Impact of intersection design on air quality
Hoving, Peter

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PREFACE

This report presents the results of my training research of the master program Energy and Environmental Sciences at the Center for Energy and Environmental studies (IVEM). About a year ago, I had to choose a subject and it seemed interesting to me to investigate the impact of the construction of beltway junctions on urban air quality. Several times a week, I cross the busiest intersection of Groningen, Julianaplein, by bus for soccer training. I was aware of the future developments at this bottleneck in the infrastructure of Groningen, but wondering whether these changes are only necessary for more traffic throughput or also desirable from an environmental perspective.

The multidisciplinary character of infrastructure appeals to my sentiment, because there are several interesting aspects within infrastructure design; the societal importance of free mobility, the economic target of accessibility with minimal congestion and good environmental performance on the other side make it a subject that could contribute to sustainable development.

I like to thank my first supervisor Henk Moll for his advice and patience. He assisted me throughout the process and asked some critical questions to reflect on the research progress and the results. I also want to thank the other IVEM students for their presence in creating a suitable working environment where a lot of discussions on all imaginable topics took place. And to conclude, I want to thank all other people that supported me in completing this report.

Peter Hoving
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SUMMARY

During the period 2000-2009, the city of Groningen has been restructuring the beltway. The redesigning of the intersections and the impact on urban air quality was the motive for the research conducted. This thesis describes the effects of intersection design on the basis of the emissions of two exhaust gases: nitrogen oxides and particulate matter. High concentrations of these exhaust gases are a threat to human health and the local environment. Therefore, this study tries to answer the question whether intersection design or policy measures can be used to improve the air quality near intersections.

The main research question was formulated as follows: What is the optimal policy for designing intersections, from the point of view of exhaust gas emissions over time with varying policy measures and changing mobility demand? To answer this question, several sub questions were formulated concerning transport characteristics, environmental characteristics and policy measures. To tackle the problem of each intersection being unique, one specific intersection was studied in this study. The bottleneck of the beltway of Groningen, Julianaplein, served as the case under consideration. All mobility data used in the model belong to this specific case.

A spreadsheet model was developed to calculate the overall emissions of nitrogen oxides and particulate matter near an intersection on an average working day. The model consists of emission factors for three vehicle categories. For these vehicle categories (heavy traffic, buses and light traffic), the average traffic intensity of Groningen on an average working day is inserted in the model for three different time slots to discriminate between quiet moments and rush hour. The results are different traffic loads during the day. The traffic load is also dependent on the capacity of an intersection. Five types of intersection are discussed in this thesis. The capacity is not the only difference between the intersections, because the performance influences the average speed and emissions as well. The performance of an intersection is defined as the percentage of vehicles that can drive according to an ideal speed profile. The rest of the vehicles will drive slower. Two congestion speed profiles were developed to account for the slower vehicles and delay due to the design of an intersection.

In general, the model showed that ground level crossings cause more emissions (about thirty percent) than grade separated junctions. The model was also used to assess the importance of the model parameters in the overall impact and the effect of policy measures on the emissions. The environmental characteristics of a vehicle are the main determinant for the overall emissions. Expected emission reductions show the highest potential for improvement, about sixty percent of the current emissions. The traffic intensity is also important, especially the intensity of heavy traffic. The light traffic category has relatively high particulate matter emissions. This leads to the conclusion that NO\textsubscript{X} emissions could be reduced by nine percent and PM\textsubscript{10} emissions by nineteen percent when light traffic would be substituted by buses.

Despite some uncertainties in the model approach, the results of this research could be used by policy makers to make well-founded choices for infrastructure projects. Especially for new infrastructure projects, the advice would be to consider grade separated junctions for intersection with high traffic intensity projections. It is a good choice for the air quality, safety and accessibility. For existing infrastructure, the most emission reduction can be achieved by new technologies. Governments should support innovative, cleaner alternatives for existing transport modes and stimulate the car manufacturing sector in the development of these cleaner vehicles.
SAMENVATTING

Tussen 2000 en 2009 vindt er een herstructurering van de ringweg van de stad Groningen plaats. Het herontwerpen van de kruispunten op de ringweg en het gevolg daarvan op de luchtkwaliteit was de aanleiding voor dit onderzoek. De scriptie bespreekt het effect van kruispunt ontwerpen op de luchtkwaliteit aan de hand van twee uitlaatgassen: stikstofoxide (NO$_X$) en fijn stof (PM$_{10}$). Hoge concentraties van deze uitlaatgassen zijn gevaarlijk voor de menselijke gezondheid en het milieu en de huidige concentratielimieten worden vooral op drukke wegen overschreden. Daarom probeert deze studie de vraag te beantwoorden of het ontwerp van kruispunten de luchtkwaliteit kan bevorderen. Ook verwachte mobiliteitsontwikkelingen en beleidmaatregelen worden geëvalueerd.

De centrale onderzoeksvraag was als volgt geformuleerd: Wat is het optimale beleid om kruispunten te situeeren, gezien vanuit voertuigemissies die veranderen in de loop van de tijd, onder invloed van verschillende beleidsmaatregelen en andere mobiliteitskenmerken. Om deze vraag te beantwoorden is de vraag opgedeeld in drie delen, betreffende transport kenmerken, milieukenmerken en beleidsmaatregelen. Omdat elk kruispunt uniek is, is de vraag beantwoord voor een specifiek geval: het huidige knelpunt van de ringweg Groningen, het Julianaplein. De mobiliteitsdata die gebruikt is in het model behoren toe aan deze specifieke situatie, terwijl het model met enige aanpassingen ook gebruikt kan worden voor andere kruispunten.

Een spreadhheet model was ontwikkeld om de emissies van NO$_X$ en PM$_{10}$ te kunnen berekenen die dichtbij het kruispunt ontstaan op een gemiddelde werkdag. Het model bevat emissiefactoren voor drie verschillende voertuigcategorieën waarvan ook de gemiddelde transportintensiteit op een werkdag bekend is, gedifferentieerd over drie verschillende perioden. Er worden vijf verschillende type kruispunten behandeld in dit onderzoek, met elk een eigen capaciteit. De capaciteit van een kruispunt en de transportintensiteit leveren een wegbezettings op die als basis dient voor het beschrijven de gemiddelde snelheid van voertuigen. De prestatie van elk type kruispunt is ook verschillend. De prestatie is gedefinieerd als het percentage voertuigen dat kan rijden volgens een ideaal snelheidsprofiel. Het model bevat ook twee vertraagde snelheidsprofielen om de snelheid van voertuigen te kunnen beschrijven die (deels) in de file staan, of moeten stoppen vanwege het type kruispunt.

Het model liet zien dat ongelijkvloerse kruisingen in het algemeen beter scoren dan gelijkvloerse kruispunten. Het verschil is ongeveer dertig procent. Verder is het model geïntegreerd om het belang van de verschillende parameters te onderzoeken, en de mogelijke verbetering als gevolg van beleidsregelgeving. De milieuprestaties van een voertuig bleken de belangrijkste factoren, aangezien verwachte technologische innovaties tot zestig procent emissiereductie kunnen leiden onder gelijkblijvende mobiliteitskenmerken. De totale transportintensiteit is ook belangrijk. Een groei van transport zorgt voor een meer dan evenredige groei van de emissies. Voornamelijk de categorie zware voertuigen is belangrijk, omdat de emissiefactoren het hoogst zijn. Lichter voertuig stoot relatief veel PM$_{10}$ uit (in vergelijking met de verschillen voor NO$_X$), waardoor een substitutiestrategie zinvol kan zijn. Meer bussen (beter openbaar vervoer) in plaats van auto’s leidt tot circa negen procent minder NO$_X$ emissies en tot ongeveer negentien procent minder PM$_{10}$ emissies.

Ondanks een aantal onzekerheden in het model, kunnen de resultaten van dit onderzoek goed gebruikt worden door beleidsmakers om onderbouwde keuzes te maken betreffende infrastructuur. In het bijzonder voor nieuwe projecten zou er het advies zijn om ongelijkvloerse kruispunten te overwegen. Dit is goed voor de luchtkwaliteit, maar ook voor de veiligheid en de bereikbaarheid. Voor bestaande infrastructuur is het advies om te richten op technologische innovaties die de voertuigemissies terug kunnen dringen. Overheden zouden op elk niveau innovatieve, schonere alternatieven voor het huidige voertuigenpark moeten stimuleren en ondersteunen. Dit kan bijvoorbeeld door strenge doelen te stellen aan de voertuigfabrikanten.
1. INTRODUCTION

The exposure of city populations to damaging levels of air pollution and noise pollution is worrying. According to the Eurobarometer survey (European Commission, 2004) 45 percent of the respondents is extremely worried about the air pollution problem. The problem tops the list of ‘hottest’ environmental issues together with water pollution and climate change. A calculation by Fletcher and McMichael (1997) shows the health effects of air pollution in Latin America, where two million children are at risk of developing cough, while 20,000 may die of air pollution. These values are comparable for all urbanised areas across the world. Due to the fact that air pollution is primary caused by anthropogenic actions, air pollution is ranked as one of the top ten contributors to preventable deaths by the World Health Organization. (Bhatnagar, 2004). This introduction will show the relevant issues of air pollution, some historical technological changes and policy regarding air pollution.

Environmental issues

Problems that can be associated with increased emissions from road transport are acidification, eutrophication, material damage, and human health. (European Commission, 2006). Human health is affected by direct air pollution and global climate change. (Kahn Ribeiro et al., 2007).

The emission of CO₂ contributes to the warming of the earth by the magnified greenhouse effect, as showed originally by Keeling (1960). Figure 1 shows the famous Keeling curve, which confirmed the relation between carbon dioxide concentration and global warming since 1958. Bull and Morton (1975) showed that a change in temperature is associated with inverse changes in death rates in both respiratory infections (pneumonia and bronchitis) and in vascular diseases (myocardial infarction and cerebral vascular accidents). These relationships are less or absent in younger subjects and marked in the elderly.

Direct exposure to exhaust gases affects human health in different ways. Figure 2 demonstrates a pyramid of health effects associated with air pollution. The figure is based on research by the American Thoracic Society (2000) and it shows the severity of health effects and the proportion of the population that is affected. In section 3, the specific health effects of the most damaging exhaust gases are discussed separately.

Acidification is the process whereby air pollution - mainly ammonia, sulphur dioxide and nitrogen oxides - is converted into acid substances. (European Commission, 2006). Acidified soil and water bodies cause loss of plant and animal life and farm crops are damaged. (Dutch Ministry of Housing, Spatial Planning and Environment, 2004). Larssen et al. (1999) argue that high concentrations of gaseous pollutants, especially within and near the cities, are likely to have severe effects on human health as well as on materials and vegetation. Negative effects on forests, including die-back, have been reported for relatively small areas near large cities. Since large, regional surveys have not been carried out, there are large uncertainties about effects on a regional level. Acid rain is considered as a serious environmental problem; however, there are difficulties in implementing effective measures to reduce the problem. (Larssen et al., 1999).
An excess input of nutrients (NO₃, NH₃) also leads to pollution of soil and water bodies. This effect is called eutrophication and the best example is the excessive growth of algae in water. Algae choke off other types of flora and fauna, so eutrophication and acidification give rise to a decrease in biodiversity.

Material damage is caused by acidification and particulate matter. Buildings and monuments, including historical sites, are deteriorated through corrosion and soiling.

It is difficult to quantify these environmental issues and rank them in importance. The fact sheet by the European Commission (2006) only estimates the costs of health damage by air pollution. The estimate is very rough, ranging from 276 to 790 billion euros in 2000. These costs are calculated on the basis of the life expectancy, supposed to be reduced by eight months on average by the level of particulate matter emissions, and by two years in the worst case scenario. One of the problems in quantifying the effects is the fact that air pollution originates from a variety of sources. Not only transport, but also other economic activities like industry, power generation and agriculture contribute for a large extent to the overall level of air quality.

Car technology
In the past, a lot of new technologies were introduced to diminish the amount of exhaust emissions. Soot filters and catalysts are the most familiar examples of implemented car technologies. The emission of nitrogen oxide has been reduced drastically after the application of catalysts (Municipality of Groningen, 2004). The effects of improved car technology in general are shown in figure 3, which is based on research of Statistics Netherlands (2007a).

The engine is an important determinant for the overall emissions. The Euro standard requires car producers to limit the emissions of new cars to a maximum level for each specific air pollutant. The next generation of standards (Euro 5) will enter into force in 2009, while new car models should meet even stricter caps, Euro 6, from September 2014. Although the emissions of petrol and diesel driven cars are regulated by the Euro standards, totally new engines are also considered. You can think about a hybrid car that combines two power sources (conventional engine and electric power cell), hydrogen and/ or fuel cell technology.

The negative effects of engine output can be altered by soot filters and after treatment devices. Soot filters reduce PM emissions by more than 90 percent. (Dutch Ministry of Housing, Spatial Planning and Environment, 2004). At the end of the year 2006, 90 percent of new diesel cars sold had a soot
filter. Advanced after-treatment devices like SCR (selective catalytic reduction) catalytic converters control NO\textsubscript{x} emissions. These catalytic converters were introduced in the late eighties.

The output of an engine is related to the fuel that is inserted as well. The sulphur content of petrol/diesel determines the emissions of sulphur dioxide. That was the reason for specific legislation restricting the maximum sulphur content to 10 mg/kg. Lately, more attention is going to the possibility of bio fuels as a substitute for petrol and diesel. Bio fuels have a CO\textsubscript{2} neutral cycle, and are assumed to affect the environment less heavily. (European Parliament, 2003).

