. I2V adaptive controller (b)*

Air quality

Compared to the adaptive controller, the I2V adaptive controller reduces NO_x concentration by 7%. See Table 7.6. The main reason for this is the reduction in the emissions factor of both LDVs and HDVs.

Table 7.9: *Concentration levels of NO_x: adaptive vs. I2V adaptive controller*

	No of vehicles (veh.)		Emission factors (gkm^{-1})		NO_x concentration (μgm^{-3})
	LDVs	HDVs	LDVs	HDVs	
Adaptive controller	2035.1	147	0.657358	11.12035	0.371589916
I2V adaptive controller	2033.7	146.8	0.608688	10.2828	0.34342978
Change %	-0.06%	-0.13%	-7.4%	-7.5%	-7.5%

7.4 Summary

In this chapter the developed algorithm was implemented on top of an actuated and an adaptive controller. The results were compared in terms of average travel time and delay per vehicle, traffic emissions as well as hourly concentration levels of NO_x. First, the actuated controller was compared with the I2V actuated controller. While average travel time and delay per vehicle remain the same for all signal groups, total traffic emissions reduced by about 7% for both CO_2 and NO_x, and about 4% for PM_{10}. Second, the adaptive controller was compared with the I2V adaptive controller. Again, for the I2V adaptive controller total traffic emissions were decreased by about 6.4%, 7.3% and 2.4% for CO_2, NO_x and PM_{10} respectively. The average travel time and delay did not change significantly. Accordingly, using I2V communication was proven to reduce traffic emissions with both the actuated and the adaptive controller. The reduction is mainly due to the smooth trajectory of vehicles approaching the intersection, decelerating less frequently at decelerations between -1 to -3 ms^{-2}. Finally, the smooth deceleration behavior of vehicles was found to have no negative impact on traffic efficiency.

Chapter 8

Conclusions and recommendations

In this final chapter, a summary and a discussion of the findings in this thesis is provided together with an outlook for future research. Section 8.1 gives the main conclusions. Section 8.2 presents the main scientific and practical contributions. A discussion of the overall results is given in section 8.3. The recommendations for future research are suggested in section 8.4.

8.1 Main conclusions

The main goal of this thesis was to study to which extent the local air quality in an urban corridor can be improved using communication between in-vehicle and road-side unit systems. The objective was to combine the recent development on road-side and vehicle-side to see the potential of new measures which use co-operative systems. To achieve this goal, first a modeling framework of traffic, emission and dispersion models was developed. Second, an indicator for local air quality was developed to support decision making on short-term local traffic measures. Third, an algorithm was developed to reduce traffic emissions through I2V communication. Finally, the developed algorithm was tested using the modeling framework. The main conclusions are drawn in the following subsections.

8.1.1 Modeling framework

To develop the modeling framework, a literature survey was conducted for various approaches of traffic, emission and dispersion models. For traffic modeling, the focus was on microscopic simulation models since they provide detailed information about individual vehicles and hence allow for an accurate estimate of traffic emissions. The most commonly used microscopic simulation models were reviewed including AIMSUN, PARAMICS and VISSIM. The VISSIM microscopic model was selected because of its detailed traffic control model including user behavior at traffic signals. For emissions modeling, various generic types of emission models were reviewed. To select the most suitable emission model, two important aspects were considered. First, the model should be able to accurately calculate emissions per vehicle and as a function of trajectories expression position as a function of time. Second, the model must be able to evaluate the effect of traffic measures. Consequently, instantaneous emission models were considered and of these the EnViVer model was selected, because of its extensive calibration for Dutch conditions and its good interface with VISSIM. For dispersion modeling, a calculation approach was used based on dilution factors calculated for different wind directions using the WinMiskam CFD model. This approach enables the calculation of concentration levels on the basis of local emission estimates on an hourly basis in combination with data on wind speed and dilution factor as well as the background concentration.

The modeling framework was evaluated at a test site of one intersection located at Bentinckplein in the city of Rotterdam. The site was selected because a kerbside monitoring station is located near the intersection, providing hourly concentration levels of NO_2, NO and PM_{10}. First, a calibration process was conducted for the VISSIM network of the Bentinckplein intersection. For that purpose, real world traffic data collected on the main street were used. The data include traffic counts and average vehicle speed per 15 minutes for two classes of vehicles: shorter and longer than 3.5 m. Using the average vehicle speed as the main calibration variable, the car-following parameters in VISSIM were adjusted to improve the ability of VISSIM to reproduce local traffic conditions at Bentinckplein. For emission modeling, no additional calibration actions were undertaken because the EnViVer model had already been calibrated and validated for Dutch traffic conditions. For the dispersion model, the total hourly concentration measurements of NO_x at the kerbside station were compared with the hourly concentration results from the modeling framework. The modeling framework was found to over-estimate the measured concentrations with a Fractional Bias = + 25%. The R^2 of the regression analysis was 0.5 with an Index Agreement of 0.75. Generally, the results were considered acceptable, taking into account that both the background concentrations as well as the meteorological data were measured outside the city.

