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Multi-objective Traffic Management for Livability

Improve Near-motorway Livability in the Netherlands

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Summary

The explosively increased traffic flow on the motorways is causing severe impact on ambient air quality and the health of those people exposed to it. Numerous diseases, such as respiratory diseases, lung diseases, and cancer, are associated with air pollutants. This is defined as the near-motorway livability problem, which seems quite serious in the Netherlands. Thus, the road authority is looking to improve air quality alongside the motorways, without compromising the current traffic efficiency.

The objective of this graduation project is therefore to find a balanced solution to improve near-motorway livability conditions. Two research methodologies are used: a literature review and a theoretical case study using simulation. Through the literature review, the research direction is determined to concentrate on the reduction of motorway traffic emissions as the way to improve the ambient air quality of motorways, thus, contribute to the enhancement of livability. Numerous strategies exist to reduce traffic emissions, and it is difficult to judge which one is better than the others. As a short term option, dynamic traffic management (DTM) is usually preferred in practice. Therefore, several DTM measures that may reduce traffic emissions have been studied, and the strategy called Mainstream Traffic Flow Control (MTFC) is adopted in this study.

MTFC is a relatively new strategy, and is considered more efficient, since it has a greater storage space than on-ramp controls. The MTFC strategy can be applied to relocate the congestion and emissions on the motorway sections near to residential areas to an upstream section which is more environmentally insensitive. What is more, MTFC will not limit the traffic flows from the on-ramps, thus it avoids increasing traffic emissions on the on-ramps, which are normally close to environmentally sensitive areas.

An MTFC strategy utilizing a combination of fixed/dynamic speed limits is used in this study, and a feedback ALINEA-like controller has been developed. A theoretical case study using VISSIM and Matlab to simulate the impacts of the proposed controller on a hypothetical motorway network has been performed. VISSIM is used to simulate the traffic flows and generate traffic and emission data, while Matlab acts as an external tool to realize the dynamic speed limit controls in VISSIM.

The simulation result is promising in reducing the traffic emissions near residential areas by 13.30% and traffic delay by 6.58%. The multi-objective optimization of the controller is performed by optimizing a generalized indicator of equally weighed traffic efficiency and traffic emissions reduction. Through tuning the regulator parameter (P) and desired

occupancy (O_c), the balanced condition is of best performance when traffic efficiency is optimized, at P = 0.4 or O_c =40.

In addition, the side-effects of the proposed controller have been studied. The traffic emissions on the motorway upstream of the target area are found to be increased. The improvement of air quality has been determined to pose no threat to climate changes in this study. But the MTFC strategy relocates the traffic risk as well as the congestion and emissions. In the upstream section, a higher crash rate is found, but the traffic safety conditions on the target section are expected to be enhanced. Apart from this, the study on driver acceptance showed that MTFC may be opposed by a few drivers, who confront the relocated congestion but do not benefit from the improved traffic flow on the target section.

Further studies could be focused on the aspects given below:

(1) Integrated network management following the four main principles of improving near-motorway livability using DTM measures; (2) take the impacts of MTFC on off-ramps into account; (3) demand management on the future induced traffic flow from on-ramps; (4) improve traffic safety in the dynamic speed limits affected section; and (5) involve a more functional traffic emission model.

Key words: Air quality, Dutch motorways, Traffic efficiency, Multi-objective optimization, Mainstream traffic flow control, VISSIM, Matlab.

Preface

This Master thesis report is the final product of my graduation work which was conducted on the behalf of Rijkswaterstaat (RWS). The research tries to provide a relatively new insight to dealing with the explosively increased motorway traffic emissions in short-term. I hope this work could contribute to further studies in this field.

During the process of study and work at Technology University of Delft, and ITS Edulab, I learned much that can support my future development. More importantly, this precious experience teaches me to better manage my life and tackle the unexpected difficulties.

My daily supervisors, Mr. Meng Wang and Mr. John Baggen from the Technology University of Delft, gave me much appreciated support during my research time. I would like to thank them for guidance in helping me build the connection between learning theories and the application of the theories to solve problems. and for their patience and critical comments.

I would like to extend my gratitude to the other committee members, Prof. Serge supervisor, Mr. Ydo de Vries , and Ms. Isabel Wilmink, for their supervisions and kind help in making the project succeeded.

I would also like to thank Mr. Ramon Landman to give me useful suggestions in developing the controller, and help me in realizing the control.

Finally, I would like to thank my parents for their support on my study aborad, and encouragement when I was facing those difficulties in study and life.

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1 Introduction

In the Netherlands, which has one of the densest motorway networks in the world, many motorways are close to residential areas. Air pollutants emitted from motorway traffic undermine near-motorway Livability through poor ambient air quality and adverse impact on human health.

Residents in the vicinity of the Dutch motorways have called on the road authorities to improve their living environment. The road authorities are hoping that improvements to Livability are not made at the expense of traffic efficiency. This thesis will examine the issue of near-motorway livability and propose a solution that meets the requirements of the two different policy objectives.

1.1 Background of the near-motorway Livability problem in the Netherlands

The Netherlands is a transport-orientated country, and most of this transport takes place by road (Ministry of Infrastructure and Environment, 2010). Road transport is considered central to the national economy, for it provides high accessibility to places such as markets, factories and companies, which are important for the international trade upon which the Dutch economy heavily depends (Linders & Odekerken-Smeets, 2006). In spite of this, transport activities give rise to environmental impacts, traffic accidents and congestion. In contrast to the benefits, the costs of the effects of transport are generally not borne by the transport users themselves (EC, 2011). These costs are called 'transport external costs', and the harm to near-motorway air quality is obviously a key aspect. Suffering from the lowered air quality in the vicinity of motorways, the people exposed are facing a high risk of illness, which has been highlighted as the main problem with near-motorway Livability[1].

To deal with the negative impacts from the transport sector, the concept of 'sustainable transport' has emerged. On a Europe-wide basis, the 2010 European Commission White Book of Transport mentioned that a modern transport system must be sustainable from an economic and social as well as an environmental point of view (European Commission, 2001). A major objective of sustainable transport is to reduce traffic emissions, like climate change related green house gas emissions (e.g. CO2), and local air quality

[1] The Livability problem in the transportation field actually includes a broad range of aspects, the provision of more transport modes, better accessibility and quiet pavements, for example (Rue et al., 2010).

related pollutants emission (e.g. PMx, SO2 and NOx). Obviously, the near-motorway Livability problem is concerned with the latter.

This thesis will be focused on the Livability problem near motorways in the Netherlands. Limited by time constraints and the author's knowledge and concerns, the scope of the Livability issue is limited to the lowered air quality alongside the Dutch motorways and the threats it poses regarding adverse impacts on the exposed people's health.

1.2 Definition of Problem

1.2.1 Near-motorway pollution problem identification

Considering the solid basis of an advanced and mature road transport, the Dutch motorway network is highly developed. Almost every town and city is connected to the motorways, some of which run quite close to residential areas, the A12 near Den Haag, A13 near Delft, and A10 near Amsterdam, for example. Those citizens who live near those motorways are enduring lowered air quality that damages their health. Thus they require the government to take Livability into account when proposing transport policies and implementing traffic management measures accordingly.

The former Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer 2 (VROM), has detected that the emission of traffic-related pollutants near motorways is at a dangerous level. The consequence is that some illnesses like lung disease are more prevalent in these areas, leading to a higher death rate (Zorana J. et al., 2010). Actions to relieve the negative impacts caused by road traffic usually bring negative impacts on traffic efficiency, such as increased travel time. It is a tough task to balance the trade-off between the objectives of maintaining traffic efficiency and improving Livability conditions near the motorways.

Dienst Verkeer en Scheepvaart[3] (DVS), is required to look for a multi-objective solution to balance those two objectives.

The problem focused on in this thesis is summarized as follows:

> In the Netherlands, lowered air quality alongside motorways poses serious threats to the exposed people's health. How can this negative impact be eliminated while maintaining traffic efficiency?

[2] In English: Ministry of Housing, Spatial Planning and the Environment.

[3] Centre for Transport and Navigation.

This thesis will look into this problem and try to find a feasible solution to attain these two objectives.

1.2.2 Research objective

Based on the problem definition, the research objective of this study is determined as follows:

> To explore a way to improve near-motorway livability without compromising traffic efficiency on motorway stretches close to residential areas in the Netherlands.