**Air quality policy**

The Dutch Cabinet prefers international, technology-based solutions to reduce air pollution. (Dutch Ministry of Housing, Spatial Planning and Environment, 2004). The idea behind this point of view is the background concentration of air pollutants. Nitrogen dioxide and particulate matter stay long in the atmosphere creating a cross border problem. (Municipality of Groningen, 2004). Therefore, it is necessary to address the air pollution issue from an international perspective. The Dutch Cabinet even asked for a five year postponement of the targets from the European Commission’s NEC (National Emissions Ceiling) Directive in anticipation of an international air quality strategy.

Current European policy is mainly based upon the Clean Air for Europe (CAFE) programme, published by the European Commission’s Environment Directorate-General. The CAFE programme was launched in March 2001 and the main objective was to develop a long-term, strategic and integrated policy advice to protect against significant negative effects of air pollution on human health and the environment. (European Commission, 2001b). CAFE is a programme of technical analysis and policy development that underpinned the development of the Thematic Strategy on Air Pollution under the Sixth Environmental Action Programme. (European Commission, 2001a).

A large input for the European directives and strategies is the work of the World Health Organization (WHO). The European Centre for Environment and Health of WHO’s Regional Office for Europe investigates and reviews the effects of environmental hazards on human health. In 1987, the Regional Office published the first edition of the air quality guidelines for Europe (World Health Organization, 1987). The guidelines provide a basis for protecting public health from adverse effects of air pollutants and for controlling those contaminants of air that are known or likely to be hazardous to human health and well being. (World Health Organization, 2006). The European Community targets for air pollution are such that no significant negative effects on health occur. (World Health Organization, 2004). This definition and the CAFE programme are integrated in the final air pollution
strategy that was offered to the European Parliament on 1 September 2005. (European Commission, 2005).

Section 3.4 will discuss relevant measures that can be taken to influence the emissions on intersections. These policy measures can be divided into categories (table 1) dependent on the authority that should implement these measures. The measures at a high government scale should be implemented on all the lower scales simultaneously.

Table 1 Policy measures divided over different governmental authorities

<table>
<thead>
<tr>
<th>Local City</th>
<th>Regional Municipality</th>
<th>National Cabinet</th>
<th>International European Commission</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Areas exclusive for 'clean' vehicles</td>
<td>- Reduction speed limit + proper enforcement - Kilometre charges heavy vehicles</td>
<td>- Air Quality Innovation Programme - Tax incentives - Energy label for cars</td>
<td>- Determining emission ceilings - Requirements car technology</td>
</tr>
</tbody>
</table>

Intersection design

One of the anthropogenic actions that causes air pollution is road transport. Cars, buses, trucks and motor vehicles emit a variety of exhaust gases while accelerating and driving across cities. Recent IVEM research showed a strong reliance on cars for transport in the Netherlands. (van der Hoek, 2006). In the Netherlands, on average 35 km is travelled daily, most of which is done by car, followed by a relatively high percentage by bike (3.7 km) and train (3.6 km). Car traffic causes most emissions, so the fact that emission ceilings are exceeded near busy roads is not surprising. The city of Groningen, in the northern part of the Netherlands, will serve as a case study for this research. The emission ceilings in Groningen are mainly exceeded in the neighbourhood of the central station, where some major intersections are situated. (Municipality of Groningen, 2004).

One of the major issues of this research is the design of intersections. Currently, there are three main determinants that are important for policy makers to identify and that determine the options they can choose from: accessibility, safety and the environment. These factors reflect on the three more general aspects of sustainable development (profit, people and planet respectively). It is difficult to weight these factors, because it depends on the situation at hand.

The concept of accessibility is central to the modelling of traffic related effects across regions. Altshuler and Rosenbloom (1977) defined accessibility as the ease of getting to destinations. Better accessibility improves the development potentials of a region and reduces transport costs, which is a strategic variable for companies. As a consequence of reduced transport costs, accessibility can have a positive impact on employment and population growth. (Polasek & Schwarzbauer, 2006). Summarising, the accessibility parameter of a planned infrastructure project is mainly determining the economic desirability.

Traffic safety and the environment are closely related in the infrastructure planning process. For example, noise nuisance and air quality fall within the environmental category, while the effects of noise nuisance and air pollution – health problems – can be accounted for in the safety (people) category. On the other hand, increasing speed limits can be good for the environment, while the safety decreases. (Mohan & Tiwari, 1999). In general, the aspects safety and environment negatively influence the accessibility, defined as the time needed to travel from point A to reach point B. Most countries demand a strategic environmental assessment to determine the environmental impact, before approving a specific infrastructure project.

1.1 Research aim

The aim of this research project is to understand the differences in exhaust gas emissions (in particular nitrogen oxides and particulate matter) that occur for different intersection designs, in order to help
policy makers in their future decision making processes about an optimal design and development of new city beltways according to air quality standards.

1.2 Research questions

Main: What is the optimal policy for designing intersections, from the point of view of exhaust gas emissions over time with varying policy measures and changing mobility demand?

*This question is addressed with a focus on the traffic conditions in the city of Groningen.*

1. Transport characteristics
- What is the total mobility demand now and in the future of the beltway in Groningen?
- How is the division of mobility demand amongst all transport modes and how will this division change over time?
- Which intersection designs are possible?
- Will the mobility demand change due to another intersection design?
- What is the average speed, the number of stops and the time of acceleration for each intersection design?

2. Environmental characteristics
- Which factors determine the emitted exhaust gasses per vehicle? Will this remain the same in the coming decades?
- What are the most important exhaust gasses for the transport modes now and in the future?
- What is the effect of each beltway design on exhaust gas emissions?

3. Policy measures
- On what factors does a policy makers’ choice for a beltway structure depend?
- Which policy measures are available to influence the amount of exhaust gas emission?
- How do these measures influence the emission of exhaust gasses?

1.3 Boundaries

The introduction showed the complexity of the air pollution problem. Several sources affect air quality. The source under consideration for this research is the transport sector, and more specifically the road traffic (cars, buses, trucks). This choice is made because of the health effects on urban populations by road traffic. Statistics Netherlands (2007b) calculated that cars emit more than half of all exhaust emissions.

The effects of intersection design will be discussed, because most places where the actual emissions exceed the emissions ceilings are located near busy road sections, like the intersections on the beltway in the city of Groningen. (Municipality of Groningen, 2004). This makes Groningen very suitable for a case study, because improvements on the beltway are implemented in the period 2000-2010. However, all results should be considered in the context of the available data. Because of the fact the intersections in Groningen are not the same as in another city, mobility demand and therefore emissions will be different.

Another boundary is that this research will focus on the most harmfully/damaging exhaust gasses to human health/environment. If the impact of an emitted gas is relatively small compared to other gasses, this substance will not be considered in the subsequent part of the research.
2. METHODOLOGY

This research consists of literature research and the development of a spreadsheet model. The literature research aims to find emission data and relations between the relevant aspects determining the overall impact of an intersection. The spreadsheet model combines all emission determining aspects and the model will serve as a basis for some future projections to compare the intersection structures under changing circumstances. Some more discussion on these elements in the following sections.

2.1 Literature research

Literature is required for the basic knowledge on the issue. Section 3.1 deals with various exhaust gases and associated health effects. Knowledge has been derived from scientific literature and health organisations such as the World Health Organization (WHO). (World Health Organization; 1946, 1987, 2003, 2004, 2006).

Data is required for the spreadsheet model in this research project. Statistical databases such as Statistics Netherlands (CBS) contains data on mobility (traffic intensity, modal split, congestion levels). Because there is one specific situation, the city of Groningen, considered in this research, there is statistical information required of municipalities and provinces (Municipality of Groningen, 2007), which can reflect in more detail on mobility data than national statistics. (Statistics Netherlands; 2007a, 2007b, 2008a, 2008b).

Research institutes like the Netherlands Organization for Applied Scientific Research (TNO) have much technological knowledge. In this study, this knowledge is useful for emission data. Emission data of TNO are twofold. They have experimental facilities to perform vehicle performance tests for emissions and fuel consumption. The other side builds on the emission measurements. TNO has developed the emission model VERSIT+ to generate representative emission data of the Dutch vehicle fleet. (Netherlands Organization for Applied Scientific Research, 2007).

2.2 Spreadsheet model

The model focuses on a particular case, namely the beltway of the city of Groningen. General emission data from literature research are combined with mobility data for the city of Groningen. The aim of the model is to assess the emissions of transport at five different beltway intersection designs. First, the current situation is described in stats and figures. After that, attention is given to future developments, like changes in mobility demand and/ or transport mode. In this section, the model setup will be discussed, focusing on hard data (exogenous) and underlying relations/ formulae’s (endogenous). The scenario approach is explained in this section. Policy measures to influence mobility are also considered. At the end, a sensitivity analysis is applied to find out which parameters are causing the highest impact for each intersection.

2.2.1 Exogenous data

To calculate transport emissions, the following basic information is required: (Smit, van Mieghem & Hensema, 2006).

1) Kind of road section (urban, residential or highway)
2) The length of the road section
3) Division of traffic in a number of vehicle categories (light versus heavy vehicles)
4) Traffic intensity of each vehicle category (number of vehicle per time unit)
5) Weighted average emission factors for each vehicle category for a specific traffic situation in a fixed year
In this research, the road section considered can be typified as an urban highway. Because of the fact that the road section belongs to the city beltway, a speed limit of 70 km/h holds for the road section. Speed is an important determinant for the model to calculate the emissions.

The southern part of the beltway for the city of Groningen is almost five kilometre long, but the length of the road section is defined from 500 metres before the middle point of the intersection until 500 metres after the middle point of the intersection (see figure 4 and appendix A).

Vehicle categories are heavy traffic (trucks), buses and light traffic (cars). Pedestrians and bicyclists are not important, because they do not emit relevant amounts of exhaust gases. Motors are included in the category cars.

For each category, the traffic intensity will be entered into the model for different moments. The time slots are night/ morning, day time and rush hour. For each time slot, the number of vehicles per hour is needed. On the basis of these statistical data, the modal split can be determined.

The vehicle categories are necessary to determine total emissions as detailed as possible. Buses and trucks pollute more than cars, and the categories are also needed to evaluate possible policy measures. Other routes for public transport can only be accounted for when buses form a separate category, as in this model. Each category had its own emission characteristics, for example due to weight and acceleration profiles. The emission data are averages for the total vehicle fleet of the category, because within each category differences occur depending on the age of the vehicles (technology etc.).

2.2.2 Endogenous data

All these individual data sets are not sufficient to determine the emissions per intersection. On the basis of speed profiles, an ‘emission profile’ can be drawn up and the overall emissions of a vehicle for each speed profile can be determined by integration of the ‘emission profile’. But the speed with which an intersection is passed depends on several factors.

Firstly, the type of intersection influences the speed pattern. This is of course the core of this investigation. For example, a level crossing with traffic lights will request that a driver stops more often than at other intersections.

A second important factor is the type of vehicle. A car or motor can accelerate faster than a bus or a truck. The time to brake and stop is different and these characteristics also determine the speed profile for, on and after an intersection.

Thirdly, the time of the day. During rush hours it will often be necessary to make more stops. The congestion level is actually highly correlated with the mobility demand. The more traffic a certain road section would pass on an equal time interval, the lower the speed will be and also the number of stops will increase at a higher mobility demand.

Due to the relationships among these factors, it is quite difficult to create exact formulas to describe the speed on an intersection. This research will use a scenario approach to tackle this problem. The scenarios are also useful to avoid another problem: namely the fact that each vehicle has its own
characteristics (acceleration pattern, emission of exhaust gases). Each driver differs as well, but in the scenario approach, averages are used. The sensitivity of parameters can be analysed to evaluate on the correctness of the assumptions and the data. More about the scenario approach in the following paragraph.

2.2.3 Scenario approach

Three scenarios are developed to represent possible speed profiles during the crossing of an intersection. The speed profiles are independent of the design of the intersection. These differences will be dealt with in a later stage by dividing the percentage for each intersection for which each scenario applies.

Ideal: This scenario describes the ideal situation in which a vehicle can drive at the maximum allowed speed without braking. In principle, this scenario holds when an intersection is designed in such a way that the traffic is not hindered by the design, or by other traffic crossing the intersection at the same moment. It takes 25 seconds from the beginning of the road section to the middle of the intersection (500 meter), and another 25 seconds to leave the road section. Average speed is 70 km/h.

Congestion low: A vehicle in this scenario is supposed to slow down before crossing the intersection, but does not need to stop completely. In comparison with the ‘congestion high’ scenario, it is possible to accelerate more rapidly towards the maximum speed. The first 500 meters take 60 seconds and the second part about 36 seconds, meaning a delay of 46 seconds in comparison with the ideal situation. This is consistent with research conducted by the Dutch Ministry of Traffic, Public Works and Water Management (2004). They concluded that a vehicle needs 1,5 to 2 times so much time in case of average congestion. Average speed is 37,5 km/h.

Congestion high: The worst scenario describes a situation where vehicles have to wait their turn to cross the intersection. A few stops will be necessary, causing a more variable speed pattern. The model consists of three nearly stops, with acceleration and braking habits assumed to be fluent. According to the Dutch Ministry of Traffic, Public Works and Water Management (2004), the same distance will take a vehicle about three or four times as long during periods with high congestion. With an average speed of 16 km/h, it takes 114 seconds to reach the middle of the intersection. Because of some traffic accumulation after the intersection as well, the second part of the road section takes also longer (70 seconds) totalling up to 184 seconds. Average speed over the complete intersection is 20 km/h.