8.1.2 An indicator for the local air quality

The development of an indicator for the local air quality was needed to support the decision on whether or not a traffic measure should be activated and when the measure might contribute to a lower pollutant concentrations. The short- and long-term EU limit values were found to send conflicting signals about the actual air quality. For example, in a certain area, while hourly concentrations always remain below the hourly limit, the yearly limit can be exceeded. The question was how to judge the hourly concentrations measurements in relationship to the yearly limit.

To develop the indicator, a reference pattern method developed by Elshout (2004) was used. Hourly concentration measurements of NO_2, NO and PM_{10} were used from a kerbside and a background station for the period of 2005-2008. Using statistical analysis, a set of air quality rules was developed for the kerbside, describing when specific measures to improve the local air quality need to be taken in order to satisfy both short- and long-term EU limit values. The rules were determined in terms of threshold values for the road-side increments for NO_2 (ΔNO_2) and NO_x (ΔNO_x) for different periods of the year (per three months).

8.1.3 Development of the algorithm

In order to support the development of the algorithm using co-operative vehicle-infrastructure systems, the impact of several road-side or vehicle-side measures was investigated. The investigation was conducted on the Bentinckplein intersection using the VISSIM microscopic traffic model and the EnViVer emission model. The measures included were traffic demand control, banning HDVs, speed restriction and Adaptive Cruise Control (ACC). These measures were assumed to be either implemented from the road-side (i.e. demand control, banning HDVs and speed restriction) or the vehicle-side (i.e. ACC). The best measures with regards to a reduction in all pollutants were found to be measures that reduce traffic demand or banning HDVs. A reducing of the demand by 20%, resulted in a reduction of the emissions of CO_2, NO_x and PM_{10} of about 23%. HDVs were found to have a significant impact on both NO_x and PM_{10} emissions. The reduction in the case of banning HDVs for NO_x and PM_{10} was larger than that obtained by reducing the total demand by 20%, taking into account that HDVs accounted for only 7% of the total demand and each HDV was replaced by 1.5 LDVs. A speed restriction to 30 kmh^{-1} reduced both CO_2 and NO_x by 16.1% and 13.4% respectively, but led to an increase of 19.6% in PM_{10} emissions. PM_{10} emissions increased more for HDVs than for LDVs. In the case of ACC, both CO_2 and NO_x emissions were reduced by 8% when only 40% of the vehicles was equipped. This finding suggests that there is a good potential to reduce emissions by changing driving patterns, especially in terms of smoothness, by in-vehicle systems.

Using I2V communication, an algorithm was developed assuming that drivers receive information about traffic signal status at 300 m from the intersection. During red phases, drivers were assumed to smoothly decelerate (using a deceleration rate of -0.45 ms^{-2}) to reduce idling times and the number of stops. During green phases, drivers were assumed to smoothly decelerate if their travel time to the stop line is larger than the maximum green time.

8.1.4 The impact of the algorithm

The modeling framework was used to test the operation of the developed algorithm. Using the External Driver Model in VISSIM, the developed algorithm was implemented on top of an actuated and an adaptive controller. The actuated controller uses detectors to sense approaching vehicles and decide whether to extend or terminate the current green phase according to the demand on the active green phase. The adaptive controller, in addition to the use of detectors, takes the decision based on the demand on the entire intersection. The results showed a reduction of traffic emissions for both the actuated and the adaptive controller using I2V communication. For the actuated controller, emissions were reduced by about 7.5% for both CO_2 and NO_x and by 4% for PM_{10}. For the adaptive controller, the reductions were about 6.5% for CO_2, 7.4% for NO_x and 3% for PM_{10}. Both the average travel time and the delay per vehicle remain the same for both the actuated and the adaptive controller when using I2V communication. This indicates that the traffic efficiency was not affected by the behavior of vehicles that smoothly decelerate during red and green times.

8.2 Main contributions

The main scientific contributions of this thesis are:

- a simulation framework was developed to evaluate the impact of traffic emissions on local air quality. The modeling framework was found to give reasonable results (R^2 of 0.5 and Index of Agreement = 0.75) when comparing with hourly concentration measurements from a kerbside station;
- an extension was made for the current control algorithm using I2V communication to reduce traffic emissions at advanced signalized intersections.

The main societal and practical contributions of this thesis are:

- the use of I2V communication was found to reduce traffic emissions and improve air quality at urban signalized intersections, which will help to meet the EU limit values;
- an indicator for local air quality was developed, which can be used by road operator and traffic system suppliers to respond to high concentration levels at hot-spot locations.