In order to realize the research objective, three main research questions and some sub-questions will be answered in this thesis:

1. *How can the near-motorway livability problem be solved?*
   - *What is the near-motorway livability problem?*
   - *What is the promising solution to the near-motorway livability problem?*
2. *How can multi-objective optimization of the dynamic traffic management measures be achieved in order to improve near-motorway livability without compromising the traffic efficiency?*
   - *Which dynamic traffic management measures may reduce motorway traffic emissions?*
   - *What multi-objective optimization methodology could be used?*
3. *How can mainstream traffic control strategy be applied to deal with the near-motorway livability problem in the Netherlands?*
   - *How can a controller be developed for the mainstream traffic flow control strategy?*
   - *How can the feasibility of the proposed MTFC strategy be assessed?*
   - *What are the impacts of the proposed MTFC strategy in terms of traffic efficiency, traffic emission, traffic safety, driver acceptance, and climate?*

1.3 Research methodology and scope

1.3.1 Research (Chapter 2-4)

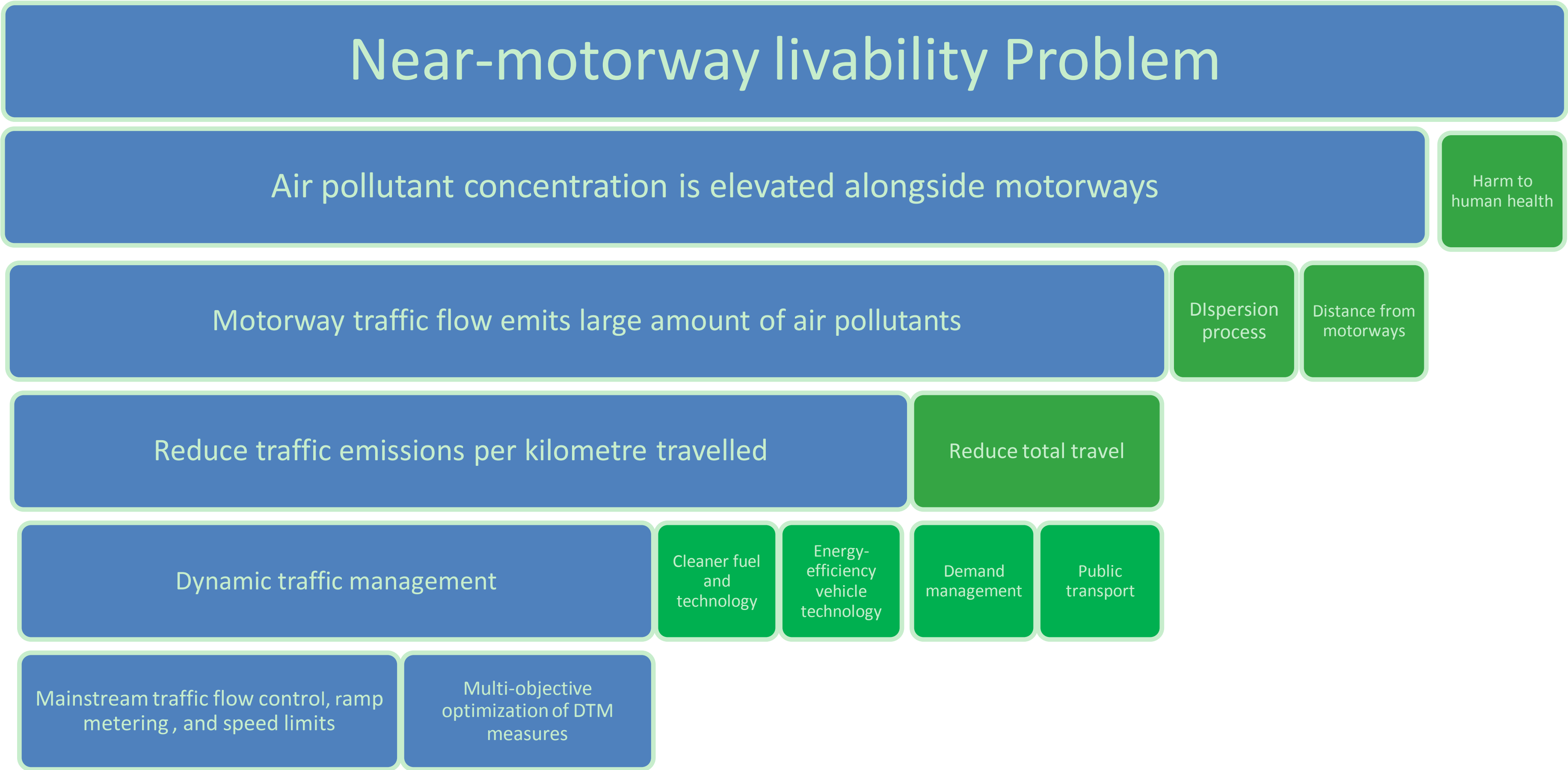


Figure 1.1: *Scoping process from Chapter 2 to Chapter 4*

The first 4 chapters actually represent the scope process (the blue parts are mainly discussed in this study) as indicated in the figure above. The research first studies the literature relevant to the near-motorway livability problem in the world and the Netherlands. Then I determine traffic emission reduction as the research direction to solve this problem. The next process is to systematically scan the possible approaches for improving the air quality. Given as a short-term option, dynamic traffic management is deemed as a promising solution. Subsequent to this is a study of the dynamic traffic management measures that may reduce motorway traffic emissions, and ways to optimize them to serve different objectives.

1.3.2 Design and case study (Chapter 5-7)

The work undertaken in this section is as indicated in the figure below. Based on the findings in the research section, a dynamic traffic management strategy will be selected and an accordingly controller will be designed. Then a case study using simulation will be conducted to analyze the feasibility and impacts of the proposed controller. The micro-traffic model simulation software VISSIM and the external control tool Matlab will be used to perform the simulation.