A graphical representation of the speed profiles is available in appendix C.

In combination with emission data, the speed profiles can be used to create graphs with the emissions on each part of the considered road section. The area beneath this ‘emission profile’ yields the total emissions of a vehicle for the specific speed scenario. Mathematical integration can be used to calculate this area for each vehicle – speed scenario combination. That is also the reason that the speed scenarios are approximated with mathematical formulas.

In sections 3 and 4, the differences between the intersections will be calculated by the division of the different speed scenarios. For each intersection, the share of vehicles that will drive according to each of the three speed scenarios will be estimated (totalling hundred percent). This is done for the three time slots separately and the sum of all situations is the total emission per intersection.

To determine emissions with as much detail as possible, there are also three different time slots defined in order to average emissions per day more solidly. The biggest difference between the different time slots is the traffic intensity, which influences speed variety at most.
Rush hour: From 7:00 am until 9:00 am and from 16:30 pm until 18:30 pm (four hours a day)
Rush hour happens twice a day, while people are travelling to or from work or school.

Day time: From 9:00 am until 16:30 pm (seven and a half hours a day)
Period between the rush hours, under normal working hours.

Night/morning: From 18:30 pm until 7:00 am (twelve and a half hours a day)
A relatively high percentage of vehicles can drive according to the ideal speed profile.
3. THE SPREADSHEET MODEL

This chapter contains the relevant information of the spreadsheet model. The findings are based on literature research and they form the input for the spreadsheet model. Historical data as well as future projections are used to evaluate different scenarios.

The health effects of various exhaust gases will be described in section 3.1. Section 3.2 describes the emission characteristics of different transport modes now and in the future. Section 3.3 discusses the possible designs for intersections and policy measures for air quality control are discussed in section 3.4. The case specific characteristics like modal split and mobility demand for the city of Groningen are addressed in section 3.5.

3.1 Exhaust gas emissions

Exhaust gas emissions are a main cause for local air pollution and these emissions may have a negative impact on human health. Combustion of fossil fuels in internal combustion engines produces a variety of pollutants, including carbon monoxide (CO), particulate matter (PM), volatile organic compounds (VOCs), nitrogen oxides (NO\textsubscript{x}), and sulphur dioxide (SO\textsubscript{2}). Most of these gases occur naturally, but human activities like car driving cause an increased concentration of health affecting contaminants in the air. These pollutants may cause all different kinds of health problems. Carbon monoxide is readily absorbed into the bloodstream where it can reduce oxygen delivery to organs and tissues. VOCs and NO\textsubscript{x} are the principal precursors for ozone and ozone is the main constituent of smog. (U.S. Department of Transportation, 1996). Particulate matter also contributes to smog and estimations by Kruize et al. (2000) show that continuous exposure to small amounts of smog decreases life expectancy with one or two years on average.

This section will discuss three different exhaust gases (particulate matter, nitrogen oxides and ozone), to learn about their sources and their particular health effects. This choice does not imply that other substances do not pose a considerable threat to human health. However, these substances appear only in very small amounts or the effects are quite known from literature. For example, carbon dioxide (CO\textsubscript{2}) contributes to global warming. According to data of the Dutch Ministry of Housing, Spatial Planning and Environment (2004), the emission of CO\textsubscript{2} is proportional to the total volume of vehicle kilometres driven. In the period 1987 to 2005, heavier (27%) and faster (30%) vehicles also increased vehicle energy use and CO\textsubscript{2} emitted. (Heavenrich, 2005). Road transport currently accounts for 74% of total transport CO\textsubscript{2} emissions. (Kahn Ribeiro et al., 2007). Not all exhaust gas emissions show proportionality with vehicle kilometres driven, and the percentages vary as well. SO\textsubscript{2} emission is mainly caused by shipping and therefore not important for this research. Legal requirements for fuels can mitigate the SO\textsubscript{2} emission. Unlead petrol and diesel with lower sulphur content – maximum of 10 mg/kg - are mandated by the Dutch Ministry of Housing, Spatial Planning and Environment (2004) to control sulphur emissions. European emission standards for the inspection of motor vehicles also reduced carbon monoxide emissions successfully with 50% since 1990. (European Commission, 2001b). The standards apply to particulate matter, nitrogen oxides and ozone as well, but sufficient effort should be made to reach better results.

3.1.1 Particulate matter (PM)

Particulate matter (fine dust) is a complex mixture of organic and inorganic substances. In literature, particulate matter is divided in two categories. Fine particles are referred to as PM\textsubscript{2.5}, because the aerodynamic diameter of the particles does not exceed 2,5 µm. PM\textsubscript{10} is a combination of fine and coarse particles. (World Health Organization, 2003). Particulate air pollution is a mixture of solid and liquid particles suspended in the air. These suspended particles vary in size, composition and origin. Particulate matter contains among others allergens, dioxins, heavy metals, polycyclic aromatic hydrocarbons (PAHs), other hydrocarbons, but also water vapour. (Municipality of Groningen, 2004).
The emission of particulate matter is caused by nature, shipping, power generation, industry, agriculture (e.g. ploughing, burning-off for field), households and road vehicles. Environmental conditions and natural sources like sea salt and wind-blown soil determine the natural background concentration, while the other sources are anthropogenic. Particulate matter in road traffic is caused by fuel burning (85%) and wearing of road surface, tires, brake lining and overhead wires. (European Commission, 2006). The residence time of particulate matter in the atmosphere is a few days to a few weeks, which leads to regional distribution of the emitted particulate matter. (Municipality of Groningen, 2006).

Airborne particulate matter can lead to a wide range of detrimental health effects, including an increased risk of premature mortality. It is estimated that the short-term exposure to particulate matter contributes to the death of thousands of people in the Netherlands, on an annual basis. (Netherlands Environmental Assessment Agency, 2005). Other health effects from particulate matter include cancer, cardiac problems and respiratory diseases. (European Commission, 1997). However, the adverse health effects are not easily quantified or summarized qualitatively.

In the European Union, some legal norms are set to control the emissions and effects of particulate matter. Table 2 shows the limits for the concentration of PM$_{10}$ that were agreed upon by the European Commission in directives 1999/30/EC and 96/62/EC. (Council of the European Union; 1996, 1999). Especially near busy highways or intersections, these limits are exceeded too often. According to Hegger and Slob (1999), living near a busy highway has currently the same health effects as smoking seventeen cigarettes each day. There are also targets for the automotive industry. For example, in 2013, particulate emissions by cars may not exceed 0.025 g/kWh. All targets that currently exist refer to PM$_{10}$ values, while research by the World Health Organization (2006) showed that fine particles (PM$_{2.5}$) penetrate deeper into the lungs. In accordance with the World Health Organization research, the inability to identify levels below which adverse health effects are not anticipated implies that every standard may leave some residual risk.

Table 2 PM$_{10}$ concentration standards for the European Union

<table>
<thead>
<tr>
<th>Start dates</th>
<th>Phase 1</th>
<th>Phase 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PM$_{10}$ limit values</strong></td>
<td>From 1 January 2005</td>
<td>From 1 January 2010</td>
</tr>
<tr>
<td>Yearly average:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daily average (24 hour):</td>
<td>40 µg/m$^3$</td>
<td>20 µg/m$^3$</td>
</tr>
<tr>
<td>Allowed number of exceedances per year:</td>
<td>50 µg/m$^3$</td>
<td>50 µg/m$^3$</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>7</td>
</tr>
</tbody>
</table>

3.1.2 Nitrogen oxides (NO$_X$)

In atmospheric chemistry the term NO$_X$ is used to describe the total concentration of nitric oxide (NO) and nitrogen dioxide (NO$_2$). For this research, these two substances suffice to describe total NO$_X$ emission, because dinitrogen monoxide (N$_2$O), dinitrogen pentoxide (N$_2$O$_5$) and a lot of other nitrogen oxides occur just in relatively small amounts in the atmosphere.

The fact sheet of the Australian Government (2007) describes nitric oxide as a sharp, sweet-swelling, colourless gas. Nitrogen dioxide is a reddish-brown gas with a characteristic pungent odour. Both nitric oxide and nitrogen dioxide are fairly toxic air pollutants that enter a human body by inhalation or absorption through the skin.

During daylight nitric oxide and nitrogen dioxide are in equilibrium with the ratio NO/NO$_2$ determined by the intensity of sunshine and ozone (O$_3$). Sunshine converts nitrogen dioxide to nitrogen oxide and ozone reacts with nitric oxide to create nitrogen dioxide again. Nitrogen dioxide is a strong oxidant and reacts with water to produce nitric acid and nitric oxide. (World Health Organization, 2006).

Sources of nitrogen oxides are road vehicles, shipping, power generation, industry, agriculture and households. Nitrogen oxides harm human health and contribute to acidification, eutrophication and

Adverse health effects of nitrogen oxides can be categorised into short term effects and long term effects. Table 3 summarises the health effects associated with a rise of NO\textsubscript{X} emissions. In principle, nitric oxide hampers the absorption of oxygen in blood by binding to haemoglobin and nitrogen dioxide negatively affects the elasticity of the lung tissue, resulting in a decreased resistance to infections.

<table>
<thead>
<tr>
<th>Short term effects</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effects on pulmonary function, particularly in asthmatics</td>
<td>Anderson et al. (1997)</td>
</tr>
<tr>
<td>Increase in airway allergic inflammatory reactions</td>
<td>Castellsagué et al. (1995)</td>
</tr>
<tr>
<td>Increase in asthma emergency hospital admissions</td>
<td>Sunyer et al. (1997)</td>
</tr>
<tr>
<td>Increase in mortality</td>
<td>Touloumi et al. (1997)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Long term effects</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Croup in pre-school children</td>
<td>Schwartz et al. (1991)</td>
</tr>
<tr>
<td>Reduction in lung function</td>
<td>Colville et al. (2001)</td>
</tr>
<tr>
<td>Cardiovascular deaths</td>
<td>Zmirou et al. (1996)</td>
</tr>
<tr>
<td>Increased probability of respiratory symptoms</td>
<td>World Health Organization (2004)</td>
</tr>
</tbody>
</table>

Eyring et al. (2005) proved that nitrogen oxides emission estimates vary strongly among several studies which means in practice, that it is hard to establish strict NO\textsubscript{X} emission standards. The complexity comes from the collection of substances, making it more difficult to measure than only one substance. That is the reason that concentration standards focus exclusively on nitrogen dioxide (see table 4). Exceedance of the standards is measured mostly near busy highways and locations with a lot of heavy traffic (trucks).

<table>
<thead>
<tr>
<th>Start date NO\textsubscript{2} limit values</th>
<th>From 1 January 2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yearly average:</td>
<td>40 µg/m\textsuperscript{3}</td>
</tr>
<tr>
<td>Hourly average:</td>
<td>200 µg/m\textsuperscript{3}</td>
</tr>
</tbody>
</table>

| Allowed number of exceedances per year:       | 18 |

3.1.3 Ozone (O\textsubscript{3})

A major difference between ozone and particulate matter and nitrogen oxides is the fact that ozone is a secondary air pollutant, meaning that it is not emitted directly into the atmosphere. Ozone arises almost entirely from chemical reactions that differ with altitude within the atmosphere. (World Health Organization, 2006). Therefore, it takes quite a long time to be formed. Highest concentrations can be found typically 100 kilometres from the source making ozone an (inter)national pollutant. Nitric oxide emissions from road vehicles may cause levels of ozone to be almost zero, because O\textsubscript{3} and NO react to form nitrogen dioxide.

Ozone is produced from nitrogen oxides and volatile organic compounds (VOCs) in the presence of sunlight. (Sillman, 1999). Ozone also occurs naturally, but human activities cause abnormal high concentrations making ozone a pollutant. Volatile organic compounds are emitted by road vehicles, shipping, power generation and industry. They contribute to ground-level ozone. (European Commission, 2006). Ground-level ozone is less concentrated, but it is more a problem for urban air quality. Colville et al. (2001) question to which extent transport emissions are responsible for this, and which modes of transport cause the most or the least generation of ground-level ozone.
The main health effects of ozone for human beings are harming the lung functioning and irritating the respiratory systems. (World Health Organization; 2003, 2004). The seriousness of respiratory complaints increases as the duration and the frequency of exposure to ozone increases. Not only has ozone been shown to worsen asthma symptoms (Romieu et al., 1996) and be associated with an increase in emergency hospital respiratory admissions (Schwartz, 1996; Spix et al., 1998) but it also damages crops. (Ashmore et al., 1980). Ozone also contributes to global warming. High temperatures are associated with more health risks, especially for elderly. During a long period of warm weather, the ozone concentrations rises as well, creating a positive feedback cycle between ozone concentration and temperature increases (with corresponding health risks).

High concentrations of ozone only occur in long periods of warm weather, caused by a complex reaction with traffic. Hot summers show a significantly higher death rate. Statistics Netherlands estimated that air pollution caused between 1,000 and 1,400 extra deaths in the warm summer of 2003 in the Netherlands, approximately two thirdly induced by high ozone concentrations. (Fischer, Brunekeef, & Lebret, 2003). National standards are not meaningful for ozone, because ozone spreads easily over large distances, which requires international cooperation towards global policy, standards and measures. An example of an effective measure is the introduction of the carbon filter in 1989. Between 1990 and 2006, VOC emissions reduced with 85%.