8.3 Discussion of the results

In this thesis, the use of I2V communication was found to reduce traffic emissions for both actuated and adaptive controllers. The reductions were about 6.5-7.5% for both CO_2 and NO_x, and about 3-4% for PM_{10} emissions. The results are promising taking into account the complex situation at the Bentinckplein intersection and the high traffic demand during the moring peak hour. However, the redults did not give insight into the impact of different penetration rates of equipped vehicles. Moreover, only I2V communication was used and not V2I communication. To fully quantify the environmental impacts of co-operative systems, V2I communication should also be used. Using V2I communication, vehicles can send information about their types and directions to the signal controller to further optimize the setting of green times for different approaches.

The promising results give rise to speeding up further development of the environmentally friendly co-operative applications within the eCoMove project (Vreeswijk et al., 2010). The eCoMove project aims to reduce the overall fuel consumption in traffic by 20%. The results are in line with other studies discussed in chapter 6. In (Gradinescu et al., 2007), the use of V2I communication was found to reduce both CO_2 and NO_x by about 6.5% and 3.2% respectively. In (Wu et al., 2010), the same reductions were obtained in terms of CO_2 emissions (between 6-8%) when the volume-to-capacity (v/c) was over 0.8.

8.4 Further research

This section suggests the recommendations for future research. The recommendations are discussed per each chapter in the following subsections.

8.4.1 Modeling challenges

In this thesis, a modeling framework of traffic, emission and dispersion models was developed. The results from the modeling framework showed that traffic emissions can be reduced using I2V communication. However, to simulate a more realistic behavior of co-operative systems, new models are needed which consider also the communication aspects between in-vehicle and roadside units systems. For this purpose traffic and communication models are used. Communication models are very important tools in evaluating the impact of co-operative systems as they provide insight into the communication aspects of co-operative systems. Co-operative systems will effectively influence drivers' behavior, only if the data between vehicles and roadside units is successfully exchanged. Recently there have been many attempts to link traffic microscopic models with communication models. One example is the EU iTETRIS (an Integrated Wireless and Traffic Platform for Real-Time Road Traffic Management Solutions) project (EU, 2010). The iTETRIS project integrates the SUMO (Simulation of Urban MObility) microscopic model (SUMO, 2010) with the ns-3 (Network Simulator) communication model (NS, 2010).

For emission modeling, validated models for engine behavior are needed to accurately estimate emissions from eco-driving solutions such as the algorithm developed in this thesis. Instantaneous power-based emission models such as (CMEM) and (PHEM) are good examples of models that consider detailed information about engine power demand. For future research, the results from the algorithm using such models can be compared with the results obtained in this thesis using the EnViVer model. Power-based emission models offer the advantage that variations of the gear choices of drivers, variable loading of the vehicles and road gradients can be simulated. However, detailed input data are needed such as engine speed, which can not be obtained from current traffic microscopic models. Assuming default values for such input will affect the accuracy of the emission calculations. Another important issue concerning emission modeling is the consideration of new vehicles such hybrid vehicles.

When calibrating a traffic microscopic simulation model for emission calculations, detailed calibration of vehicles' acceleration distribution is needed. This requires detailed empirical data such as data collected by cameras or GPS equipped vehicles. Moreover, traffic data collected from the field for the calibration process should not only differentiate between LDVs and HDVs, but further differentiate between different types of HDVs emission category (i.e. heavy duty medium and heavy duty heavy vehicles).

For dispersion modeling, dedicated background station is needed to obtain a better representation of the air quality level for the study area. Finally, the modeling framework developed in this thesis should be validated using another test site with different road topography and traffic conditions.

8.4.2 An indicator for the local air quality

For a further improvement of the local air quality indicator developed in this thesis, it is recommended to use air quality data of longer period, for example 5 years. Threshold values for the road-side increments for NO_2 and NO_x were determined for periods of three months. To obtain more accurate results, these threshold values can be decided for shorter periods, for example per month. This will be possible with the use of a database measurements of longer period.

8.4.3 Algorithm development

In this thesis, an algorithm was developed using I2V communication to reduce traffic emissions at signalized intersections. Only one vehicle trajectory was assumed for both LDVs and HDVs. Drivers of both vehicle types were assumed to smoothly decelerate (using -0.45 ms^{-2} deceleration) until they stop by the stop line or end of the queue. A further reduction of traffic emission may be obtained by optimizing trajectories for different vehicle types. Furthermore, the algorithm can be implemented from the road-side using V2I communication. For example, vehicles can send information about their types and directions to the signal controller to further optimize the setting of green times for different approaches. Information about the direction of vehicles can be obtained directly from navigation systems. For the actuated and adaptive controller, the information about the exact number of vehicles taking left and right turns are obtained from the detectors at the lane extension for left and right turns. These detectors are located few meters away from the stop line.

8.4.4 Additional experiments

This thesis focused only on the local impact of the algorithm in terms of traffic emissions as well as concentration levels. Results from simulations show that the algorithm can substantially reduce local emissions and concentration levels. Additional benefits may be achieved by considering a corridor of controlled intersections. For a prober evaluation, the impact of the algorithm in terms of air quality must be studied on street level as well as on the total background level. Moreover, the impact of various penetration rates of equipped vehicles should be studied. This will provide insight into the impact of the system in the early stages of deployment.