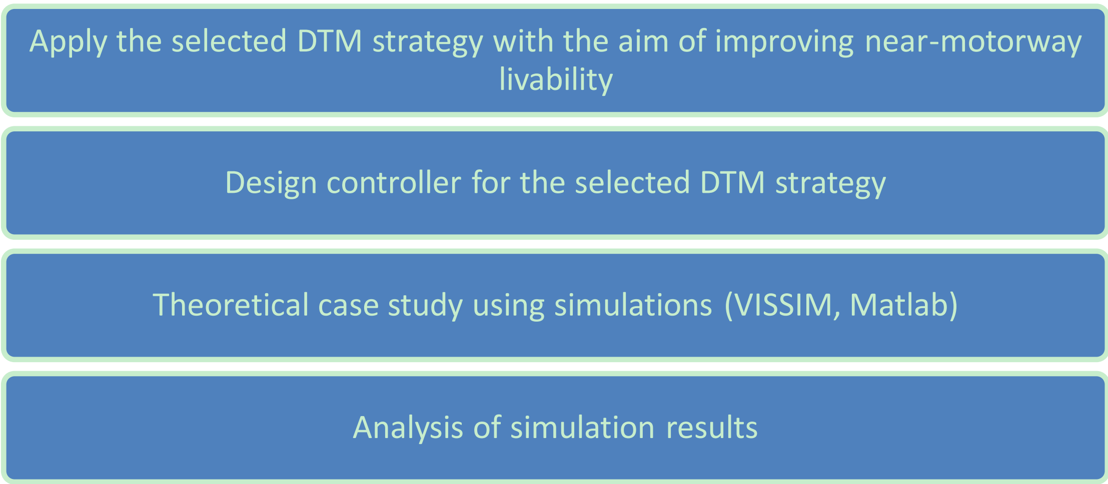


Figure 1.2: *Work process from Chapter 5 to Chapter 7.*

1.4 Reading guide

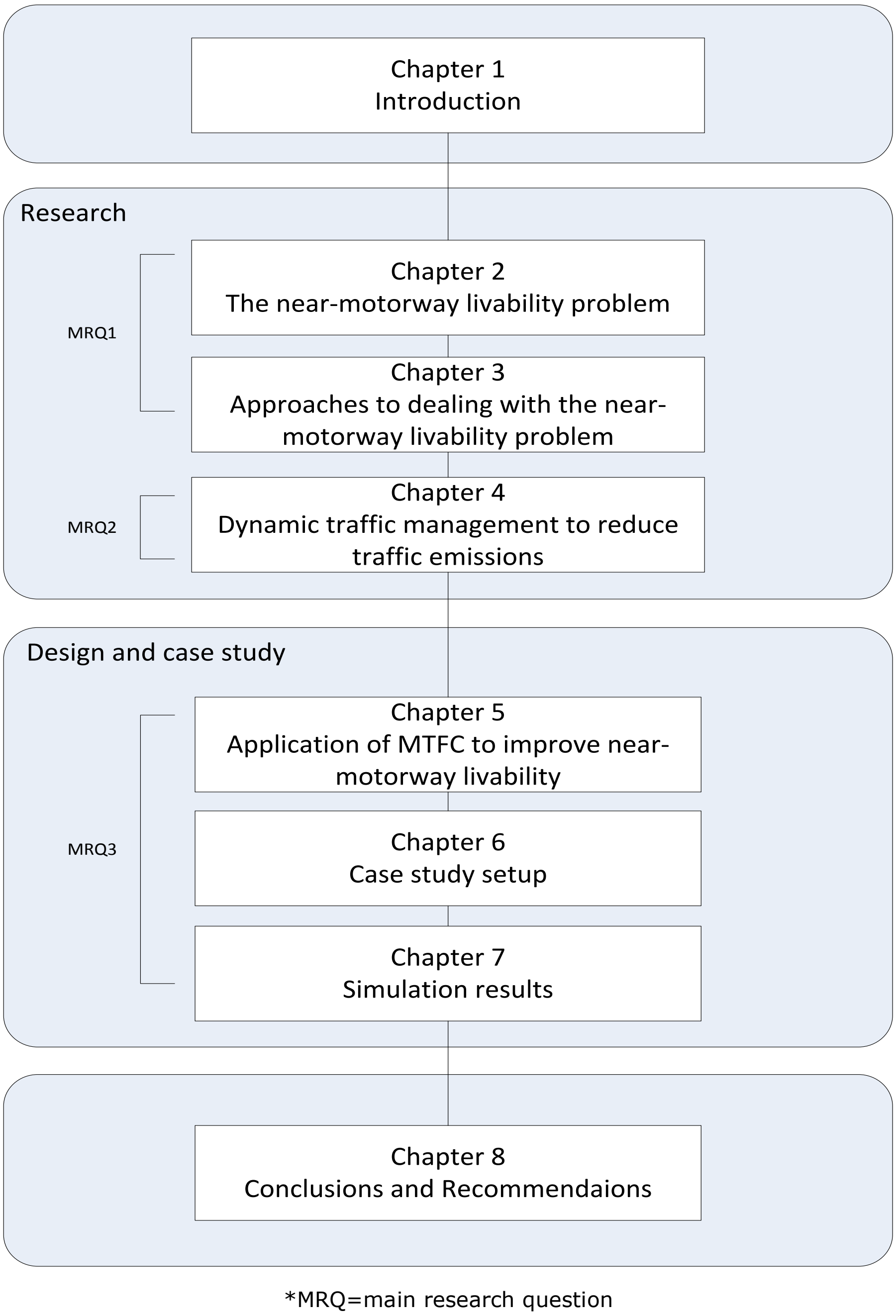


Figure 1.3: *Thesis structure overview.*

Figure 1.3 sketches the thesis structure which provides the readers with a reading guide.

Chapter 2 introduces the general livability problem in different countries. Included is the analysis of how motorway traffic emissions impact the ambient air quality to determine the study direction for the remaining sections.

Chapter 3 reviews the existing solutions to the near-motorway livability problem. Dynamic traffic management, cleaner fuel and vehicles, energy-efficiency vehicle technology, demand management, and public transport are further analyzed. Based on the analysis, dynamic traffic management is deemed as a promising solution in the short-term for the Netherlands.

Chapter 4 analyzes three DTM strategies that may reduce motorway traffic emissions and then introduces a multi-objective optimization concept for the DTM measures, in order to deal with the different objectives.

Chapter 5 applies the MTFC strategy to improve near-motorway livability, and develops an ALINEA-like controller.

Chapter 6 outlines the setup of a theoretical case study. The case study method, software selection, setting and calibration, and other related preparation tasks are included in this chapter.

Chapter 7 summarizes the case study results, and analyzes the effectiveness of the proposed controller and its impacts on network performance.

Chapter 8 summarizes the research process, and answers the three main research questions in conclusion. Finally it proposes several recommendations on the policy and operational levels.

2 The near-motorway livability problem

The near-motorway livability problem in the Netherlands as defined in Section 1.1 refers to a local living environment issue. In detail, it is the issue that the elevated concentrations of air pollutants alongside the Dutch motorways pose threats to human health.

Near-motorway livability is complicated and involves many aspects. This chapter tries to explain how motorway traffic emissions affect the air quality, and narrows down the research scope for the remainder of this thesis.

In this chapter, the research question given below will be answered:

- ***What is the near-motorway livability problem?***

This chapter starts with a literature review on the issue of near-motorway traffic emissions (Sections 2.1 & 2.2). Section 2.3 illustrates how motorway traffic emissions impact the ambient air quality to determine the direction for the rest of the study.

2.1 The near-motorway Livability problem in the world

Air quality alongside motorways is deteriorating, and people who are exposed to those air pollutants are experiencing a high risk of becoming unhealthy. This viewpoint has been proven by many studies throughout the world.

Brugge (2007) and his colleagues from Tufts University published a report, 'Near-highway pollutants in motor vehicle exhaust: A review of epidemiologic evidence of cardiac and pulmonary health risks', to summarize the previous studies and discuss the traffic pollution issue in the areas near highways. Increasing evidence shows that a range of traffic pollutants are elevated at downwind locations near motorways. People who live or spend a long time within approximately 200m of motorways are exposed to these pollutants, more than those living at more distant locations, and even face more severe conditions compared with those living on busy urban streets.

Table 2.1 summarizes some key studies which link health effects to heavy traffic flows in different countries, primarily in Europe and the US.

Table 2.1: Previous studies on the impacts of traffic pollutants on air-quality and health

Researchers	Study location	Findings
Jermann, et al. (1989)	Germany	This is a study on 48 children, who lived in an area with high traffic density, and 72 children, who lived in a small city with low traffic density. The blood levels of benzene in children who lived in the high-traffic-density area were 71% higher than those of children who lived in the low-traffic-density area. What's more, the blood levels of toluene and carboxyhemoglobin were also substantially higher (56% and 33% higher, respectively) among children long-term exposed to vehicle emissions. The diseases, Aplastic anemia and leukemia, are considered related to the long-term exposure to benzene.
Edwards, et al. (1994)	Birmingham, United Kingdom	This study determined that living near major roads was linked to the risk of hospital admission for asthma in children. Children admitted with asthma were substantially more likely to live in an area located along a main road.
Duhme, et al. (1996)	Munster, Germany	This study revealed the relationship between truck traffic and asthma symptoms. This study was taken by analyzing the questionnaire forms filled by 3,703 German students who were between the ages of 12-15 years in 1994-1995. The associations between both wheezing and allergic rhinitis and truck traffic were determined. Other possible confounding variables, including indicators of socio-economic status, smoking, etc., did not influence the associations largely.
Knox and Gilman (1997)	United Kingdom	This study found a cancer corridor within three miles of major polluters, including motorways, airports, power plants, etc. By analyzing the data related to the children who died from cancers during 1953-1980, including the places where they were born and died, research found the areas within a few hundred yards from the pollution facility (including motorway) are of the most dangerous. This risk decreases when people get away from those pollution facilities.
Szagun and Seidel (2000)	Baden-Wurttemberg, Germany	This study compared the effect of traffic-related air pollution and traffic accidents. The result indicated that the number of deaths caused by motor vehicle emission is much more than that caused by traffic accidents.
Wilhelm, Ritz (2002)	Los Angeles County, United States of America	This study found those women, who live near high traffic, have a higher risk (around 10-20%) of bearing infants with a symptom of premature birth and rather low weight. Statically, the risk of low birth weight and premature birth increase 19% and 11% respectively, with the one part per million increases in annual average carbon monoxide concentration.
Lin, Munsie, Hwang, Fitzgerald, and Cayo (2002)	Erie County, New York, United States of America	This study found that children living in the areas, which are within 200 meters of the heavy truck traffic, are in a higher risk of suffering from asthma. The study was based on the hospital admission records for asthma among those children (ages 0-14) and residents living close to heavy traffic.