3.1.4 Health effects

In the previous paragraphs, some specific health effects of PM, NO\textsubscript{X} and O\textsubscript{3} were discussed already. It does not cover all health problems associated with the transport sector. For example, noise nuisance causes sleep disruption and lack of sufficient sleep causes a lot of other problems, including hearing loss and rising blood pressure. Severe health problems caused by the transport sector that occur at a relatively low level are the consequence of traffic accidents.

Health is defined by the World Health Organization (1946) as a state of physical, psychological and social wellbeing. Figure 2 presented a pyramid of health effects. The pyramid is a qualitative representation, because it is extremely difficult to quantify health effects. This difficulty stems from the mobile characteristic of air pollution and a person’s susceptibility to air pollution. Elderly people have little resistance and are more likely to suffer from short time periods of exposure.

Air pollution science is rarely concerned with emissions from individual vehicles. Since road vehicles typically travel along common routes, from the perspective of a source of emissions they form a line source. In the case of road vehicles, road networks are typically broken up into individual sections between junctions referred to as road links, and emissions from individual road links are added together to compile an inventory of total traffic emissions. Dispersion modelling uses formulae to calculate downwind concentrations from line sources that are modified from those used for point sources.

3.2 Emissions per vehicle category

Vehicle exhaust emissions can be controlled by increasing the engine efficiency, increasing the vehicle efficiency and/ or cleaning up of the emissions. Progress in electronic ignition, fuel injection systems and electronic control unit has contributed to increased engine efficiency. Periodic vehicle inspection is an example to maintain vehicle efficiency. There is no European law that dictates vehicle inspections, but most countries mandate vehicle inspection with intervals of one or two years. Cleaning up of the emissions is necessary to meet emission targets.

The spreadsheet model developed for this thesis needs emission factors for each vehicle category. Tailpipe emissions are measured since 1966, when the first emission test cycle was enacted in the state of California. Since that time, a lot of efforts have been made to measure tailpipe emissions. For
this particular research, CAR emission factors are used. (Hoen, 2006). These factors were published by the Netherlands Environmental Assessment Agency and are derived from the emission model VERSIT+ that was developed by TNO Automotive. (Smit, van Mieghem & Hensema, 2006). Figure 5 and 6 show the NO\(_X\) and PM\(_{10}\) vehicle emission factors in grams per kilometre. The model does not include ozone, because it is a secondary pollutant from which the emissions are difficult to allocate to traffic due to the complex formation, as discussed in section 3.1.3.

**Figure 5** NO\(_X\) vehicle emissions (now: 2005, future: 2020)

**Figure 6** PM\(_{10}\) vehicle emissions (now: 2005, future: 2020)
In the spreadsheet model, the emission factors are extrapolated and described by power functions. The power functions in table 5 hold for the case of Groningen, where a speed limit of 70 km/h is enforced. As can be seen from the light traffic emission factors, increasing speed further towards 100 km/h will cause higher emissions per kilometre.

Table 5 Power functions describing the NO\textsubscript{X} and PM\textsubscript{10} emissions for the basic scenario

<table>
<thead>
<tr>
<th>speed (km/h)</th>
<th>NO\textsubscript{X} emission</th>
<th>PM\textsubscript{10} emission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy traffic</td>
<td>( z = 58,096 \cdot y^{-0.416} )</td>
<td>( z = 2,4397 \cdot y^{-0.4024} )</td>
</tr>
<tr>
<td>Buses</td>
<td>( z = 36,481 \cdot y^{-0.307} )</td>
<td>( z = 2,0432 \cdot y^{-0.5009} )</td>
</tr>
<tr>
<td>Light traffic</td>
<td>( z = 1,1293 \cdot y^{-0.1951} )</td>
<td>( z = 0,1482 \cdot y^{-0.2695} )</td>
</tr>
</tbody>
</table>

Merging the emission graphs with the speed scenario leads to emission profiles for nitrogen oxides and particulate matter, see appendix B. It becomes clear that low speed causes high emissions simulating standstill periods. The integral of the emission profiles gives the amount of emission for each combination of a speed scenario with a vehicle category. Table 6 shows the results of these integrals. Obviously, heavy traffic with huge delay emits the most and light traffic in an ideal situation emits the least NO\textsubscript{X} and PM\textsubscript{10}.

Table 6 Vehicle emissions over the road section (one kilometre) in grams, basic scenario

<table>
<thead>
<tr>
<th>Speed Profile</th>
<th>Vehicle category</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Heavy traffic</td>
</tr>
<tr>
<td>NO\textsubscript{X}</td>
<td>9,922</td>
</tr>
<tr>
<td>Congestion low</td>
<td>12,099</td>
</tr>
<tr>
<td>Congestion high</td>
<td>15,924</td>
</tr>
<tr>
<td>PM\textsubscript{10}</td>
<td>0,301</td>
</tr>
<tr>
<td>Congestion low</td>
<td>0,584</td>
</tr>
<tr>
<td>Congestion high</td>
<td>0,532</td>
</tr>
</tbody>
</table>

In the paragraphs below, the vehicle categories are discussed separately. Which vehicles belong to each category and some background knowledge about the differences and similarities between the categories. The categorisation is made on the basis of statistical data by Statistics Netherlands (2007b).

3.2.1 Heavy traffic

The largest share of heavy traffic vehicles are trucks. Trucks are defined as carriage vehicles from which the sum of the empty weight and the cargo capacity is more than 3500 kilogram. Tractors (vehicles for pulling trailer) are also vehicles that fit into this category. Tractors will only cause an ignorable small percentage of the emissions in this category, because this research focuses on beltways while tractors drive mostly on country roads.

3.2.2 Buses

Buses are vehicles equipped to transport nine passengers or more, the driver not included. The category buses covers public transport, but also coaches. Public transport schedules can be used to count the number of times that local and regional buses pass the intersection under investigation. The mobility demand for coaches is difficult to count due to the irregular schedule of trips.

3.2.3 Light traffic

Light traffic includes passenger cars (at most 8 passengers), motorcycles and delivery vans. Delivery vans are cargo vehicles with a maximum weight, empty weight plus cargo capacity, of 3500 kilogram.
Emission factors of these vehicles differ significantly. Motorcycles have lower emission factors than passenger cars. Delivery vans emit the most nitrogen oxides and particulate matter because these vehicles are heavier than normal passenger cars. The emission factors in figure 5 and 6 are average factors for this category.

3.3 Possible designs of intersections

In general, the difficulty in coordinating infrastructure planning is intensified by the different authority levels governing transportation, land use and air quality issues. Transportation plans are regularly drawn at the regional level, while land use plans, by contrast, are drawn at the municipal or country level. (Berke et al., 2006). Regional transportation (beltways) concerns often conflict with local land use policies or the implementation of air quality standards.

In the following subsections, some intersections will be discussed. Which characteristics typify the intersection and in which situation will the intersection be the main choice to solve the problem of intersecting traffic. According to Wheeler et al. (1998) most intersections serve economic needs (high accessibility). But for the purpose of this report, the air quality issue is addressed more specifically for a 4-way intersection, characterised by four road segments (arms) that come together at the intersection.

The capacity will be used in the model to determine the traffic load. Traffic load is a percentage that describes the relation between the mobility demand and the capacity of the road section.

\[
\text{Traffic Load} = \frac{\text{Traffic Intensity}}{\text{Road Capacity}} \quad \text{or} \quad L = \frac{1}{C}
\]

The capacity of one driving lane is 2000 vehicles per hour. (U.K. Department for Transport, 2008). However, the actual capacity of a road section is limited by land availability and the maximum number of driving lanes for an intersection. The structure of the intersection can also act as a bottleneck for traffic throughput. The number of driving lanes multiplied by 2000 vehicles is the maximum capacity of an intersection.

The traffic load will be applied to estimate the share of vehicles that will drive according to each speed scenario. In general, when the traffic intensity exceeds the road capacity, vehicles will stand still (congestion high). When the traffic intensity lies under the road capacity, all three speed scenarios occur. The ideal scenario is more likely to occur when the traffic load is below 0.8 and the congestion low scenario is supposed to be dominant when the traffic load is between 0.8 and 0.95. A traffic load over 0.95 favours the congestion high scenario. (Directorate-General for Public Works and Water Management, 2006). The actual division also depends on the structure of an intersection.

The structure of an intersection influences the speed profile. Table 7 shows the main differences between the intersections under consideration. The numbers are qualitative and they are explained in the next sections. The general probability in combination with the traffic load will serve as a basis for the division over the different scenarios.

<table>
<thead>
<tr>
<th>Intersection:</th>
<th>General probability of the speed scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ideal: Congestion low: Congestion high</td>
</tr>
<tr>
<td>Level crossing (priority road)</td>
<td>4: 1: 4</td>
</tr>
<tr>
<td>Level crossing (traffic lights)</td>
<td>2: 2: 5</td>
</tr>
<tr>
<td>Roundabout</td>
<td>1: 5: 3</td>
</tr>
<tr>
<td>Grade separated junction (viaduct)</td>
<td>5: 3: 1</td>
</tr>
<tr>
<td>Multilevel junction (interstate exchange)</td>
<td>4: 3: 2</td>
</tr>
</tbody>
</table>
In the following sections, performance graphs are presented and explained for each type of intersection. In these graphs, the percentage of vehicles that will drive according to each of the three speed profiles is shown for a traffic load between 0.6 and 1.0. It is assumed that the relative distribution over the speed profiles is equal to the values at 0.6 or at 1.0 when the traffic load is below 0.6 or above 1.0 respectively. The actual capacity and the performance graphs of the intersections are based on the results of the Transportation Research Board (2000), presented in their Highway Capacity Manual.

3.3.1 Level crossing with priority road

A level crossing where the traffic demand from one arm to the other (normally east-west or north-south) is far more than the traffic demand for the other combinations can be designed with the “right-of-way” rule. The arms with the most related traffic is called the priority road, and all traffic from the other arms that cross the intersection should give way to the vehicles on the priority road. It is possible to add turn lanes to this type of intersection to make it possible for vehicles to filter before turning left or right. An advantage of this intersection is that the largest traffic flow should not stop too often. But it is quite difficult to apply this type of intersection where traffic demand is huge. Figure 7 shows the performance graph of this type of intersection, especially notable due to small part of ‘congestion low’.

When turning traffic from a two-lane priority road is facilitated with filtering lanes, through traffic vehicles on the priority road can pass the intersection on four lanes simultaneously. The absence of filtering lanes decreases the capacity of the intersection with 12.5%.

![Figure 7 Performance graph of a level crossing with priority road principle](image)

3.3.2 Level crossing with traffic lights

This intersection uses traffic signals to indicate which traffic is allowed to proceed. On the basis of electric signals, traffic demand can be measured and the traffic lights can be regulated by the traffic demand to assure nice traffic flow. Additionally, a ‘green wave’ system can be applied to favour traffic in one direction, mostly on the major road, by giving more green light to the major traffic stream.
This type of intersection is especially applicable in situations where traffic demand on all four arms is quite high. A disadvantage is the high percentage of stops that vehicles have to make from each direction. See figure 8.

![B: Level crossing (traffic lights)](image)

**Figure 8** Performance graph of a level crossing with traffic lights control

Traffic lights cause a large amount of congestion. On average, 40% of the time a direction will have a green light (Smeed, 1957), causing the capacity of the road to be relatively small.

### 3.3.3 Roundabout

A roundabout has some major advantages compared to the other possibilities. The clearance of traffic is quite good, and the roundabout can be scaled according to the local traffic demand. At small scale roundabouts (single lane traffic, low speed), land use is comparable with ordinary level crossings. Intersections with heavier traffic demand (two-lanes, higher speed) require comparable roundabout dimensions. See figure 9 and 10.

![Figure 9 (left) Single lane roundabout](image)

![Figure 10 (above) Two-lane roundabout](image)

The capacity of a single lane roundabout is about 60 percent of a two-lane roundabout. The capacity of a two-lane roundabout is not double, because traffic on the outside lane will also block the access to the left lane. Measurements for two-lane roundabouts mostly indicate a capacity that is 35 percent lower than the level crossing with priority road. Three-lane roundabouts are not often applied to
secure the safety of all traffic participants. The uniqueness of a three-lane roundabout would increase the risk of accidents and more accidents would result in more congestion.

Before entering a roundabout, vehicles have to reduce their speed to make the turn. In comparison with a level crossing, fewer stops are expected when the roundabout is scaled according to the traffic demand. However, when the traffic load increases, the roundabout will be occupied causing queues on the arms. See figure 11 for the corresponding performance graph of a roundabout.

![Figure 11 Performance graph of a roundabout](image)

3.3.4 Grade-separated junctions

Grade-separated junctions differ from the previously discussed intersections by their three-dimensional character. Intersecting traffic is prevented by a viaduct, which enables vehicles to drive continuously passing crossing vehicles below or across the viaduct. A disadvantage is the absence of turning possibilities. However, the traffic throughput is high most of the time, as can be seen in figure 12. It is possible to add exit lanes from the major road toward the minor road. In that case, a kind of

![Figure 12 Performance graph of a grade separated junction](image)
level crossing is created for turning traffic from the major road onto the intersecting road with the least traffic. Construction costs for viaducts are higher than for level crossings, but the grade separation scores well in safety measures.