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Summary

Road transport has expanded the scope of human mobility, increasing the distances people travel. However, the recent increase in the number of vehicles has resulted in many adverse consequences in terms of safety, efficiency and the environment. Traffic emissions are known to be the main source of air pollution in urban areas. In particular, traffic is responsible for the emissions of nitrogen oxides (NO_x), particulate matter (PM), volatile organic compounds (VOC) and carbon monoxide (CO), as well as the green house gas carbon dioxide (CO_2). To reduce these emissions, the EU directives have set limit values for the concentration of several air pollutants. However, in many European cities pollutant concentrations are still exceeding the limits at hot-spots locations (e.g., busy streets). Local short-term traffic measures (e.g., speed adaptation) can be used to help reducing the concentrations at these hot-spot locations.

Today while demand for environmental aspects has increased and is expected to increase even further, a new development has occurred in the applications of co-operative vehicle-infrastructure systems. Using co-operative systems, vehicles and road infrastructures can communicate with each other through Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I or I2V) communication. With V2V and V2I, information will be available about vehicles' locations and their surroundings as well as weather conditions. Therefore, co-operative systems can be used to improve road safety and efficiency. Moreover, co-operative systems can be used to make road traffic more environmentally friendly by reducing traffic emissions and improving air quality. For example, co-operative systems can provide personalized advice to drivers to avoid unnecessary acceleration and excessive speed as well as to select the most energy efficient route. Recently, co-operative systems have gathered a considerable interest through different European projects such as CVIS, SAFESPOT and COOPERS. The applications within these projects were mainly developed for safety and efficiency objectives, and not specifically for environmental objectives. Although traffic efficiency applications will help to reduce traffic emissions, larger benefits can be achieved using applications that specifically target environmental issues. Some environmentally friendly co-operative applications are under development as part of an EU funded project called eCoMove. However, the environmental benefits of these applications have not been fully quantified.

The main goal of this thesis is to evaluate to which extent the local air quality in an urban corridor can be improved using co-operative systems. To achieve this goal, first a modeling framework of traffic, emission and dispersion models was developed. Second, an indicator for local air quality was developed to support decision making on short-term local traffic measures. Third, an algorithm was developed using I2V communication to influence the traffic flow in real-time and help reducing traffic emissions. Finally, the developed algorithm was tested using the modeling framework.

To develop the modeling framework, a literature survey was conducted for various approaches of traffic, emission and dispersion models. For traffic modeling, the focus was on microscopic simulation models since they provide detailed information about individual vehicles and hence allow for an accurate estimate of traffic emissions. The most

commonly used microscopic simulation models were reviewed including AIMSUN, PARAMICS and VISSIM. The VISSIM microscopic model was selected because of its detailed traffic control model including user behavior at traffic signals. For emissions modeling, various generic types of emission models were reviewed. To select the most suitable emission model, two important aspects were considered. First, the model should be able to accurately calculate emissions per vehicle and as a function of trajectories expression position as a function of time. Second, the model must be able to evaluate the effect of traffic measures. Consequently, instantaneous emission models were considered and of these the EnViVer model was selected, because of its extensive calibration for Dutch conditions and its good interface with VISSIM. For dispersion modeling, a calculation approach was used based on dilution factors calculated for different wind directions using the WinMiskam CFD model. This approach enables the calculation of concentration levels on the basis of local emission estimates on an hourly basis in combination with data on wind speed and dilution factor as well as the background concentration.

The modeling framework was evaluated at a test site of one intersection located at Bentinckplein in the city of Rotterdam, The Netherlands. The site was selected because a kerbside monitoring station is located near the intersection, providing hourly concentration levels of NO_2, NO and PM_{10}. First, a calibration process was conducted for the VISSIM network of the Bentinckplein intersection. For that purpose, real world traffic data collected on the main street were used. The data include traffic counts and average vehicle speed per 15 minutes for two classes of vehicles: shorter and longer than 3.5 m. Using the average vehicle speed as the main calibration variable, the car-following parameters in VISSIM were adjusted to improve the ability of VISSIM to reproduce local traffic conditions at Bentinckplein. For emission modeling, no additional calibration actions were undertaken because the EnViVer model had already been calibrated and validated for Dutch traffic conditions. For the dispersion model, the total hourly concentration measurements of NO_x at the kerbside station were compared with the hourly concentration results from the modeling framework. The modeling framework was found to over-estimate the measured concentrations with a Fractional Bias = + 25%. The R^2 of the regression analysis was 0.5 with an Index Agreement of 0.75. Generally, the results were considered acceptable, taking into account that both the background concentrations as well as the meteorological data were measured outside the city.

The development of an indicator for the local air quality was needed to support the decision on whether or not a traffic measure should be activated and when the measure might contribute to lower pollutant concentrations. The short- and long-term EU limit values were found to send conflicting signals about the actual air quality. For example, in a certain area, while hourly concentrations always remain below the hourly limit, the yearly limit can be exceeded. The question was how to judge the hourly concentrations measurements in relationship to the yearly limit.