Zhu, Hinds, Kim, Sioutas (2002)	Southern California, United States of America	This study observed an approximate 250% higher concentration of ultrafine particles in the air near Interstates 405 and 710. The pollution decreased back to normal level steadily about 300 meters, downwind from the motorway. Apart from that, researchers found the ultrafine particles are more toxic than larger particles, even though they have the same chemical composition.

The results of these previous studies have revealed that exposure to motorway traffic pollution, especially particulates, has an adverse impact on cardiovascular health and lung function. In addition, a strong association has been found between traffic pollutants and cancer, low birth rates, asthma and other respiratory diseases. The table below summarizes the association between the health effects and vehicular pollutants:

Table 2.2: *Health effects associated with vehicular pollutants*

Pollutants	Health effect
Lead	Ingestion of lead aerosols has been linked to cardiovascular disease, brain and kidney failure. Chronic effects include behavioural and development problems among children, elevated blood pressure, problems with metabolizing Vitamin D and anemia. Exposure to lead has also been associated with decreased sperm count in men, and increased likelihood of spontaneous abortion among pregnant women.
Particulate matter	Causes cardiopulmonary diseases, cardiovascular diseases, respiratory diseases, lung cancer and other cancers.
VOC	Toxic and precursor of ozone formation. It is also known to cause harmful effects on the immune system, the neural network and haemoglobin.
NO_2	NO_2 has been shown to have toxic effects on human health, including altered lung function, respiratory illness and lung tissue damage.
CO	CO causes oxygen deprivation (hypoxia) displacing oxygen in bonding with haemoglobin. This can cause cardiovascular and coronary problems, increase risk of stroke and impair learning ability, dexterity and sleep.
Ozone (O_3)	Ozone is dangerous to human health: it interferes with respiratory functions, leads to reduced lung capacity and increases the intensity of lung infections.
SO_X	So_x is associated with various bronchial conditions, which can be acute even at relatively low levels of exposure for children and asthma patients.

Source: (Gorham, 2002).

Those studies also suggest that children and older people are particularly easily negatively affected by traffic pollutants. Moreover, studies have shown that girls tend to experience higher risk than boys. The next section looks at this issue in the Netherlands, where this thesis is conducted.

2.2 The near-motorway livability problem in the Netherlands

As a whole, air quality in the Netherlands has been considerably improved in recent years as the result of a large reduction in traffic pollutants emissions. Nevertheless, NOx and PMx concentration levels are still rather critical, especially alongside the motorways (McCrae, 2009).

A motorway is a type of broad highway designated specifically for high speed traffic and without traffic lights. The density of the Dutch motorway network is 57.5 kilometre per 1,000 km^2, the densest motorway network in the European Union. Some motorways, such as the A12 near Den Haag, the A13 near Overschie (Rotterdam), and the A10 near Amsterdam, are close to residential areas. Brauer, et al. (2003) from Utrecht University conducted a study that focused on explaining the variability of annual traffic pollutant concentration caused by traffic-related variables, and found that air quality along Dutch motorways is seriously deteriorating.

Figure 2.1: *One stretch of A13 across through Overschie area, indicating that numbers of houses are located 200m (radius of circle is 200m long) of the motorway.*

Figure 2.1 above is derived from Google Maps and depicts the A13 motorway through Overschie. In this area, the distance between the A13 and the nearby residential areas is extremely small. In the figure, the yellow radius line is 200m long, i.e. the area covered by the yellow circle is within 200m of the motorway. Evidently, a lot of buildings are located within 200m of the motorway. The studies in the previous section have pointed out that residents living within 200m of motorways suffer from the traffic emissions. In fact, this is reported as a critical environmental problem in the Overschie area. The negative impacts on human health caused by motor vehicle emissions determined by the studies have proven the validity of the local residents' concerns about their health. Considering the problem as a matter of endangered health, instead of exceeded environmental threshold values, they called for the Ministry of Transport to take action.

Indeed, not only in Overschie, but across the Netherlands, most people are exposed to motorway traffic pollution. According to the Asthma Fund in the Netherlands, 275 primary schools are too close to a motorway, which means roughly 60,000 children attend schools that are less than 300m from a motorway. Within these distances, there is a high risk of pollution from soot particles, says the Asthma Fund (2011).

Apart from the Asthma Fund, in the Netherlands, other researchers have conducted many studies, too. As early as 1973, a study of 1498 children in 13 schools conducted in the Province of South Holland succeeded in establishing a relationship between school proximity to motorways and asthma prevalence (Speizer & B. G. Ferris, 1973). This was the first time in the Netherlands that traffic pollution was connected with human health (in this case children were the research target, because they easily influenced by traffic pollution). The next study focusing on traffic pollution and children's health was carried out 24 years later when Van Vliet et al. (1997) continued to investigate truck traffic intensity and the concentration of emissions detected in near-highway schools. Through a study of 1068 Dutch students, they found that those students living within 100m of motorways suffered much more from asthma, wheezing, coughs, and runny noses, of which asthma (particularly among girls) was found to be strongly associated with the increasing density of truck traffic.

In regard to adults, a study in 2002 looked at the adverse impacts of long-term exposure to traffic pollution on 5000 adults. The result showed that those people, who lived near motorways were experiencing twice the risk of dying from heart or lung disease and 1.4 times the risk of dying from any cause in comparison with those people living away from motorways (Hoek, Brunekreef, Goldbohm, Fischer, & van den Brandt, 2002).

Looking at the studies listed in Section 2.1, near-motorway Livability in the Netherlands is as same as in other countries. Heavy traffic flow brings traffic pollutants to lower ambient air quality, which makes those people exposed suffer a higher risk of becoming unhealthy.

2.3 How motorway traffic emissions contribute to the near-motorway Livability problem

The process of motorway traffic emissions impacts on the ambient air quality and human health as exhibited in the figure below:

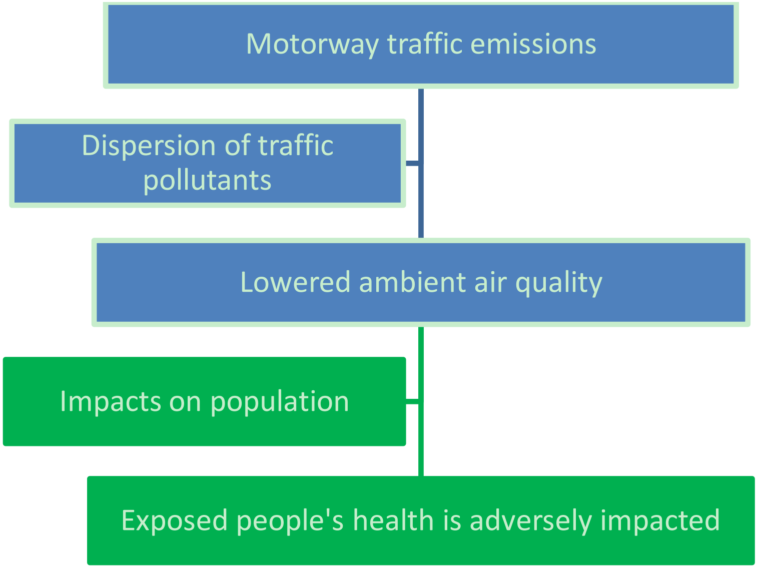


***Figure 2.2:** Pictorial representation of the near-motorway Livability problem.*

This section will focus on the impacts of traffic emissions on ambient air quality (the blue part). Air quality could be used as the indicator of exposure to the air pollutants, rather than a direct measure of this exposure (and human health) (McCrae, 2009). How human health is impacted by air pollutants is a rather complicated and disputed issue (see Appendix A for more information). Moreover, Rijkswatersttat does not have an exact plan to study the human health issue. Thus the green part is not discussed in this thesis.

2.3.1 Air quality standards

Air is a form of mixed gases which we breathe every day. Pure air consists of 21% oxygen and 78% nitrogen by volume, along with other substances and gases (Health-Canada, 2006). 'Air quality' stands for the purity of the atmosphere, viewed in regard to the concentrations of the air pollutants (solid, liquid or gaseous).