The capacity of a viaduct without exit lanes is maximal. For a 4-way intersection with two lanes in each direction, 16,000 vehicles can pass each hour. Two times two lanes in two directions can handle two thousand vehicles per hour each. However, it is important that the traffic comes from all directions equally when calculations are made with this capacity. With exit lanes, the main road keeps its capacity, while turning traffic reduces the capacity of the minor road and the overall capacity towards 75 percent of the optimal grade-separated junction.

3.3.5 Multilevel junctions

A multilevel junction is designed as a grade-separated junction with possibilities to change direction towards the other arms without opposing traffic. Exit lanes and access lanes are added to the normal lanes. Construction can become complex and expensive, requiring more materials for all the extra lanes. But in comparison with the sole viaduct more accessibility can be guaranteed. Congestion is often a result of traffic changing lanes. The length of the exit and access lanes determines the severity of the congestion. See figure 13 for the performance graph of multilevel junctions.

Multilevel junctions have the highest capacity. Even in the most advanced form, there is no opposing traffic that using the same road. Therefore, multilevel junctions can reach the maximum capacity like a viaduct, but with turning still being possible.

![E: Multilevel junction (interstate exchange)](image)

**Figure 13 Performance graph of a level crossing**

3.4 Policy measures

The basic model will be altered several times in chapter 4 to check the sensitivity of the results. The changes that can occur are varying mobility demand (potentially caused by expansion of the city and the city population) or in the supposition that policy measures are introduced to influence the model characteristics. In this section, the policy measures that are dealt with in chapter 4 are discussed. In principle, good policies satisfy the SMART principle. These policies are defined by Harmsen et al. (2003) as specific, measurable, agreed upon, realistic and time-related.
3.4.1 Cleaner vehicle fleet

Over the last decades, the vehicle fleet has become cleaner. During this report, some possibilities for governmental interference were already discussed. Figure 3 in the introduction showed the decline of emissions since 1990. The improvements result mainly from international measures. New requirements for the car manufacturers are introduced to decrease the amount of exhaust gases from one vehicle. So should car manufacturers limit carbon dioxide emissions to 120 gram per kilometre instead of 160. Figure 14 and 15 show the emissions standards (Euro norms) that are used in the European Union for passenger cars according to Council Directive 70/220/EEC and following amendments. (European Commission, 2003). Table 8 shows the emission standards for heavy duty vehicles. An important difference is the unit of measuring the emissions. For passenger cars, emissions are expressed in grams per kilometre and for buses and trucks, emissions are expressed in grams per kilowatt-hour, making the standards not directly comparable.

Table 8 European emission standards for heavy duty vehicles

<table>
<thead>
<tr>
<th>Standard</th>
<th>Date</th>
<th>NOx (g/kWh)</th>
<th>PM (g/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Euro 0</td>
<td>1988 - 1992</td>
<td>2,60</td>
<td>none</td>
</tr>
<tr>
<td>Euro I</td>
<td>1992 - 1995</td>
<td>1,23</td>
<td>0,40</td>
</tr>
<tr>
<td>Euro II</td>
<td>1995 - 1999</td>
<td>1,10</td>
<td>0,15</td>
</tr>
<tr>
<td>Euro III</td>
<td>1999 - 2005</td>
<td>0,66</td>
<td>0,10</td>
</tr>
<tr>
<td>Euro IV</td>
<td>2005 - 2008</td>
<td>0,46</td>
<td>0,02</td>
</tr>
<tr>
<td>Euro V</td>
<td>2008 - 2012</td>
<td>0,46</td>
<td>0,02</td>
</tr>
<tr>
<td>Euro VI</td>
<td>under consideration</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

At a national level, a government can introduce additional requirements or other measures to control the vehicle fleet. In the Netherlands, an energy label was established in January 2001 subsequent to European regulation. (European Parliament, 2000). The fuel performance of a vehicle is characterised by a type and a colour showing the deviation to the average vehicle in the same category. A clean vehicle brings a customer a tax concession while a polluting vehicle is overtaxed. The energy label focuses on CO	extsubscript{2} reduction, but the tax bonuses/penalties are also differentiated for particle emissions. (Dutch Ministry of Finance, 2008).

To make calculations, the renewal rate of a vehicle fleet must be considered. Based on the data of Statistics Netherlands (2008a) it can be concluded that the average lifetime of a vehicle is circa nine years. In general, it is necessary to differentiate the three vehicle categories, because the average lifetime of a passenger car is four years shorter than the lifetime of a truck or a bus, mainly due to the investment costs. A cleaner vehicle fleet can consist of electric cars, hybrid cars and/ or cars driving on bio fuels.
3.4.2 Promoting public transport

The public transport sector is an important determinant for the overall emissions in the transport sector. Only buses are covered in the research, but the same line of reasoning yields for trams and trains. Cleaner buses are one way to decrease emissions, assuming that the amount of vehicles remains the same. Another way to diminish the emissions of transport on an intersection is by transport mode substitution. The division of the mobility demand over the vehicle categories should be changed in favour of public transport, meaning that light traffic is substituted by buses.

The introduction of the public transport credit card is an example of promotion. The idea is that passengers can pay fast for public transport, but the security issue is an obstacle for immediate introduction in the Netherlands, where only some pilot projects are completed. The attractiveness of public transport depends on three major factors: costs, accessibility and comfort. When the costs of public transport are lower than the costs of cars, travellers are more likely to switch towards the bus. In principle, this can also be seen for freight traffic, where trucks can be substituted by trains. A bus network and the line schedule of a city determine the time to travel from origin to destination, so more buses can reduce the required travel time to catch up or overtake the leading position of cars. Especially during rush hours, buses can drive faster due to priority regulations. Expanding the bus network can reduce the necessary time for travellers to reach bus stops. Of course, all proposals above need good planning and underlying information technology.

In the city of Groningen, public transport should get a boost from the Kolibri project. A tram network with underlying bus transversia at the edge of town are planned to be operational near 2020. According to the Municipality of Groningen (2006), the Kolibri project is meant to relieve the inner city of traffic problems, but a successful introduction will also carry along improvements on the feeding ways like the beltway. Nowadays, 75% of the 160,000 daily people that visit Groningen travel by car. When this percentage is decreased, the results will also be visible in the number of vehicles counted on the beltway and accordingly the emissions of NO\textsubscript{X} and PM\textsubscript{10}.

3.4.3 Road charging/ Congestion charging

The Dutch cabinet agreed upon the introduction of a road charge in 2011. (Dutch Ministry of Traffic, Public Works and Water Management, 2007). The measure is meant to distribute the costs of the infrastructure sector more fairly over the users of the infrastructure. People that drive more will pay more. Some demonstration projects are planned to implement the system slowly. A set-off for the kilometre charging will be the removal of the purchase tax on new motor vehicles.

Road charges are a nice method because vehicle characteristics can determine the price per kilometre and the overall costs for a driver. In that way, road charging can reduce the pollution by the vehicle fleet over time because people will search for cheaper transport (for example by cleaner cars). Differences in the tariff system will be difficult to enforce, but they can show the user some of the arguments for the costs. Research by Steg and Kalfs (2000) and Weggemans, van Veenendaal & Mesken (1999) showed that people will only change their mobility pattern when costs increase. With road charging, the excessive mobility users (lots of kilometres, polluting vehicles) will pay more than before, but according to the Dutch National Platform Different Payment for Mobility (2005) people that drive less than average (18,000 kilometres per year) will pay less than before. The biggest polluters will experience increased expenses, hopefully resulting in a change of their driving behaviour.

Another possibility with a variable tariff is the option to charge more for time and place specific driving. Rush hour kilometres will cost more than driving at night and well-known traffic bottlenecks will also be charged heavier. In this system, transport users think that they pay for congestion. For that reason, it is sometimes called congestion charging. To deal with this criticism, the Dutch government
plans to build additional infrastructure to the existing traffic bottlenecks in the introduction period of the road charging.

A cordon fee (account driving) is often confused with road charging, but a cordon fee is only for drivers that enter a specific region, for example an inner-city. These drivers will pay to use pre-defined roads. This toll system occurs in many countries across Europe, but the system was not approved in the Netherlands in 1998, because it was a tax system that did not affect all drivers equal such as kilometre charging where each driver pays for each kilometre driven.

3.4.4 Speed limits

The main goal of speed limits is safety and a regular look of the traffic situation. But over the last decade, speed limits are also used to control emissions and to increase the accessibility. Especially during rush hours, a lot of cities are interested in the possibility of variable speed limits. These speed limits are communicated to the road user through digital road signs.

Since May 2002, the Netherlands has been experimenting with 80 km/h (50 mph) zones on highways with a regular speed limit of 120 km/h. These zones are located where highways cross suburban areas. The first zone to be implemented was on A13, connecting Rotterdam to The Hague, at the Rotterdam suburb of Overschie. This was generally accepted as a success (Netherlands Organization for Applied Scientific Research, 2003), so in 2005, the experiment was expanded with four new zones in Rotterdam, the Hague, Utrecht and Amsterdam. The new zones have had mixed results, causing great controversy and calls for the removal of them. This controversy comes from the question whether the travel time is decreased (as a result of less congestion) or not. The environmental gains from a decreased speed limit are obvious for the time that congestion does not cause vehicles to drive slower than 50 km/h. As shown in figure 5 and 6, the ‘environmental top speed’ of a car is between 50 and 70 km/h and the environmental top speed of buses and trucks is approximately 80 km/h. The main conclusion by the Netherlands Organization for Applied Scientific Research (2003) about the results of speed limits was that it is highly location dependent.

3.4.5 Environmental zones

Environmental zones are another policy to discourage people and companies to drive old, polluting vehicles. The idea is to create city areas with restricted access for certain vehicles. Only clean vehicles are allowed. The first step towards environmental zones is the introduction of car exclusive zones, initially limiting the access of heavily polluting trucks to city centres. The city of Amsterdam had an experimental project where vehicles manufactured before 1992 were kept out of the city centre. On the basis of the Euro norms, Amsterdam will continue with the environmental zones in 2010.

Keuken (2008) claims that environmental zones are sensible from a health point of view, but the measure is not a cure-all for local councillors to meet air quality standards. Especially on particulates, city traffic is a limited contributor. In 2007, fifteen percent of the vehicles in the Netherlands were manufactured before 1992 according to Statistics Netherlands (2008a). This share of vehicles pollutes more than the other vehicles, but especially for particles, the background concentration causes the reduction of emissions to be relatively small. (Keuken, 2008).

The concept of environmental zones can be used to discourage terminating traffic. Section 3.4.2 discusses the substitute method to diminish the share of light traffic by more buses, while light traffic can be used to replace trucks. To achieve this substitution, heavy traffic with Groningen as destination is excluded from the beltway. Special transferia at city boundaries should be developed to transfer the cargo in vans. The average load of a truck is about twenty tons, which can be substituted by circa twenty vans (considered light traffic).
3.5 Case: City of Groningen

This research focuses on one specific city which brings some unique characteristics with itself. Until now, the spreadsheet model only uses generic data and relations. In this chapter, the mobility properties of the city of Groningen will be discussed. The traffic intensity and the transport mode allocation are depending on the local and regional situation and the regional importance of a particular city, for instance concerning employment. In section 3.2 was mentioned that the mathematical description of the vehicle emissions only yield for situations where a speed limit does not exceed 90 km/h. This does not give problems, because the speed limit on the beltways of the city of Groningen is 70 km/h.

3.5.1 Traffic intensity

According to the Municipality of Groningen (2007), the number of inhabitants of Groningen in 2007 was 181,845. Projections by Statistics Netherlands (2008b) indicate that the city will expand towards 211,010 inhabitants in 2020. In combination with the number of movements per person per day, the number of inhabitants can be used as an indicator for the mobility demand. The number of movements per day – 3,05 – remains almost constant since 1995, just as the distance – 32 km – covered per person per day. (Statistics Netherlands, 2007c). It was already stated in section 3.4.2 that 160,000 people visit the city of Groningen each day, from which 75% uses the car. (Municipality of Groningen, 2006).

This research uses the traffic intensity for an average working day, because problems arising from the transportation sector (accessibility, environment and safety) occur mostly on busy moments where mobility demand is high. Appendix C shows the number of vehicles that pass different sections of the beltway of Groningen on an average working day. It is clear that the southern part of the beltway, the connection between highways A7 and A28 (also known as Julianaplein), forms the bottleneck. In practice, the Julianaplein is the only spot on the Groningen beltway with congestion problems. Therefore, the calculations will be made for this intersection, handling 86,700 vehicles per day. (Municipality of Groningen, 2007). All locations show a general trend of increased traffic intensity, by more than two percent each year.

It is important to know how the traffic demand is dispersed over the day. Three time slots were developed to calculate the traffic load for different periods. The traffic load influences the speed pattern by increased congestion. The next subsection will divide the total mobility demand over the vehicle categories to create an overall table for the mobility demand at the Julianaplein.

3.5.2 Transport mode allocation

In this research, the transport modes are divided over three vehicle categories. Literature (Archilla & Morrall, 1996; Directorate-General for Public Works and Water Management, 2006) suggests that heavy traffic accounts for sixteen percent of all highway traffic. The intersection under consideration can be typified as a highway, connecting two parts of the European highway A7 and the A28 (see appendix C), and so this percentage is used for the basic scenario.

Literature is not conclusive about the percentage of buses, but one percent seems reasonable. Based on the line schedule of Arriva (2008), some 560 buses cross the Julianaplein each working day. Together with some extra buses during busy moments (especially during rush hours) and other bus services like touring cars, the number of buses will actually lay around one percent (870 vehicles per day). The data of Arriva (2008) is used for the distribution of the buses over the different time slots.