To develop the indicator, a reference pattern method developed by Elshout (2004) was used. Hourly concentration measurements of NO_2, NO and PM_{10} were used from a kerbside and a background station for the period of 2005-2008. Using statistical analysis, a set of air quality rules was developed for the kerbside, describing when specific measures to improve the local air quality need to be taken in order to satisfy both short- and long-term EU limit values. The rules were determined in terms of threshold values for the road-side increments for NO_2 (ΔNO_2) and NO_x (ΔNO_x) for different periods of the year (per three months).

In order to support the development of the algorithm using co-operative vehicle-infrastructure systems, the impact of several road-side or vehicle-side measures was investigated. The investigation was conducted on the Bentinckplein intersection using the VISSIM microscopic traffic model and the EnViVer emission model. The measures included were traffic demand control, banning Heavy Duty Vehicles (HDVs), speed restriction and Adaptive Cruise Control (ACC). These measures were assumed to be either implemented from the road-side (i.e. demand control, banning HDVs and speed restriction) or the vehicle-side (i.e. ACC). The best measures with regards to a reduction in all pollutants were found to be measures that reduce traffic demand or banning HDVs. A reduction of the demand by 20% resulted in a reduction of the emissions of CO_2, NO_x and PM_{10} of about 23%. HDVs were found to have a significant impact on both NO_x and PM_{10} emissions. The reduction in the case of banning HDVs for NO_x and PM_{10} was larger than that obtained by reducing the total demand by 20%, taking into account that HDVs accounted for only 7% of the total demand and each HDV was replaced by 1.5 LDVs. A speed restriction to 30 kmh^{-1} reduced both CO_2 and NO_x by 16.1% and 13.4% respectively, but led to an increase of 19.6% in PM_{10} emissions. PM_{10} emissions increased more for HDVs than for LDVs. In the case of ACC, both CO_2 and NO_x emissions were reduced by 8% when only 40% of the vehicles was equipped. This finding suggests that there is a good potential to reduce emissions by changing driving patterns, especially in terms of smoothness, by in-vehicle systems.

Using I2V communication, an algorithm was developed assuming that drivers receive information about traffic signal status at 300 m from the intersection. During red phases, drivers were assumed to smoothly decelerate (using a deceleration rate of -0.45 ms^{-2}) to reduce idling times and the number of stops. During green phases, drivers were assumed to smoothly decelerate if their travel time to the stop line is larger than the maximum green time.

The modeling framework was used to test the operation of the developed algorithm. Using the External Driver Model in VISSIM, the developed algorithm was implemented on top of an actuated and an adaptive controller. The actuated controllers uses detectors to sense approaching vehicles and decide whether to extend or terminate the current green phase according to the demand on the active green phase. The adaptive controller, in addition to the use of detectors, takes the decision based on the demand on the entire intersection. The results showed a reduction of traffic emissions for both the actuated and the adaptive controller using I2V communication. For the actuated controller, emissions were reduced by about 7.5% for both CO_2 and NO_x and by 4% for PM_{10}. For the adaptive controller, the reductions were about 6.5% for CO_2, 7.4% for NO_x and 3% for PM_{10}. Both the average travel time and the delay per vehicle remain the same for both the actuated and the adaptive controller when using I2V communication. This indicates that the traffic efficiency was not affected by the behavior of vehicles that smoothly decelerate during red and green times.

In conclusion, this thesis gives more insight into the impacts of co-operative systems on the environment. To assess these impacts a modeling framework of traffic, emission and dispersion model was developed. The use of I2V communication was found to reduce traffic emissions for both actuated and adaptive controllers without affecting traffic efficiency. The reductions were about 6.5-7.5% for both CO_2 and NO_x, and about 3-4% for PM_{10} emissions. The promising results found in this thesis give rise to speeding up further development of environmentally friendly co-operative applications within the eCo-Move project. To fully quantify the impact of co-operative systems on the environment, it is recommended to study the impact of V2I communication as well. Using V2I communication, vehicles can send information about their types and directions to the signal controller to further optimize the setting of green times for different approaches. Moreover, the system shoud be demonstrated in a test site to validate the model results.

Samenvatting

Door de verbeterde mogelijkheden om over de weg te reizen, worden er steeds meer verplaatsingen gemaakt en zijn de reisafstanden in de loop van de jaren steeds groter geworden. Deze toename in het aantal voertuigkilometers heeft geresulteerd in diverse negatieve consequenties op terreinen als veiligheid, efficiëntie en leefbaarheid. Uitstoot door het verkeer is de belangrijkste bron van luchtverontreiniging in stedelijke gebieden. In het bijzonder is verkeer verantwoordelijk voor de uitstoot van stikstofoxiden (NO_x), fijnstof (PM), vluchtige organische stoffen (VOS) en koolmonoxide (CO), en het broeikasgas koolstofdioxide (CO_2). Om deze uitstoot de verminderen, zijn krachtens Europese regelgeving limietwaarden ingesteld voor de concentraties van verschillende verontreinigende stoffen. In veel Europese steden worden deze limieten echter nog steeds overschreden in zogeheten hot spots, zoals drukke straten. Lokale, kortdurende verkeersmaatregelen zoals snelheidsaanpassing kunnen worden ingezet om de concentraties in hot spots te verminderen.