The European Union (EU) has developed an extensive range of health-based standards in terms of concentrations. In general, air quality can be viewed as safe if the concentration of air pollutants meets those standards.

The air quality standards on sulphur dioxide (SO2), NO2, oxides of nitrogen (NOX), particulate matter (PM10), benzene, carbon monoxide (CO), ozone, etc. are established in the 'Daughter' directives of the European Council Directive 96/62/EC. In 2005, the standard on PM2.5 was introduced in the new Air Quality Directive (European Commission, 2011). Further, in 2008, the new directive - Directive 2008/50/EC - came into force.

In Dutch national law, the Europe Directives on air quality have been transposed as the Air Quality Decree. Viewing these standards as absolute limits rather than targets, the legislation is more strictly applied in the Netherlands than in most other EU members (Reeves, Bendall, McCrae, & Boulter, 2008). In the Netherlands, PMx and NOx are considered as the two critical traffic-emitted pollutants (Wismans, Berkum, & Bliemer, 2011). Table 2.3 lists their definition and the relevant European standards in terms of concentration.

Table 2.3: *Definition and European norms with respect to PMx and NOx.*

	Pollutants		
	Nitrogen oxides (NOx)	Particulate matter (PMx)	
Definition*	NOx is comprised of different kinds of gases composed of oxygen and nitrogen. With the impact of sunlight, these gases transform into acidic air pollutants, like nitrate particles.	PMx is also known as airborne particles or simply particles. The major components are very small solids and/or liquids. PMx changes largely in chemical composition and size. Generally, PM10 depicts particles of 10 µm or less in diameter, which can be further classified into coarse particles ($PM_{2.5-10}$) and fine particles ($PM_{2.5}$).	
European norms for NOx and PMx expressed in*	NO_2	PM_{10}	$PM_{2.5}$
Concentration	200 µg/m3	50 µg/m3	25 µg/m3
	40 µg/m3	40 µg/m3	
Averaging period	1 hour	24 hours	1 year
	1 year	1 year	
Permitted exceedences each year	18 days	35 days	n/a
	n/a	n/a	

*The definition section was derived from source: http://www.hc-sc.gc.ca/ewh-semt/air/out-ext/effe/talk-a_propos-eng.php
**The norms were derived from source: http://ec.europa.eu/environment/air/quality/standards.htm

It must be noted that the air quality pollution legislation introduced here is not only focused on the near-motorway air quality, but is on a nationwide basis (e.g. urban areas). However, the high density of population and high level of traffic make it difficult to meet those standards in the Netherlands, particularly in the vicinity of the motorways.

2.3.2 Contribution of traffic emissions to the lowered ambient air quality

The sources of air pollutants are diverse, and comprise both natural and human sources. Table 2.4 lists some major sources of air pollutants.

Table 2.4: *Example sources of air pollutants*

Types	Sources
Natural	Smoke from forest fires, wind-blown dust from soil and volcanoes, bacteria, fungi and chemicals released by plants and animals.
Human activities	Motor vehicle exhaust, industrial processes (pulp and paper mills, ore smelters, petroleum refineries, power generating stations and incinerators), and the burning of fossil fuels such as gas, oil, coal and wood.

*Source: http://www.hc-sc.gc.ca/ewh-semt/air/out-ext/effe/talk-a_propos-eng.php

Among the air pollutant sources listed in table above, traffic flows have been blamed for generating a large amount of traffic pollutants to lower the air quality (Krzy anowski, Kuna-Dibbert, & Schneider, 2005). Motor vehicle traffic emissions are widely considered to be the single largest contributor to ambient air pollution in many developed countries (Pereira, 2011). In detail, traffic can be responsible for 20% of the total PM10-Concentration and can locally be responsible for 60% of the total NO2-Concentration (Beek et al., 2007).

Air pollutants from traffic emissions comprise diverse compositions, among which some well-known traffic pollutants are carbon monoxide, nitrogen and sulphur oxides, unburned hydrocarbons (from fuel and crankcase oil), particulate matter, polycyclic aromatic hydrocarbons, and other organic compounds that derive from combustion.

2.3.3 Factors that influence ambient air quality

In the vicinity of motorways, the concentrations of the pollutants, which are used to assess the air quality, are mainly affected by traffic density, wind speed, wind direction and the distance from motorways (Zhu, et al., 2002).

Among the 3 factors:

- Traffic density influences the total amount of traffic pollutant emission: The heavy traffic density increases the pollutant concentration near motorways.
- Wind speed/direction influence the dispersion process of the emitted pollutants: The stronger the wind, the less the concentration of pollutants; and higher concentrations are observed at downwind locations than at upwind locations.
- Distance factors also have influence on traffic pollutant dispersion: As the distance from the motorway increases, the pollutant concentrations are decreased, e.g. in the vicinity of motorways, the pollutant concentration right

near the motorway could be 25 times greater than the concentration at a location 300m downwind of the motorway (Zhu, et al., 2002).

Dutch researchers concluded a set of more comprehensive factors that influence the air quality near motorways as given below:

- The background concentration: for example, the background air originating from the continent.
- The location and surroundings of the motorways: this will influence the dispersion.
- The type of road surface: different types of surface have their own characteristics.
- The nature of the traffic on the road: e.g. volume, composition and speed, and vehicle emission characteristics.
- The distance of the location from the road: the concentration decreases as this distance increases. Eventually, it approaches the background concentration.
- The meteorological conditions: they affect the chemical transformation and dispersion of pollutants.
- The time of year: for example, in winter, more maintenance activities will contribute to the concentration of PMx.
- Factors that affect the rates of chemical transformations: e.g. light intensity (McCrae, 2009).

Another study also indicated that the computation of air pollutant concentrations is dependent on (a) the amount of emitted traffic emissions and (b) the dispersion process (Beek, et al., 2007).

On the basis of the studies above, it could be concluded that there are three main factors as indicated in the figure below that influence the air quality alongside the motorways.

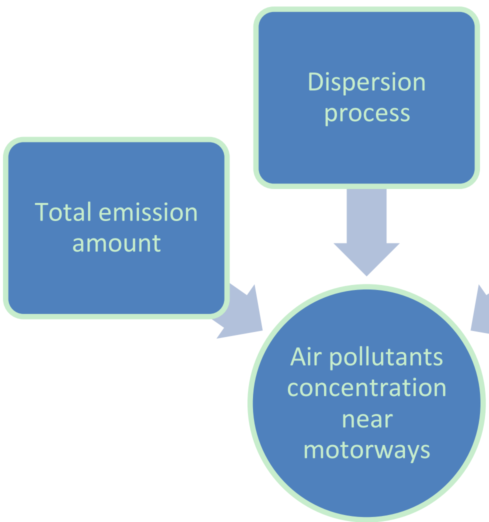


Figure 2.3: *Three main factors that influence air pollutant concentration alongside motorways.*

2.3.4 Dutch response to the deteriorating air quality near motorways

In order to meet the air quality standards, a number of strategies and measures have been launched in the Netherlands, like the National Cooperative Air Quality Programme, which essentially comprises a package of policies to improve Dutch air quality. Furthermore, precise initiatives to improve the air quality near the Dutch motorways are:

- Reduction of speed limits on the certain motorway sections, in 2005
- Air Quality Innovation Programme (IPL) established in 2005

However, it appears that the existing approaches will not guarantee compliance to the air quality standards: more measures and policies are needed (McCrae, 2009).

From the perspectives of the factors that influence the air quality, these measures and policies could be aimed at either reducing the traffic's contribution to the air pollutant concentrations (reduce the total amount of traffic emissions), or influencing the dispersion of air pollutants.

The research direction of the remainder of this study will pay attention to the first choice, namely air pollution prevention, since it may be more effective and easy for human intervention.

2.4 Conclusion

Based on the studies on the near-motorway livability problem in different countries, it can be concluded that vehicular pollutants have been determined to be associated with quite a number of issues, including cardiac and pulmonary diseases, cancer, low-birth rate, asthma, and other respiratory diseases, etc.

Health-based air quality standards are the response of the European Union to the severer situation caused by traffic pollution. Three factors that influence the air-quality near motorways are: total emission amount, dispersion process and distance from motorways, of which the total emission amount is relatively easy to influence. Thus, this thesis will only concentrate on how to reduce motorway traffic emissions in order to improve livability in the vicinity of motorways in the Netherlands.