For the heavy traffic category, the traffic intensity per time slot is almost equal. This category consists of trucks, which differ from other transport modes in the fact that Groningen is not the origin or destination of the trip. The southern beltway is part of an European highway. The heavy traffic
category characterises itself as through traffic. Based on this characteristic, it is assumed that the same number of vehicles crosses the intersection each hour per day.

Light traffic diverges less equally over the different time slots. Measurements by U.S. Department of Transportation (2001) indicate that during rush hours, almost ten percent of the vehicles that pass over the whole day will pass in one hour. Therefore, 40% of all light traffic can be counted during rush hours. At ‘night/ morning’, only 1.5% of the daily vehicles will pass the intersection each hour, totalling 18.75%. The percentage of vehicles that pass during day time is 41.25% (5.5% per hour).

All data presented in the last two sections is combined in table 9. The total mobility demand is divided over the vehicle categories and time slots as described before. The data will be altered in some scenarios in the next chapter, to compare the different intersections on air quality.

*Table 9 Mobility demand divided over vehicle categories and time slots*

<table>
<thead>
<tr>
<th>Time Slots</th>
<th>Heavy traffic</th>
<th>Buses</th>
<th>Light traffic</th>
<th>Vehicles per day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Night/ morning</td>
<td>580</td>
<td>15</td>
<td>1.079</td>
<td>20,919</td>
</tr>
<tr>
<td>(12.5 hours)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Day time</td>
<td>580</td>
<td>55</td>
<td>3.955</td>
<td>34,421</td>
</tr>
<tr>
<td>(7.5 hours)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rush hour</td>
<td>580</td>
<td>70</td>
<td>7.190</td>
<td>31,360</td>
</tr>
<tr>
<td>(4 hours)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vehicles per day:</td>
<td>13,920 (16.1%)</td>
<td>880 (1.0%)</td>
<td>71,900 (82.9%)</td>
<td>86,700 (100%)</td>
</tr>
</tbody>
</table>
**4. RESULTS**

This chapter describes the results derived from the spreadsheet model. Section 4.1 summarizes the main results of the basic scenario, or rather: the current situation. This section will be used as a reference for all the other sections, in which the impacts of the different parameters are measured under *ceteris paribus* conditions. Except for one parameter, all other model data will be the same. In most cases, three different values are considered to check for linear behaviour.

The spreadsheet model delivers the results in total emissions per day. The total emissions can be divided over the vehicle categories to assess the most polluting kind of vehicle. It is necessary to compare these percentages with the share of the traffic intensity that the vehicle category represents. Another option is to divide the total emissions over the time scenarios to see on which moments the most emission take place. These percentages are especially important to assess the potential improvement that policy measures have to offer. In the figures, the different intersections are represented by the characters A-E, as follows:

- A Level crossing with priority road rules
- B Level crossing with traffic lights
- C Roundabout
- D Grade separated junctions (viaduct)
- E Multilevel junction (interstate exchange)

**4.1 Model outcome basic scenario**

Figures 16 to 19 show the emissions in the current situation, called the basic scenario, which will serve as reference for the changes that are discussed in sections 4.2 to 4.4. The graphs show the same pattern when the intersections are compared. The intersections with more levels score better than the ground-level intersections. There is a difference of 29.4% NO\(_X\) emissions and 34.0% of PM\(_{10}\) emissions between the worst and the best intersection.

The most explicit aspect that can be concluded from figures 17 and 19 is the impact of heavy traffic in comparison with light traffic. Considering the marginal amount of trucks (only 16.1% of all vehicles falls in the heavy traffic category), the contribution of 77.5% to overall NO\(_X\) emissions and 55.5% to overall PM\(_{10}\) emissions is very high. Buses contribute circa four percent to the NO\(_X\) emissions and three percent to the PM\(_{10}\) emissions, while the category only represents one percent of the total traffic intensity.

The results show also a major difference between the NO\(_X\) and PM\(_{10}\) emissions. Figure 5 and 6 showed already that the difference between heavy traffic and light traffic especially exists for NO\(_X\), causing the NO\(_X\) emissions to be more dependent on the amount of trucks than the PM\(_{10}\) emissions. For policy measures concerning particulate matter in particular, the larger share of light traffic in PM\(_{10}\) emissions can be an important factor. In contrast, an objective to decrease NO\(_X\) concentrations near intersections would focus on the reduction of heavy traffic.

The heavy impact by heavy vehicles is also shown in figures 16 and 18. The calculations show almost the same amount of emissions during each time slot, while the actual number of vehicles belonging to ‘day time’ and ‘rush hour’ are the highest. It is important to stress, that the time slots are not equal in time. ‘Rush hour’ covers four hours, ‘day time’ is a period of seven and a half hours and ‘night/ morning’ is the longest time slot of twelve and a half hours. As expected, one hour in the time slot ‘rush hour’ will have more emissions (6.5% of day total) than an hour in the ‘day time’ (4.3%) and the ‘night/ morning’ time slot (3.4%). But the differences are less than the traffic intensity would suggest because of the higher proportion of heavy traffic at night and the associated higher emission factors of heavy traffic.
Figure 16  NO$_x$ emissions per day in basic scenario, divided over time slots

Figure 17  NO$_x$ emissions per day in basic scenario, divided over vehicle categories

Figure 18  PM$_{10}$ emissions per day in basic scenario, divided over time slots
4.2 Impact of more mobility demand

Section 3.5 addressed the mobility data of the city of Groningen. The spreadsheet model has been used to review the impact of three possible changes in the mobility demand. The three situations are called Most Probable (MP), Low Estimate (LE) and High Estimate (HE) discussing an increase of traffic intensity of respectively 20%, 10% or 30%.

The MP situation is an approximation based on the population growth expectation. Historical records show that the number of movements per person stays the same since 1995 so extra mobility will only be needed by more people. The projections mentioned in section 3.5.1 describe an increase of sixteen percent of the population until 2020. However, in recent years, traffic intensity on the beltway of Groningen increased more heavily than the growth of the population would suggest. Therefore, a mobility demand increase of twenty percent is considered to be the most probable.

If the population growth would be smaller than expected, or the number/length of movements would decrease, the traffic intensity would rise with circa ten percent. This LE situation results in an increase of emissions of more than ten percent. In the ‘night/morning’ time slot, the emissions increase with just about ten percent. An increase of the traffic intensity does also increase the traffic load. A higher traffic load enlarges the chance that vehicles to drive according to the congestion speed scenarios. This is even clearer when the mobility is increased further.

An increase of twenty percent will have more impact on the traffic load in the different time slots. The multilevel junction can still handle all traffic in the same way, meaning that the overall emissions will grow with twenty percent, parallel to the increase of the mobility. The viaduct construction would have more emissions than expected during rush hours, while a roundabout and a level crossing with priority rules would see the emissions rise during day time. A level crossing with traffic lights has already a traffic load above one during day time and rush hours in the basic scenario, but even during night/morning, the traffic load rises above 0.6. For the vehicle categories, it can be seen that the relative impact of heavy traffic increases when the increased traffic load causes more delay.

The HE situation handles an increase of 30%. Historical data showed an increase of traffic intensity of more than two percent each year on the beltway of Groningen. When this pattern continues towards 2020, the number of vehicles would increase with more than 30%. For the grade separated junctions, the traffic load rises above 0.6 during rush hours causing more than 30% of extra emissions. But these options seem the only realistic options when the mobility demand would be that high in 2020. The ground level intersections would have enormous amounts of congestion during ‘day time’ and ‘rush
hours’. The NO\textsubscript{X} and PM\textsubscript{10} emissions at a level crossing with priority road would increase with respectively 36.1% and 36.9%. The difference between the best and the worst type of intersection also increases with more traffic. Because the average performance and capacity of level crossings is lower than for grade separated junctions, congestion will occur sooner for the level crossings. For the HE scenario, level crossings emit 31.5% more NO\textsubscript{X} and 35.8% more PM\textsubscript{10} emissions than multilevel junctions, instead of 29.4% and 34.0% respectively in the basic scenario.

4.3 Impact of transport mode attractiveness

This research only consists of three different ‘transport modes’, called vehicle categories. Although it may seem impossible to describe the reality with only three categories, it was already concluded in section 4.1 that the emissions by trucks are out of proportion to the amount of trucks in relation with all vehicles. Estimations by the Dutch Ministry of Traffic, Public Works and Water Management (2004) show an increase of heavy traffic from sixteen percent now to twenty percent in 2020. This section will present the results of the spreadsheet model for another percentage of heavy traffic. The most probable scenario has twenty percent of heavy traffic. Again, a low estimate and a high estimate of 10% and 25% were also performed. It is unlikely that the percentage of heavy traffic would change at this moment, but the share is changed in the current situation because it is interesting to see the effect of more or less heavy traffic.

With twenty percent heavy traffic, the impact of light traffic decreases with almost five percent for all intersections, but the overall impact of the intersections increases with 17.8% to 18.5% of NO\textsubscript{X} emissions and 11.0% to 12.0% of PM\textsubscript{10} emissions. This comes through the extra trucks, which simply emit more NO\textsubscript{X} and PM\textsubscript{10} per kilometre.

A high estimate of 25% heavy traffic would result in between 40.2% and 41.8% extra NO\textsubscript{X} emissions and 24.9% to 27.3% more PM\textsubscript{10} emissions in comparison with the basic scenario. These results show that overall emissions are highly dependent on the share of the heavy traffic. Especially for NO\textsubscript{X}, each extra truck is worrying.

The spreadsheet model is also used to see what happened when the share of heavy traffic would decrease to ten percent of all vehicles. It would mean an average decline of 28.0% of the NO\textsubscript{X} emissions and 18.0% of the PM\textsubscript{10} emissions for all intersections. For the rest, the results are the opposite of the results for a higher percentage of heavy traffic.

4.4 Impact of policy measures

The following subsections discuss the effects of the policy measures discussed in section 3.4. This will be done on the basis of the information on these policy measures and calculations performed with the spreadsheet model.

4.4.1 Cleaner vehicle fleet

A cleaner vehicle fleet can be modelled by editing the emission factors. Figure 5 and 6 showed the expected emission factors, which can be implemented in the model by altering the power functions describing the emissions. This is done for the current situation, assuming an unrealistic sudden transition towards a clean vehicle fleet. The future emission factors are expectations for 2020, so the earlier assumptions for 2020 (twenty percent increase of traffic intensity and a share of twenty percent heavy traffic) are also added from the previous sections.

The future emission factors on the current situation would result in a decline of the NO\textsubscript{X} emissions with 59.5% and a decline of the PM\textsubscript{10} emissions with 60-65%. The division over the vehicle
categories changes in favour of heavy traffic that has five percent less impact. The light traffic sector accounts for five percent extra to the total emissions.

With twenty percent more traffic intensity and an increased share of heavy traffic that is expected at the time the emission factors will hold, the decline of emissions will be between 41.6% and 43.5% for NO\textsubscript{X} and between 46.8% and 53.3% for PM\textsubscript{10}. The impact of heavy traffic is at the same level as the basic scenario. The benefits for this category from better emission factors are undone by the extra amount of heavy traffic and the general increase in mobility (including heavy traffic).

A cleaner vehicle fleet can be achieved by introduction and implementation of (international) emission standards. The policy measure does not influence the mobility characteristics at all, so the problem of congestion and accessibility need to be addressed specifically.

4.4.2 More public transport

The model is also used to calculate what happens with the emissions when light traffic is substituted by buses. There is a difference in bus passenger load between the time slots. During rush hour, more buses drive, but the average load of a bus is also higher than at the other time slots. One bus corresponds with fifteen vehicles out of the ‘light traffic’ category during the ‘night/morning, while one bus substitutes 30 vehicles during ‘day time’ and 45 vehicles during ‘rush hour’. Three scenarios were reviewed. First, ten percent of the light traffic is substituted by buses. Secondly, the substituting percentage is increased to 25%. The final scenario is a doubling of the current number of buses.

The results are relatively small. A substitution of ten percent light traffic results in a decline between 0.7% and 3.6% of NO\textsubscript{X} emissions and a decline between 3.4% to 6.3% of the PM\textsubscript{10} emissions. When 25% of the light traffic is substituted by buses, NO\textsubscript{X} emissions are diminished with 1.7% to 7.0% and PM\textsubscript{10} emissions with 7.8% to 13.5%. Again, it becomes clear that a reduction of light traffic leads to more gains in PM\textsubscript{10} emissions. The substitution would influence the division over the time slots. The most traffic is replaced during the busiest time slots, so the emissions decline especially during day time and rush hour.

Figure 20 and 21 show the results for the most extreme improvement of public transport. A reduction between 3.8% and 9.1% of NO\textsubscript{X} emissions and between 13.5 and 19.4 of PM\textsubscript{10} emissions can be obtained when the number of buses is doubled. It would result in a decline of light traffic by 31.0%. The figures show also that the NO\textsubscript{X} emissions of 1.760 buses are almost equal to the impact of 44.113 vehicles from the light traffic category. For PM10, the impact of light traffic decreased from over 40% to circa 30%.

![Figure 20: NO\textsubscript{X} emissions per day with two times as many buses to substitute light traffic](image-url)
The figures show almost the same pattern when the different intersections are compared. However, the gap between a level crossing with traffic lights and a roundabout increased from one percent to seven percent. This can be explained by the decline of light traffic. The overall intensity falls and because roundabouts have a higher capacity, the distribution over the speed scenarios will favour the better scenarios sooner than for the level crossing with traffic lights.