Terwijl de aandacht voor milieuaspecten is toegenomen, en de verwachting is dat dit verder zal toenemen, zijn er nieuwe ontwikkelingen in de toepassing van coöperatieve voertuigwegkant systemen. Door gebruik te maken van coöperatieve systemen kunnen voertuigen en infrastructuur met elkaar communiceren via voertuig-voertuig (V2V) of voertuig-infrastructuur (V2I of I2V) communicatie. Met V2V en V2I zal informatie beschikbaar zijn over de locatie van voertuigen en bijvoorbeeld weersomstandigheden. Coöperatieve systemen kunnen zo een bijdrage leveren aan een verhoogde verkeersveiligheid en efficiëntie. Bovendien kunnen de systemen bijdragen aan een reductie van de uitstoot van schadelijke stoffen. Het systeem kan bijvoorbeeld aan een bestuurder een persoonsgebonden advies geven om onnodig optrekken en remmen te voorkomen, of om een energiezuinige route te nemen. Coöperatieve systemen zijn recentelijk onderwerp van studie in verschillende Europese projecten, zoals CVIS, SAFESPOT en COOPERS. De ontwikkelde toepassingen in deze projecten richten zich voornamelijk op veiligheid en doorstroming, en niet specifiek op leefbaarheidaspecten. Hoewel toepassingen op het gebied van doorstroming de emissies helpen verminderen, zijn grotere reducties haalbaar bij toepassingen die specifiek gericht zijn op milieuaspecten. Een aantal milieuvriendelijke coöperatieve toepassingen zijn in ontwikkeling als onderdeel van het EU project eCoMove. De effecten op emissies zijn echter nog niet volledig gekwantificeerd.

Het doel van dit proefschrift is te bepalen in hoeverre lokale luchtkwaliteit in een stedelijke corridor kan worden verbeterd met coöperatieve systemen. Hiertoe is allereerst een modelraamwerk ontwikkeld met verkeers-, emissie- en dispersiemodellen. Vervolgens is een indicator voor lokale luchtkwaliteit opgesteld, welke beslissingsondersteunend functioneert bij kortdurende verkeersmaatregelen. In de derde stap is een algoritme ontwikkeld om de verkeersstroom real-time te benvloeden met I2V communicatie, om zodoende emissies te verminderen. Tenslotte is het algoritme getest in het modelraamwerk.

Voor het ontwikkelen van het modelraamwerk is literatuuronderzoek gedaan naar verschillende verkeers-, emissie- en dispersiemodellen. Bij de verkeersmodellen lag de focus op microscopische modellen, omdat deze modellen gedetailleerde informatie over individuele voertuigen bevatten en berekenen, wat een goede bepaling van de emissies mogelijk maakt. De meestgebruikte microscopische modellen zijn bekeken, inclusief AIMSUN, PARAMICS en VISSIM. Uiteindelijk is er gekozen voor VISSIM vanwege de gedetailleerde verkeersregeling, met onder meer het gedrag van bestuurders bij verkeerslichten. Diverse algemene emissiemodellen zijn bekeken voor het modelleren van de uitstoot. Twee belangrijke aspecten waren doorslaggevend bij de selectie van het model. In de eerste plaats moest het model accurate berekeningen per voertuig uitvoeren en deze kunnen weergeven in de vorm van een trajectorie. Ten tweede moest het model geschikt zijn voor het evalueren van verkeersmaatregelen. Uit diverse modellen is EnViVer geselecteerd, vanwege de uitgebreide calibratie voor de Nederlandse situatie en de goede samenwerking met VISSIM. Voor het modelleren van de dispersie is gekozen voor een rekenmethode op basis van verdunningsfactoren voor verschillende windrichtingen, volgend uit het WinMiskam CFD model. Deze methode maakt het mogelijk om concentraties te berekenen aan de hand van lokale emissieschattingen per uur, gecombineerd met data voor windsnelheden en verdunningsfactoren, alsook achtergrond concentraties.