3 Approaches to dealing with the near-motorway livability problem

Chapter 2 shows that elevated concentrations of air pollutants result in exposed people in the vicinity of motorways experiencing high risks of becoming unhealthy. In addition, the factors that influence air pollutant concentrations are illustrated, out of which this thesis will focus on ways to reduce the amount of traffic emissions by intervening in the motorway traffic flow, in order to improve the ambient air quality.

This chapter will compare the possible approaches to further narrow down the research scope to a promising way to reduce traffic emissions in the Netherlands.

In this chapter, the following question will be answered:

- ***What is the promising approach to the near-motorway livability problem?***

Section 3.1 gives an overview of popular possibilities to reduce traffic emissions from the literature. Section 3.2 elaborates on the shortcomings of each approach. Section 3.3 compares the given alternatives based on the time dimension and the factors that influence traffic emissions. It concludes eventually, that given as a short-term option, dynamic traffic management is preferred in the following study in this thesis.

3.1 Systematic overview of the approaches to reducing traffic emissions

Comprehensive approaches exist to reduce traffic emissions, as concluded by Gorham (2002):

- **Technical approaches**

Vehicle technology and fuel technology, etc.

- **Systemic approaches**

Dynamic traffic management (traffic speed control, smoothing traffic flow, restraining traffic flow, etc.) and congestion pricing, etc.

- **Behavioural approaches**

Policy approaches to reduce the amount of travel or to encourage the use of alternative modes to reduce polluting car use. Examples include encouraging public transport, land planning to reduce travel need, etc.

Litman (2011) also summarized the approaches to reduce emissions, which fall into two major categories:

- **Per unit emission reduction**:

Efficient vehicle technology, fuel efficiency standards, and cleaner energy, etc.

- **Total vehicle travel reduction**

Demand management (like congestion pricing, distance-based fees), promoting public transport (like transit encouragement), etc.

Although the classification methods are different, the approaches in Gorham's study are coherent with Litman's. These approaches either focus on reducing the per-unit emission or reducing total travel demand.

In general, there are five major sound approaches:

- Dynamic traffic management[4] (DTM)
- Cleaner fuel and vehicles
- Energy-efficiency vehicle technology
- Demand management
- Public transport

In the following sections, the benefits of using these approaches on traffic emission reduction and some practical examples of these approaches will be briefly elaborated.

3.1.1 Dynamic traffic management

Basis of dynamic traffic management

Many studies, for instance, Traffic Control system Handbook (2005) published by the US Department of Transportation, have stated that three key indicators of traffic flow are:

- Flow (q) = Number of vehicles passing a certain point during a given time period, in vehicles per hour (veh/h)
- Speed (v) = The rate at which vehicles travel (km/h)

[4] Some certain DTM measures are used to restrain the traffic inflow. It is, however, different from demand management. DTM is efficient at influencing traffic flow once travellers are in their automobiles or have decided to use them; while demand management is effective for influencing people's demand to make a trip prior to the decision being made (Schreffler, 2011).

- Density(k) = Number of vehicles occupying a certain space. Given as veh/km/lane.

The fundamental equation that reflects the relation between those indicators is:

$$k = q / v$$

Figure 3.1 shows the fundamental diagram reflecting the relationship between the flow, speed and density. Note that the situation shown is ideal, but the actual traffic flow is dynamic, depending on the variability in traffic demand and traffic supply.

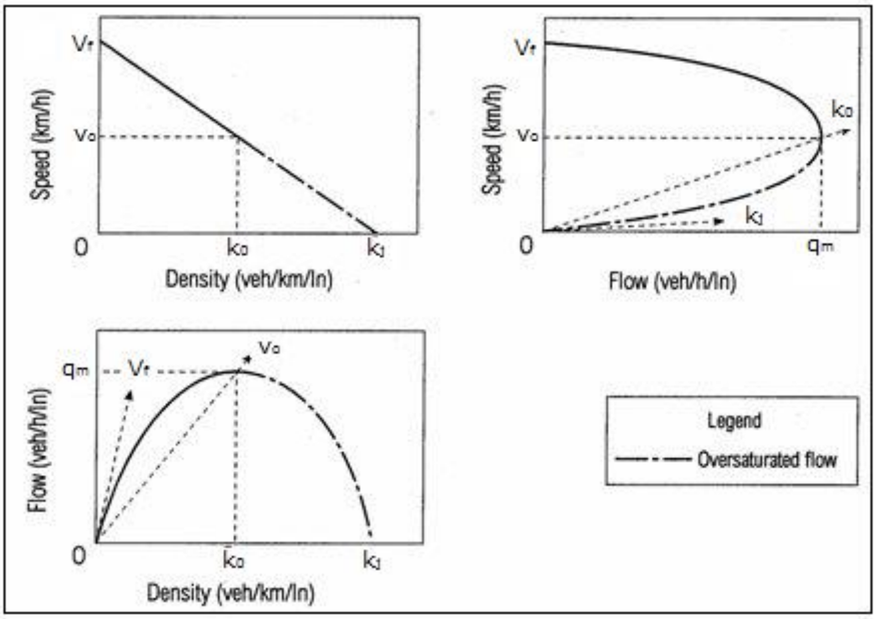


Figure 3.1: *Generalized relationships among Speed, Density, and Flow Rate on uninterrupted-flow roads. Source: (Gordon, et al., 2005)*

Free flow speed (V_f) remains in light traffic conditions until density reaches the critical density (k_0), meanwhile, the traffic flow reaches the maximum flow (q_m). Apart from that, speed is decreased to V_0, corresponding to the critical density. When the density exceeds the critical density, the flow starts to decrease until the density reaches the jam density (k_j), where all traffic is stopped. When the density is below the critical density, the flow keeps stable and free. When the density is in excess of the critical density, the flow becomes congested, and the motorway capacity decreases.

Obviously, if the density can be maintained extremely close to, but still under, the critical density, the motorway can operate at its full capacity and traffic throughput is optimized. This is impossible without human intervention, since modern traffic is as variable and unpredictable as the weather (Rijkswaterstaat, 2003).

Benefits of using dynamic traffic management

Dynamic traffic management has been developed in response to the dynamic traffic conditions. It associates the rising congestion problem and the environmental problems, making better use of road network capacity (TNO, 2010). The collection, processing, integration and presentation of reliable data on traffic flow will make a great contribution to eliminating congestion and reducing the adverse environmental effects of transportation (Civitas, 2011b).

An example is that in the Netherlands, a project called '80km zone' was tested in five trial locations to observe its impact on the reduction of traffic emissions. The results showed a local reduction of NOx by 20-30% and PMx by 10%[5] (Stoelhorst, 2008).

Another example is the lorry restraining system in Hagen, Germany. In the case where the concentration of air pollutants (e.g. NOx) exceeds the threshold, access of lorries larger than 3.5t will be restricted. The model calculations of NOx and PMx reduction were 14% and 11%, respectively (Eltis, 2008).

3.1.2 Clean fuel and vehicles

Clean fuel and vehicles refers to promoting the use of hydrogen fuel cell, bio-fuel, compressed natural gas (CNG), electric-vehicles, and hybrid vehicles. Fewer or even zero traffic emissions can be realized by using clean fuel and vehicles, by which many expect to achieve the independence from fossil fuel and high oil prices, and contribute to a green transport system.

In Europe, numerous projects have been conducted to promote the use of clean fuel and vehicles. The CNG promotion campaign was implemented in Bremen, Germany from 2002-2006, forming a CNG fleet of 297 vehicles. The CNG fleet showed a reduction in NOx emissions of 77%, and a reduction in PM10 off 99% compared with the use of diesel (Civitas, 2011c). In Bristol, electric vehicles and vehicles using liquefied petroleum gas have been introduced in the city, with the aim of reducing PMx and NOx emissions (Civitas, 2011a). Other similar projects includes the support for clean fuel and clean public and private fleets in Burgos, Spain; transition towards a clean vehicle fleet in Genova, Italy; and bio-fuel and clean vehicles in Donosita, Spain.