4.4.3 Road charging

Road charging was discussed in section 3.4.3. Conclusions were that introduction and implementation of a road charging system could bring on different results. For example, driving becoming more expensive would favour public transport. This possibility is discussed in the previous section. Less driving due to the higher expenses is covered in the LE variant in section 4.2. To solve most traffic problems, a tariff system can be used. A higher price for driving during rush hours in particular would modify the traffic intensity. The road capacity is used more efficiently causing less congestion.

The model was used to assess the optimal solution where the total traffic intensity divides equally over each moment of the day. This optimal solution would practically be unreachable, for example due to working conditions. The results of what is called the optimal solution are interesting. For the multilevel junction, the overall emissions stay the same, but the division over time slots is somewhat different. The impact of the ‘night/ morning’ increases for all intersection while the emissions during the other time slots decrease. The overall emissions do not decrease in all cases. The capacity of a level crossing with traffic lights is not big enough to let all traffic pass. The traffic load of the busiest moments decreased, but is still above one, while the chance on congestion increased during night/ morning. An option would be to create a three-lane road section with more capacity. In that case, road charging would reduce emissions a little bit like the way it would happen at a grade separated junction. The biggest gain can be obtained at roundabouts and priority road regulated crossings, but it would only be a maximum decrease of ten percent of the emissions.

It is important to mention that road charging does not set percentages for vehicles that can drive each hour, but the measure is a tool to reach the desired percentages. For the second case that was reviewed, some more realistic percentages are used. The lower estimate assumes that each hour during the ‘rush hour’ time slot, 7.5% of all light traffic would pass the intersection instead of 10%. The percentage for ‘day time’ decreases from 5.5% to 4.67%. The total traffic intensity is supposed to remain the same, so more traffic will drive during the night/ morning. The gains or losses are marginal up to plus or minus five percent of the emissions. On the basis of this model, road charging is not reasonable when considered with a focus on an air quality.
4.4.4 Speed limits

It was already mentioned before that the speed of a car determines the actual emission at that specific moment. Figure 5 and 6 showed the emission factors of nitrogen oxides and particulate matter. In the model, these data is approximated by power functions which only hold for road sections with a maximum speed limit of 90 km/h. Below that speed limit, an alteration of the speed limit will cause the model to change the speed profiles and subsequently the emission profiles. The model calculations were performed for speed limits of 50, 60 and 80 km/h.

The results follow the power functions. A high speed limit is better, so a speed limit of 80 km/h will result in a small decrease of emissions of a few percents (1-5%), while the overall emissions with a lower speed limit would be higher than in the current situation (3-6% for a speed limit of 60 km/h and 8-14% for a speed limit of 50 km/h). There are no remarkable differences in the vehicle categories or time slots. In general, a higher speed is good for the emission caused by heavy traffic, but the benefit is extremely small. Potential externalities like increasing congestion are not included in the model. All in all, the model results together with uncertainties do not make sense to create much improvement by altering the speed limit.

4.4.5 Environmental zones/ Substitution heavy traffic

Section 3.4.5 described the potential of environmental zones. The results that can be achieved were partly discussed in the previous sections, because it is a combination of less vehicles (fifteen percent) and cleaner vehicles. The older vehicles are dirtier, so the average emission factors could be reduced by circa fifteen percent. These reductions projected on the situation in Groningen would result in between 26,7% and 30,7% less emissions. However, the question should be raised whether the owners of forbidden vehicles would drive new vehicles, or that they would use the bus for transportation.

Another option is to exclude terminating heavy traffic from the beltway by substituting trucks by vans. One truck can be replaced by twenty vans, increasing the overall traffic intensity considerably. The results show that twenty light vehicles emit almost the same amount of NO\textsubscript{X}, because the overall emissions of nitrogen oxides only increase by a maximum of 1,8%, 5,0% or 6,1%, respectively for scenarios with five, ten or twenty percent terminating heavy traffic. However, the prevention of heavy traffic has more negative effects on particle emissions. In comparison, the difference between the emission factors are less for PM\textsubscript{10}, so the scenarios would cause circa 6,5%, 14,1% or 27,5% more PM\textsubscript{10} emissions respectively.
Figures 22 and 23 show the results for a substitution of twenty percent of the heavy traffic. For NO\textsubscript{X}, the impact of light traffic increases with fifteen percent at the expense of heavy traffic. The transition of the impact is even twenty percent for particulate matter. Not only from an urban air quality point of view is substitution of trucks by vans undesirable, but accessibility decreases due to more vehicles.

Just like the situation were light traffic was substituted by buses, a roundabout shows a lower rise of emissions than a level crossing with traffic lights. A difference with the first substitution is that the traffic intensity actually increases in this scenario. But the traffic load results show that the traffic intensity during ‘night/ morning’ only exceeds the road capacity for the level crossing with traffic lights, the type of intersection with the lowest capacity. The increased traffic load during ‘night/ morning’ causes more vehicles to drive according to the ‘congestion high’ speed profile. Therefore, the emissions increase more at the level crossing with traffic lights. Compared to a multilevel junction, 36.1% more NO\textsubscript{X} and 38.3% more PM\textsubscript{10} emissions are calculated for a level crossing with traffic lights.

![Figure 23 PM\textsubscript{10} emissions per day when twenty percent of heavy traffic is substituted by light traffic](image)

4.5 Overview results

Appendix D shows the results of all scenarios that were discussed previously in this chapter (summarised in table 10). The outcomes vary as a result of the traffic load. To handle the variation, the results are shown as ranges. Scenarios with large ranges of outcomes indicate that decision makers should consider their specific situation more closely when they want to implement that scenario. The range indicates quite a difference for a different intersection structure. The difference in the basic scenario is circa 30% of extra emissions for the worst intersection, compared to the best intersection.

Appendix B does not provide information about the distribution over the vehicle categories and time slots. Wherever the results are deviating from the expected changes (due to the adjustments in the model), it is mentioned in the previous sections. For half of the scenarios, the changes in NO\textsubscript{X} and PM\textsubscript{10} are in the same range. The differences for NO\textsubscript{X} and PM\textsubscript{10} are caused by other divisions of the vehicle categories. Heavy traffic determines the NO\textsubscript{X} results, while large differences in the share of light traffic can especially be seen in the PM\textsubscript{10} results.
Table 10  Overview of scenarios that were discussed

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Adjustment(s) to basic scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>20% more vehicles</td>
</tr>
<tr>
<td>B</td>
<td>10% more vehicles</td>
</tr>
<tr>
<td>C</td>
<td>30% more vehicles</td>
</tr>
<tr>
<td>D</td>
<td>20% heavy traffic</td>
</tr>
<tr>
<td>E</td>
<td>10% heavy traffic</td>
</tr>
<tr>
<td>F</td>
<td>25% heavy traffic</td>
</tr>
<tr>
<td>G</td>
<td>Expected emissions factors of 2020 on current situation</td>
</tr>
<tr>
<td>H</td>
<td>20% more vehicles + 20% heavy traffic + Expected emissions factors 2020</td>
</tr>
<tr>
<td>I</td>
<td>Number of buses doubled to substitute light traffic</td>
</tr>
<tr>
<td>J</td>
<td>10% light traffic substituted by buses</td>
</tr>
<tr>
<td>K</td>
<td>25% light traffic substituted by buses</td>
</tr>
<tr>
<td>L</td>
<td>Vehicle per hour 'rush hour': 7.5% + vehicle per hour 'day time': 4.67%</td>
</tr>
<tr>
<td>M</td>
<td>Vehicle per hour 'rush hour' en 'day time': (1/24)% = 4.2%</td>
</tr>
<tr>
<td>N</td>
<td>Speed limit: 50 km/h</td>
</tr>
<tr>
<td>O</td>
<td>Speed limit: 60 km/h</td>
</tr>
<tr>
<td>P</td>
<td>Speed limit: 80 km/h</td>
</tr>
<tr>
<td>Q</td>
<td>15% less vehicles + 15% less emissions heavy and light traffic (Amsterdam)</td>
</tr>
<tr>
<td>R</td>
<td>5% (terminating) heavy traffic substituted by light traffic</td>
</tr>
<tr>
<td>S</td>
<td>10% (terminating) heavy traffic substituted by light traffic</td>
</tr>
<tr>
<td>T</td>
<td>20% (terminating) heavy traffic substituted by light traffic</td>
</tr>
</tbody>
</table>

Appendix D does not allow a comparison between the different types of intersection. In general, the worst option is the level crossing with traffic lights, followed by a roundabout. A multilevel junction has the lowest emissions. When the overall emissions increase, it becomes clear that the difference between the options also increases. The contrary applies as well.

The results show that emissions are dominantly influenced by the environmental characteristics of a vehicle. The structure of an intersection determines the emissions partly. The traffic intensity is a major factor as well, in particular the number of trucks. The automobile industry has an important task to lower vehicle emissions per kilometre. Because the policy measures discussed show just marginal effects, the government should focus on limiting the growth of traffic intensity.
5. CONCLUSIONS AND DISCUSSION

This thesis researched the issue of air quality problems near intersections on beltways. This section will summarize the main findings of the conducted research on the basis of the research questions from section 1.2. Furthermore, a critical reflection on the usefulness and relevance of the preliminary conclusions is presented in this section, while the thesis will be closed with policy recommendations based on this thesis.

5.1 Answering research questions

The main research question for this thesis was:

What is the optimal policy for designing intersections, from the point of view of exhaust gas emissions over time with varying policy measures and changing mobility demand?

Several sub questions were studied in order to answer the main research question. Below, the results will be discussed in three stages: the transport characteristics, environmental characteristics and policy measures are discussed. The sub questions in section 1.2 were divided over these three topics.

Transport characteristics

The spreadsheet model includes three speed profiles to describe the speed of vehicles in three situations: an ideal situation and two congestion levels with more stops and acceleration necessary. Five types of intersection are compared, with own characteristics for each of them. The division of the speed profiles is different for each of the intersections creating differences between the intersections. The results showed that level crossings cause circa 30% more emissions than grade separated junctions.

The overall emissions are also heavily influenced by the number of vehicles crossing an intersection. Expected growth in mobility would cause more congestion by a higher traffic load. The increase in emissions is calculated to be higher than the growth in mobility. The emissions are strongly influenced by the division over the three vehicle categories that were defined. The share of heavy traffic increases over time, from sixteen percent now to twenty percent in 2020.

Environmental characteristics

The emission factors per vehicle category show that the actual emissions are dependent on the actual mass of a vehicle. Heavy vehicles emit more nitrogen oxides and particulate matter than light vehicles. A combination of the emissions factors with the speed profiles learned that speed is another determinant for the actual emissions. A low speed is maintained on a longer distance, which results in high emissions near intersections.

New car technologies reduced the emissions of NOX and PM_{10} between 1990 and 2006 with 40%. Improvements in car technologies are expected to continue until 2020. The emission factors that are forecasted show a potential emission reduction of another 60% in the year 2020 compared to the current situation. To achieve this reduction, all other data should remain the same. When the predicted traffic intensity and the increasing share of heavy traffic are also included in the model to increase the reliability, the NOX emissions are calculated to decline with circa 42,5% and the PM_{10} emissions would decline with circa 50%.

Policy measures

Three factors exist that are significant for policy makers to choose for intersection design from a sustainability point of view: people, planet and profit (represented by safety/ health, environment and accessibility). Environment is the only issue considered in this research where five policy measures where described and calculated. A lower speed limit (current speed limit is 70 km/h) would cause higher emissions because the emission factors are higher. On safety and accessibility, the results could
be somehow better with a lower speed limit. On the other hand, a higher speed limit is not in accordance with safety policy.

A complicated system of kilometre charging could be used to influence the division of the total traffic over the day. The results are positive (up to ten percent) when the capacity of the intersection is high enough. When the capacity is small, the traffic load is high during the whole day, causing an increase of overall emissions. The measure is complicated, because the tariff system should be extremely differentiated to reach an equal distribution over the whole day. Public resistance is another disadvantage for this measure.

A ban of polluting vehicles was discussed at the hand of an existing example in Amsterdam, where vehicles manufactured before 1992 were kept out of the city centre as a demonstration project. When owners of these vehicles would not substitute their polluting vehicle, the traffic intensity and the average emissions per kilometre are supposed to decrease. The overall emissions can potentially be reduced with 29%.

Two substitution strategies were treated in this thesis. First, improvements in the public transport sector were assumed to substitute light traffic by buses. When the current number of buses would be doubled (buses drive twice as often), overall NO\textsubscript{X} emissions could decline up to nine percent, while the reduction of light traffic causes the potential decrease in PM\textsubscript{10} emissions to be at maximum nineteen percent. A second substitution that was discussed is the replacement of terminating heavy traffic by light traffic. Trucks with destination Groningen should transfer their load to vans at overload transferia at the city boundaries. Even with twenty percent of heavy traffic substituted, the NO\textsubscript{X} emissions change just slightly with a few percent in the wrong direction. It means that twenty light vehicle emit almost the same amount of NO\textsubscript{X} as one heavy vehicle. Light vehicles emit relatively much particles, so the substitution of heavy traffic leads to more PM\textsubscript{10} emissions (between 25% and 30% for twenty percent less heavy traffic).