Het modelraamwerk is getest op de proeflocatie Bentinckplein in Rotterdam. Deze locatie is gekozen vanwege de aanwezigheid van een meetpunt voor de luchtkwaliteit. Het meetpunt levert per uur concentraties aan voor NO_2, NO en PM_{10}. In eerste instantie is het VISSIM netwerk van het kruispunt gecalibreerd op basis van de werkelijke kruispuntgegevens. Hiervoor zijn verkeersgegevens van de hoofdstroom op het kruispunt verzameld. De gegevens omvatten intensiteiten en gemiddelde snelheden per 15 minuten, verdeeld naar twee voertuigklassen (langer en korter dan 3.5 meter). Met behulp van de werkelijke gemiddelde snelheden zijn de parameters van het voertuigvolgmodel in VISSIM gecalibreerd, zodat VISSIM de lokale verkeerssituatie beter nabootst. Er is geen extra calibratie uitgevoerd voor de emissies, omdat EnViVer al gecalibreerd en gevalideerd is voor Nederlandse omstandigheden. Voor het dispersiemodel is een vergelijking uitgevoerd tussen de gemeten concentraties NO_x per uur en de concentraties per uur die volgen uit het model. Er is geconstateerd dat het model een overschatting van de concentraties geeft met een Fractional Bias van +25%. De correlatiecoëfficient R^2 van de regressieanalyse was 0.5 met een Index Agreement van 0.75. De resultaten worden beschouwd als acceptabel, gegeven dat de achtergrondconcentratie en de meteorologische gegevens zijn gemeten buiten de stad.

De ontwikkeling van een indicator voor de lokale luchtkwaliteit was nodig om het moment te bepalen waarop maatregelen geactiveerd moeten worden, en wanneer de maatregelen bijdragen aan een verbeterde luchtkwaliteit. Geconstateerd is dat de korte- en langetermijn-EU-limietwaarden conflicterende signalen afgeven over de luchtkwaliteit. Voor een bepaald gebied was het bijvoorbeeld mogelijk dat de uurlimieten niet werden overschreden, terwijl de jaarlijkse limiet wel werd overschreden. Hieruit ontstond de vraag hoe de concentraties per uur beoordeeld moesten worden in relatie tot de jaarlijkse concentraties.

Voor de ontwikkeling van de indicator is een referentiepatroon gebruikt dat is ontwikkeld door Elshout (2004). Concentraties per uur van NO_2, NO en PM_{10} zijn betrokken van een wegkantstation en een achtergrondstation over de periode 2005-2008. Middels statistische analyse is voor het wegkantstation een set regels voor luchtkwaliteit ontwikkeld, waarin is aangegeven wanneer bepaalde maatregelen genomen moeten worden om zowel aan de korte- als langetermijnlimietwaarden te voldoen. De regels zijn opgesteld als drempelwaardes voor de wegkanttoenames voor NO_2 (ΔNO_2) en NO_x (ΔNO_x) voor verschillende perioden in het jaar (per drie maanden).

Om de ontwikkeling van het algoritme dat gebruik maakt van coöperatieve voertuig-infrastructuur-systemen te ondersteunen, is de invloed van verscheidene infrastructurele en voertuigmaatregelen onderzocht. Het onderzoek is uitgevoerd op de kruising Bentinckplein met behulp van het VISSIM microscopische verkeersmodel en het EnViVer emissiemodel. De onderzochte maatregelen behelsden het ingrijpen op de verkeersvraag, het verbieden van zware voertuigen, snelheidsbeperking en Adaptive Cruise Control (ACC). Deze maatregelen worden beschouwd als infrastructurele maatregelen (het ingrijpen op de verkeersvraag, het verbieden van zware voertuigen, snelheidsbeperking) of als voertuigmaatregelen (ACC). De beste maatregelen met betrekking tot het reduceren van alle uitlaatgassen bleken het ingrijpen op de verkeersvraag en het verbieden van zware voertuigen. Het verlagen van de verkeersvraag met 20% leidde tot een reductie van ongeveer 23% in de uitstoot van CO_2, NO_x en PM_{10}. Zware voertuigen bleken een aanzienlijke invloed te hebben op de uitstoot van zowel NO_x als PM_{10}. De reductie in de uitstoot van NO_x en PM_{10} door het verbieden van zware voertuigen was groter dan in het geval van het verlagen van de verkeersvraag met 20%, rekening houdend met het feit dat zware voertuigen slechts 7% van de totale verkeersvraag omvatten en dat elk zwaar voertuig is vervangen door 1.5 lichte vrachtwagens. Een snelheidslimiet van 30 kmh^{-1} verminderde de uitstoot van zowel de CO_2 als de NO_x met respectievelijk 16.1% en 13.4%, maar zorgde voor een toename in de uitstoot van PM_{10} met 19.6%. De uitstoot van PM_{10} nam sterker toe voor zware voertuigen dan voor lichte vrachtwagens. In het geval van ACC nam de uitstoot van zowel CO_2 als NO_x met 8% af bij een penetratiegraad van ACC van 40%. Deze bevinding suggereert dat er een potentieel bestaat voor het reduceren van de uitstoot door het veranderen van rijgedrag en dan in het bijzonder door verkeersstromen te egaliseren.