[5] In some locations, extra congestion was observed

3.1.3 Energy-efficient vehicle technology

With an increase in the efficient use of energy, lower fuel consumption and lower traffic emissions are expected. The attempt to improve energy-use efficiency by enhancing vehicle technology can be realized in diverse ways, most of which are aimed at using energy more efficiently. Improving gearboxes to reduce fuel consumption is one of the promising measures, according to Borgmann (2010). For example, by improving the dampers and oil pumps in conventional automatics, an economy improvement of 3% with gasoline engines and 6% with diesels is expected. Some other examples include:

- **Lightweight Materials**
  An effective way to improve fuel-efficiency is to reduce the weight of the vehicle. However, reducing weight with the same materials and structural design may compromise passenger safety. Therefore, newer vehicles are making extensive use of advanced materials such as composite or plastic body panels, and high-strength, lightweight aluminium structural components. Furthermore, conventional materials can improve safety while reducing weight, if more sophisticated structural designs are used.
- **Decreased Resistance**
  Another way to improve fuel efficiency is to decrease resistance, such as the resistance between the wheels and the road, or wind resistance. Rolling friction can be limited through the use of low-resistance tyres. Wind resistance can be decreased through redesigning the body to a more aerodynamic shape.
- **Variable Valve Timing**
  Computers can be used to electronically adjust valve timing to optimize engine efficiency. This improved efficiency can be used to lower fuel consumption and/or increase power output. Variable valve timing is currently available on many passenger vehicles.
- **Cylinder Deactivation**
  Fuel consumption can also be reduced through cylinder deactivation. When less power is needed, one or more engine cylinders can be deactivated. These cylinders can then be reactivated if power needs increase.

Actually, the strict European Union standards for vehicle emissions have pushed vehicle manufacturers to improve their products to be cleaner.

3.1.4 Demand management

The impacts of transport on air quality are closely related to travel distance. Demand management aims at reducing total vehicle travel, leading to lower fuel consumption and less pollution. Road pricing is an effective demand management measure that is widely used in European countries, since it can reduce traffic demand and also internalize the external cost, which is the negative impact caused by the drivers, but not borne by them (Hau, 1992).

Some projects have been conducted in urban areas, for example:

In Stockholm, a congestion tax was implemented aimed at eliminating congestion and reducing emissions in the city centre. This project defined a cordon around the city centre and charges a variable fee for vehicles crossing the cordon between 6:30 am and 6:30 pm. The result of this road pricing showed a 14% reduction in vehicle kilometres travelled and a 10-14% decrease in emissions (Doan, 2010).

In 2003, a congestion pricing project was introduced in London. The concept is similar to the congestion tax in Stockholm in that a cordon around central London was defined. Vehicles crossing the cordon between 7:00 am and 6:00 pm will be charged. The result of this project showed an average decrease of 70,000 vehicle trips compared to the year before the congestion pricing. This has definitely contributed to traffic emission reduction in the central area of London. Just in 2003, the total NOx emissions in the cordon area were reduced by 12%, and the PM_{10} was reduced by 11.9% compared with the traffic emission situation in 2002 prior to the implementation of congestion pricing (Beevers & Carslaw, 2005).

Apart from these, some road pricing projects have focused on countrywide motorways and are distance-based, for example:

In Germany and the Czech Republic, all trucks, irrespective of national registry, have been charged countrywide since 2005 and 2007 respectively. A main objective in both projects was to promote the shift from polluting trucks to cleaner vehicles. Although it is difficult to conclude the resulted emission reduction, the environmental benefits in these two countries can be evidenced by the incentives for cleaner vehicles and the movement of fewer empty trucks (Doan, 2010).

In the Netherlands, a road pricing project is in process. This project plans to charge a distance-based fee for trucks countrywide by 2012 and for all vehicles by 2018. A major goal of this project is to enhance the environment.

3.1.5 Public transport

Public transport provides a more environmentally friendly transport option. Although sometimes a public transport vehicle fleet generates more air pollutants than individual vehicles, the reduced amount of vehicle trips is expected to lead to lower total traffic emissions (Gorham, 2002). It is probable that promoting public transport is able to address congestion problems as well as air quality problems.

Most European countries have already developed public transport services, like trains, trams, buses and metros. Since motorways often connect several cities, most motorway users travel between cities. Public transport services for those drivers could be trains, the metro, tram and buses. Trains can meet either short or long distance travellers' demand, whereas metro, tram and bus usually serve short distance travellers.

A successful example of promoting public transport to reduce private vehicle use is the integrated regional public transport service in Germany, Austria, and Switzerland. The proper coordination of fares and services has substantially enhanced the quality of the public transport, which offers a real alternative to private vehicles region-wide (Pucher & Kurth, 1995). A higher usage of public transport has been found after the implementation of this integrated regional public transport service.

In regard to railway systems, the high speed train (HST) has been proven to be competitive against private cars. A study focused on the HST service between Madrid-Barcelona estimated a 10% decrease in private car use after the introduction of HST (GONZÁLEZ - SAVIGNAT, 2004).

3.2 Shortcomings of the approaches to reduce traffic emissions

In this section, the shortcomings of these approaches towards reducing per unit traffic emissions and reducing total vehicle travel will be illustrated respectively.

3.2.1 Shortcomings of the approaches that reduce per unit emission

The major shortcomings of each approach are as elaborated below:

DTM measures can be used to reduce motorway traffic emissions. If these measures, however, can also contribute to increasing the effective capacity of existing motorways, additional traffic demand may be induced (Gorham, 2002). This induced traffic causes extra emissions that may result in less emission reduction or even increased emissions compared with the situation before the implementation of the DTM measures. Another shortcoming of DTM is that it is a short-term option, which implies a limit in meeting the explosively increasing traffic demand in future (Weng, 2010).

The disadvantage of using bio-fuel is that its effectiveness in reducing PMx and NOx emission is disputed. Daniel, et al. (2006) indicated that bio-fuel produces fewer particulate matters compared with diesel when the engine is in a steady state, but emits more when the engine is in a transient state. In regards to NOx, bio-fuel performs much worse in that it produces large amounts of NOx. In regard to hydrogen fuel cells, they are still a rather unrealistic technology. However, in the long term, hydrogen technology and the new generation of bio-fuels, which are expected to perform better in traffic emission reduction, will play a more important role (Uyterlinde, Wilde, & Hanschke, 2009).

The main shortcoming of clean vehicles and efficient vehicle technology is that it is less possible to replace normal vehicles in the short term. Most energy-efficiency technologies are still in various stages of development and have not yet proven marketable to most consumers (D. Yacobucci, 2004). In regard to electric and hybrid vehicles, the high additional cost (mainly due to the cost of battery) is an obstacle for large scale market penetration (Uyterlinde, et al., 2009).

3.2.2 Shortcomings of the approaches that reduce total vehicle travel

The major disadvantages of these approaches are as elaborated below:

One shortcoming of demand management is that it is likely to confront many obstacles in practice. Taking road pricing as an example, the successful experiences in London and Stockholm are aimed at reducing congestion and emissions in urban areas; and the road pricing in Germany and Czech is only targeting trucks. It is difficult to come up with appropriate road pricing for all vehicle types in the short term. The fact that the planned road pricing for all vehicle types is making slow progress in the Netherlands reflects this difficulty. Particularly, there is lower acceptance if the road pricing is initiated for environmental reasons. This has been proved by the Dutch GOES MASS PUBLIC MODULE, which is part of a large-scale international study into citizens' environmental perceptions, values, and behaviours, that shows that Dutch people do not accept policies that limit personal choice (Ester & Vinken, 2000).

One major shortcoming of public transport is its uncertainties, which refers to the fact that the actual departure and arrival times may differ from the official timetables. Private transport also has uncertainties, but public transport is more affected by this. This is because travellers on public transport often use more than one public transport service; uncertainties are more likely to result in missed connections, which lead to increased travel times, especially in the case of low frequencies (Rietveld, Bruinsma, & Van Vuuren, 2001). In Europe, the level of ownership of private vehicles is quite high[6]. A high level of public transport service is important to attract these potential users (Beirão & Sarsfield Cabral, 2007). Furthermore, having a high level of public transport is costly, and may lead to high fares that are in conflict with the objective of providing affordable transport to the poor (Gorham, 2002). Subsidies for public transport from the government are a common solution, but may increase the burden on the government against a background of economic recession.

3.3 Comparison of the approaches

Each approach that may reduce traffic emissions has its advantages and disadvantages, thus, it is difficult to simply indicate which is preferable over the others. This section concludes the general factors that influence motorway traffic emissions, based on which further comparison of the approaches illustrated in previous sections will be given.