Overall conclusion

The emissions near intersections are mainly caused by the environmental characteristics of vehicles. The structure of an intersection shows the second best results, but it is difficult to redesign existing infrastructure to achieve the potential profit without causing too many negative effects like more congestion and needless expenditures. Emissions also rise due to ever growing traffic intensity. Heavy traffic is the vehicle category that causes the most emissions. Light traffic has relatively high PM\textsubscript{10} emissions compared to the other vehicle categories. But all in all, the highest profits can be achieved by reduction of the vehicle emissions per kilometre. Governments have a task to set SMART emission targets for the automotive industry to decrease the emission factors.

The policy measures discussed show marginal improvements in the best cases. The best results come from a ban for polluting vehicles on certain road sections. However, the same vehicles will choose other routes shifting the problem to other areas. Another possible counter effect that could neutralize the gains by a ban is that drivers use cleaner cars for the protected road section. Positive results (about ten percent less emissions) are also noted for an improvement of the public transport system. Passenger cars (light traffic) are substituted by buses.

5.2 Critical reflection

The outcomes of the model are indicative for the potential changes in emissions. However, the spreadsheet model consists of some estimations that could be refined by more research towards future changes. With complex software, the model could also be expanded and perfected by using more than three vehicle categories with emission factors for all traffic modes. With proper data available, other emissions, like ozone, CO\textsubscript{2} or SO\textsubscript{2} could be added to the spreadsheet model too.
Other expansions of the model would be to include more different intersections. A limitation of available land could be inserted to compare feasible intersection by skipping the ones that are not suitable for a specific situation. The five types of intersection are also averaging a handful of intersections. Capacity can be influenced by the addition of turning/exit lanes. The actual effects of slight alterations to the structure of an intersection should be known to create thorough results. More policy options could be reviewed as well. When the spreadsheet model contains accurate data to replace the time slots by continuous traffic intensity information, it is easier for decision makers to intervene in the current situation.

The whole research focuses on the environmental side of intersection design with the exception of noise nuisance caused by the transport sector. Noise production could be included, but the problem is the perception of people which is hard to simulate in the spreadsheet model. Future research could try to implement social and economical factors in the model as well. For instance, costs of intersection structures and an available budget could be added to create a potential list of intersections for a specific location. A social factor for future research is the problem of externalities. For example, would a road section be used more when congestion is attacked by increasing the capacity of that road section? And what are the dominant forces for people to choose their transport mode? When will they change their mobility behaviour? These questions are not answered in this thesis, but it could provide a closer insight in the complex problem of intersection design.

Although there is still room for improvement, the spreadsheet model can be used for policy recommendations. The presented results should be interpreted on a qualitative basis. The emission changes that were calculated in the scenarios show excellent which factors are the most promising for an improvement of the urban air quality. The next section continues on the actual advices for policy makers that could be justified on the basis of this research.

5.3 Policy recommendations

For policy makers, it is important to know which parameters of the problem are manipulable. To review the options for the government, it is interesting to introduce a famous formula from environmental sciences to describe human activity.

Impact = Population × Affluence × Technology (IPAT equation)

The IPAT equation is also useful for the problem of emissions by the transport sector. The number of persons asking transportation is P, while affluence can be described by the number/length of movements per person and technology is the average emission per movement. The impact is the overall emission of exhaust gases. It is difficult for governments to alter the P and A value. Possibilities to change these factors are the stimulation of home working and the location of living-employment-zones. Raising awareness towards the environmental issue of their mobility behaviour could also show some potential, but it will be hard to get people out of their car and even harder to get product manufacturers close to their customers with their plant. They make their respective choices on the basis of comfort and necessary travel time and the costs of settlement and labour.

The best steering wheel to influence the overall emissions is technology. Vehicle emissions can become better by reducing loads, increasing motor efficiency or other fuels. Car manufacturers are the main actors to make cleaner vehicles, but governments have a role in the stimulation of research or they can set targets with rewards or penalties attached for the good and bad performers. Tax incentives for cleaner vehicles (alternative transport modes) are possible as well.

This research also showed that grade separated intersections are better for urban air quality than ground-level junctions. A higher speed can be maintained by more vehicles, so the accessibility is good. Less congestion occurs, because the capacity of grade separated junctions is higher. The fact that opposing traffic is prevented is also good for the safety issue of intersection design. The advice to
prefer grade separated intersections is extremely interesting for new infrastructure projects, because road operations at existing road sections cause undesirable delay.

The most important take home message is that transport activity is not completely reliable as indicator for economic growth. Urban air quality affects human health causing higher expenses in the health care sector. In the long run, cleaning up the pollutants will be costly and difficult as well.
REFERENCES


Smit, R., Mieghem, R. van, & Hensema, A. (2006). Algemene PM\(_{10}\), \( NO_X \) en \( NO_2 \) emissiefactoren voor Nederlandse snelwegen. TNO-rapport 06.OR.PT.029.1/RS. TNO Automotive, Environmental Studies & Testing (EST), Delft, the Netherlands. 5 December 2006.


APPENDICES

Appendix A: City map of Groningen with beltway highlighted

The traffic intensity (vehicles on average working day in 2006) on eight different locations is shown in the table below. Based on counting data by the Municipality of Groningen (2007).

<table>
<thead>
<tr>
<th>Location</th>
<th>Traffic Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>35.100</td>
</tr>
<tr>
<td>II</td>
<td>26.700</td>
</tr>
<tr>
<td>III</td>
<td>27.000</td>
</tr>
<tr>
<td>IV</td>
<td>31.800</td>
</tr>
<tr>
<td>V</td>
<td>33.600</td>
</tr>
<tr>
<td>VI</td>
<td>39.200</td>
</tr>
<tr>
<td>VII</td>
<td>40.200</td>
</tr>
<tr>
<td>VIII</td>
<td>86.700</td>
</tr>
</tbody>
</table>
Appendix B: Graphical representation of the three speed scenarios

The shaded area is the intersection itself.
Appendix C: Emission profiles

1. NO\textsubscript{X} emission profile

The “light traffic” profiles represent five vehicles, instead of one vehicle.
2. $\text{PM}_{10}$ emission profile

The “light traffic” profiles represent five vehicles, instead of one vehicle.
Appendix D: Overview results

The next two pages show the results of the different scenarios studied in this thesis. Below, the adjustments of each scenario to the basic scenario are described. The figures show also the difference of the changes for the intersections by ranges. Multilevel junctions show the lowest increase in emissions or the highest decrease. The difference between multilevel junctions (best) and level crossings with traffic lights (worst) are 29.4% NO\textsubscript{X} emissions and 34.0% PM\textsubscript{10} emissions. A large range of results in the figures indicates a rise of the gap between the different types of intersections. Compared with results of the scenarios, 30% extra emissions is quite high, making the structure of an intersection a good option in air quality policy.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Adjustment(s) to basic scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>20% more vehicles</td>
</tr>
<tr>
<td>B</td>
<td>10% more vehicles</td>
</tr>
<tr>
<td>C</td>
<td>30% more vehicles</td>
</tr>
<tr>
<td>D</td>
<td>20% heavy traffic</td>
</tr>
<tr>
<td>E</td>
<td>10% heavy traffic</td>
</tr>
<tr>
<td>F</td>
<td>25% heavy traffic</td>
</tr>
<tr>
<td>G</td>
<td>Expected emissions factors of 2020 on current situation</td>
</tr>
<tr>
<td>H</td>
<td>20% more vehicles + 20% heavy traffic + Expected emissions factors 2020</td>
</tr>
<tr>
<td>I</td>
<td>Number of buses doubled to substitute light traffic</td>
</tr>
<tr>
<td>J</td>
<td>10% light traffic substituted by buses</td>
</tr>
<tr>
<td>K</td>
<td>25% light traffic substituted by buses</td>
</tr>
<tr>
<td>L</td>
<td>Vehicle per hour 'rush hour': 7.5% + vehicle per hour 'day time': 4.67%</td>
</tr>
<tr>
<td>M</td>
<td>Vehicle per hour 'rush hour' en 'day time': (1/24)% = 4.2%</td>
</tr>
<tr>
<td>N</td>
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</tr>
<tr>
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<td>Speed limit: 60 km/h</td>
</tr>
<tr>
<td>P</td>
<td>Speed limit: 80 km/h</td>
</tr>
<tr>
<td>Q</td>
<td>15% less vehicles + 15% less emissions heavy and light traffic (Amsterdam)</td>
</tr>
<tr>
<td>R</td>
<td>5% (terminating) heavy traffic substituted by light traffic</td>
</tr>
<tr>
<td>S</td>
<td>10% (terminating) heavy traffic substituted by light traffic</td>
</tr>
<tr>
<td>T</td>
<td>20% (terminating) heavy traffic substituted by light traffic</td>
</tr>
</tbody>
</table>
1. Changes in overall NO$_x$ emissions per scenario
2. Changes in overall PM$_{10}$ emissions per scenario
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### Appendix G: List of abbreviations

<table>
<thead>
<tr>
<th>Short</th>
<th>Long</th>
</tr>
</thead>
<tbody>
<tr>
<td>am</td>
<td>Before noon (Latin: Ante Meridiem)</td>
</tr>
<tr>
<td>C</td>
<td>Road Capacity (used in $L = I/C$)</td>
</tr>
<tr>
<td>CAFE</td>
<td>Clean Air For Europe</td>
</tr>
<tr>
<td>CBS</td>
<td>Statistics Netherlands</td>
</tr>
<tr>
<td>CO</td>
<td>Carbon monoxide</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>‘day time’</td>
<td>Time slot ‘day time’ (9:00 am – 16:30 pm)</td>
</tr>
<tr>
<td>EC</td>
<td>European Commission</td>
</tr>
<tr>
<td>EEC</td>
<td>European Economic Community</td>
</tr>
<tr>
<td>g/km</td>
<td>Gram per kilometre (notation for vehicle emissions)</td>
</tr>
<tr>
<td>g/kWh</td>
<td>Gram per kilowatt-hour (notation for emission standards)</td>
</tr>
<tr>
<td>HE</td>
<td>High Estimate (notation for high estimate scenario)</td>
</tr>
<tr>
<td>I</td>
<td>Traffic Intensity (used in $L = I/C$)</td>
</tr>
<tr>
<td>IPAT</td>
<td>Impact = Population $\times$ Affluence $\times$ Technology</td>
</tr>
<tr>
<td>IVEM</td>
<td>Center for Energy and Environmental Studies</td>
</tr>
<tr>
<td>km/h</td>
<td>Kilometre per hour (notation for speed)</td>
</tr>
<tr>
<td>L</td>
<td>Traffic Load (used in $L = I/C$)</td>
</tr>
<tr>
<td>LE</td>
<td>Low Estimate (notation for low estimate scenario)</td>
</tr>
<tr>
<td>MP</td>
<td>Most Probable (notation for most realistic scenario)</td>
</tr>
<tr>
<td>N$_2$O</td>
<td>Dinitrogen monoxide</td>
</tr>
<tr>
<td>N$_2$O$_5$</td>
<td>Dinitrogen pentoxide</td>
</tr>
<tr>
<td>NEC</td>
<td>National Emissions Ceiling</td>
</tr>
<tr>
<td>NH$_3$</td>
<td>Ammonia</td>
</tr>
<tr>
<td>‘night/ morning’</td>
<td>Time slot ‘night/ morning’ (18:30 pm - 7:00 am)</td>
</tr>
<tr>
<td>NO</td>
<td>Nitric oxide</td>
</tr>
<tr>
<td>NO$_2$</td>
<td>Nitrogen dioxide</td>
</tr>
<tr>
<td>NO$_X$</td>
<td>Nitrogen oxides</td>
</tr>
<tr>
<td>O$_3$</td>
<td>Ozone</td>
</tr>
<tr>
<td>PAH</td>
<td>Polycyclic aromatic hydrocarbon</td>
</tr>
<tr>
<td>pm</td>
<td>After noon (Latin: Post Meridiem)</td>
</tr>
<tr>
<td>PM</td>
<td>Particulate matter</td>
</tr>
<tr>
<td>PM$_{10}$</td>
<td>Thoracic fraction of particulate matter (size fraction $\leq 10 \mu m$)</td>
</tr>
<tr>
<td>PM$_{2.5}$</td>
<td>Respirable fraction of particulate matter (size fraction $\leq 2.5 \mu m$)</td>
</tr>
<tr>
<td>‘rush hour’</td>
<td>Time slot ‘rush hour’ (7:00 am - 9:00 am and 16:30 pm - 18:30 pm)</td>
</tr>
<tr>
<td>SCR</td>
<td>Selective catalytic reduction</td>
</tr>
<tr>
<td>SMART</td>
<td>Specific, Measurable, Agreed upon, Realistic and Time-related</td>
</tr>
<tr>
<td>SO$_2$</td>
<td>Sulphur dioxide</td>
</tr>
<tr>
<td>TNO</td>
<td>Netherlands Organization for Applied Scientific Research</td>
</tr>
<tr>
<td>U.S.</td>
<td>United States (of America)</td>
</tr>
<tr>
<td>VERSIT+</td>
<td>TNO road traffic emission model</td>
</tr>
<tr>
<td>VOC</td>
<td>Volatile organic compound</td>
</tr>
<tr>
<td>WHO</td>
<td>World Health Organization</td>
</tr>
<tr>
<td>$\mu g/m^3$</td>
<td>Microgram per cubic metre (notation for concentration standards)</td>
</tr>
<tr>
<td>$\mu m$</td>
<td>Micrometer</td>
</tr>
</tbody>
</table>