De invloed van I2V communicatie is getest op basis van een algoritme waarin is aangenomen dat alle bestuurders informatie ontvangen over de status van het verkeerslicht op 300 meter van de intersectie. Tijdens de roodfases is aangenomen dat bestuurders geleidelijk afremden (met een versnelling van -0.45 ms^{-2}) om de tijd dat een voertuig stilstaat en het aantal stops te verminderen. Tijdens de groenfases is aangenomen dat bestuurders geleidelijk afremden in het geval dat de reistijd tot de stopstreep groter is dan de maximale groentijd.

Het modelraamwerk is gebruikt om de werking van het ontwikkelde algoritme te testen. Met behulp van het External Driver Model in VISSIM is het ontwikkelde algoritme geïmplementeerd bovenop een voertuiggestuurd en adaptief verkeerslicht. Een voertuiggestuurd verkeerslicht gebruikt detectoren om naderende voertuigen te detecteren om te kunnen beslissen of de huidige groentijd moet worden verlengd naar aanleiding van de vraag tijdens de actieve groenfase. Het adaptieve verkeerslicht neemt naast de detectoren, de verkeersvraag van het gehele kruispunt mee in de beslissing. De resultaten tonen een reductie van de uitstoot voor zowel het voertuiggestuurde als het adaptieve verkeerslicht door gebruik van I2V communicatie. Voor de voertuiggestuurde verkeerslicht is de uitstoot verminderd met ongeveer 7.5% voor zowel CO_2 als NO_x en met 4% voor PM_{10}. Voor het adaptieve verkeerslicht zijn de reducties ongeveer 6.5% voor CO_2, 7.4% voor NOx en 3% voor PM_{10}. Zowel de gemiddelde reistijd als de vertraging per voertuig bleven gelijk voor de voeruiggestuurde en de adaptieve verkeerslicht bij het gebruik van I2V communicatie. Dit wijst erop dat de efficiëntie niet is beïnvloed door het gedrag van voertuigen die geleidelijk afremmen tijdens rood- en groenfases.

Concluderend kan gesteld worden dat dit proefschrift meer inzicht geeft in de invloed van coöperatieve systemen op de leefomgeving. Om deze invloed te bepalen is een modelraamwerk met verkeers-, emissie- en dispersiemodellen ontwikkeld. Geconstateerd is dat het gebruik van I2V communicatie de uitstoot vermindert voor de voertuigafhankelijke en voertuigadaptieve regeling, terwijl de doorstroming niet wordt benvloed. De verminderingen in uitstoot zijn ongeveer 6.5-7.5% voor CO_2 en NO_x, en 3-4% voor PM_{10}. De veelbelovende resultaten in dit proefschrift kunnen bijdragen aan het versnellen van de introductie van milieuvriendelijke coöperatieve toepassingen binnen het eCoMove project. Om de totale impact van coöperatieve systemen op de omgeving te kunnen kwantificeren, wordt aanbevolen de invloed van V2I communicatie ook te onderzoeken. Met V2I communicatie kunnen voertuigen informatie sturen naar het verkeerslicht over het voertuigtype en de richting om de instellingen van de groenfases verder te kunnen verbeteren. Bovendien wordt aanbevolen om het systeem in een werkelijke proefopstelling te testen, om de modelresultaten te valideren.

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About the author

Mohamed Mahmod was born in Atbara, Sudan, on 31 of January 1979. In 2003 he received his BSc in Electrical Engineering from University of Khartoum, Sudan. In January 2006 he received his Master in Electrical Engineering at the University of Halmstad, Sweden. For his Master thesis he worked with Volvo Technology Corporation together with his colleague Issam Abbas, investigating numerous Intelligent Transportation Systems (ITS) applications from different European projects such as PReVENT, SAFESPOT, and CVIS. The thesis has been rewarded with the Triona and WSP scholarship given to the best Master thesis related to ITS field.

In November 2006, Mohamed started his PhD at the Centre for Transport Studies of the University of Twente, under the supervision of Prof. Bart van Arem. His work includes conducting research, visiting conferences and work shops as well as teaching assistance and student supervision. As a part of his PhD, he also worked at TNO, Mobility and Logistic, as a part time researcher participating in small projects within the ITS field. In January, 2010 he visited the PATH program at the University of California, Berkeley collaborating on developing an algorithm for receiving green time information at signalized intersections. The work carried out during his PhD resulted in this thesis.

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Summary

Road transport has expanded the scope of human mobility, increasing the distances people travel. However, the recent increase in the number of vehicles has resulted in many adverse consequences in terms of safety, efficiency and the environment. This thesis gives more insight into the impacts of co-operative vehicle-infrastructure systems on the environment. Results show that traffic emissions can be reduced at signalized intersections using Infrastructure-to-Vehicle communication to influence drivers' behaviour in real-time.

About the Author

Mohamed Mahmod received his Master's degree in Electrical Engineering from University of Halmstad, Sweden in January, 2006. In November, 2006 he started his PhD at the Centre for Transport Studies, University of Twente. His research interests include co-operative systems, traffic and emission modeling.

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