3.3.1 Factors that influence motorway traffic emissions

Many factors can influence motorway traffic emissions. Beek, et al. (2007) indicated that traffic emission are related to: vehicle level (vehicle characteristics, driving behaviour), and section level (traffic volume, traffic composition). Keuken, et al. (2010) revealed that motorway traffic emissions are dependent on the vehicles' average speed, and, more importantly, on traffic dynamics (congested flow has high traffic dynamics, while free flow has low traffic dynamics).

In general, motorway traffic emissions are related to the 4 factors shown in Figure 3.2:

[6] A report from World Bank shows that citizens in the Europe EMU owned 570 private vehicles per 1,000 people in 2003 (Bank, 2006).

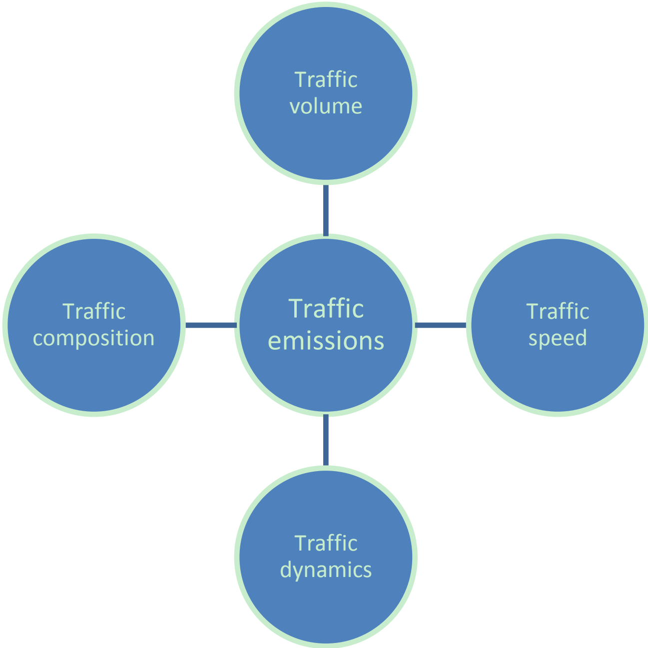


***Figure 3.2:** Interacting factors of traffic emissions.*

- Traffic volume: When more and more vehicles run on the motorways, the number of traffic pollutants they emit goes up accordingly. This is proved by many studies, such as Nesamani, et al. (2007) who indicate that an increase in traffic volumes increases vehicular emissions significantly.

- Vehicle composition: Different vehicle compositions have different impacts on emissions (Nesamani, et al., 2007). Some vehicles like heavy goods vehicles (HGV) emit much more pollutants than light duty vehicles, thus a higher portion of HGVs means a more severe traffic emission situation.

- Traffic speeds: Very low or very high traffic speeds are found to generate higher emissions. Previous theoretical studies, have revealed the relationship between traffic emissions and traffic speed. When traffic speed is low (below 40km/h), the highest exhaust PM10 emissions are detected, but for NOx the emissions go up dramatically when traffic speed is higher than 100km/h (Keuken, et al., 2010). The lowest PM10 and NOx traffic emissions have been found at average traffic speeds ranging from 60km/h to 100km/h (LAT, 2006).

- Traffic dynamics: this refers to behaviours like stop-and-go, acceleration and deceleration. These are often observed in congestion. Previous studies have found a definite relationship between traffic congestion and traffic emissions. For example, Levy, et al. (2010) found that, when comparing travelling conditions of congestion and free flowing traffic in which the estimated average speed is similar, emissions during congested driving conditions are

50% higher. In addition, this variability of driving behaviour can also happen in free-flowing traffic owing to speed differences caused by aggressive driving, adverse weather conditions, roadway environment and signal control. Vlieger, et al. (2000) found that aggressive driving increases emissions compared to normal driving.

3.3.2 Comparison of the approaches

This section will further compare the approaches elaborated on in Section 3.1, based on the factors that influence motorway traffic emissions and the time dimension,[7] as shown in .

Table ***3.1***.

Table 3.1: *Comparison of the approaches*

Objective	***Dynamic traffic management***	***Cleaner fuel and vehicle***	***Energy-efficiency vehicle technology***	***Demand management***	***Promoting public transport***
Reduce traffic volume	Yes	No	No	Yes	Yes
Reduce heavy emitting vehicles in traffic composition	Yes	Yes	Yes	Yes	Yes
Reduce traffic dynamics	Yes	No	No	No	No
Speed control	Yes	No	Yes	No	No
Time scales of implementation	Short-term	Long-term	Long-term	Long-term	Long-term

It can be seen from the table above that only DTM is able to have positive impacts on all the four factors. From this point of view, it seems DTM is the most promising approach to reduce traffic emission. However, it is uncritical to make such a statement without considering the total potential on the reduction of traffic emissions, which is usually case specific.

In spite of this, given as a short-term alternative, DTM is preferred in practice. The Dutch air quality innovation programme, which was created in pursuit of improving air quality alongside Dutch motorways, identifies dynamic traffic management as an effective way to reduce traffic emissions (Rijkswaterstaat,

[7] The time dimension of an approach refers to the length of time period this approach covers.

2010). Thus, in this study, dynamic traffic management is deemed as a promising approach to reduce the motorway traffic emissions in the short term in the Netherlands.

One notable fact is that according to a previous survey on the public acceptance of the implementation of a DTM measure[8] which was conducted to serve different objectives, 3 out of 4 drivers showed their support as a whole. However, the least support (57%) is found for the objective of improving local air quality, while the strongest support is for implementation in bad weather conditions (Stoelhorst & Schreuder, 2010).

In the long term, when the DTM is reaching its limit in meeting the explosively increasing traffic demand, other approaches could be integrated to work on the reduction of traffic emissions to improve the ambient air quality near Dutch motorways.

3.4 Conclusion

This chapter systematically reviews the approaches that may reduce traffic emissions, such as dynamic traffic management, demand management, public transport, clean fuel and vehicles, and energy-efficiency vehicle technology, all of which have been applied to reduce traffic emissions from reducing either per-unit traffic emissions or total travel demand.

It is difficult to unambiguously indicate which approach is better than the others, but given as a short-term option, DTM is viewed as a promising solution to the urgent near-motorway livability problem. Thus, dynamic traffic management is preferred in this study, although in the long term it will definitely face a limit in meeting the demand to control the explosively increasing amount of vehicles. By then, those alternative approaches will be able to play their roles in assisting with dealing with the problems. This is beyond the scope of this thesis, and further studies are needed.

[8] The DTM measure is dynamic speed limits.

4 Dynamic traffic management to reduce traffic emissions

Chapter 3 concludes that dynamic traffic management is a promising approach to reduce motorway traffic emissions in the Netherlands in the short term. Nowadays, Dynamic Traffic Management is recognized by many researchers as an effective measure to enhance network performance. Nevertheless, the road authorities are not expecting the improvement of Livability at the expense of other aspects, like travel time, traffic safety, etc. This leads to the merger of the Multi-objective optimization of traffic systems (Wismans, et al., 2011).

In this chapter, the following question will be answered:

- ***Which dynamic traffic management measures may reduce motorway traffic emission?***
- ***What multi-objective optimization methodology could be used?***

Section 4.1 analyzes three dynamic traffic management measures that are capable or have the potential of reducing traffic emissions. Section 4.2 elaborates on the multi-objective optimization of using dynamic traffic management measures to reduce traffic emissions.

4.1 Dynamic traffic management measures to reduce traffic emissions

Dynamic traffic management (DTM) now is preferred over traditional traffic management when dealing with the rising congestion problem, environmental problems and making better use of road network capacity. A number of DTM measures or strategies, which are now aimed at or have potential in reducing traffic emissions, will be examined in this section.

4.1.1 Speed limit

In the Netherlands, speed limit reduction has proved to be effective in traffic emission reduction (T. R. C. Rijkswaterstaat, 2007). Two methods of speed control are popular today: fixed and dynamic speed limits.

Fixed speed limit

Fixed speed control is able to reduce traffic emissions through 2 means:

- Lower the average traffic speed to generate lower emissions

Previous theoretical studies have revealed the relation between traffic emissions and traffic speed. When traffic speed is low (below 40km/h), the highest exhaust PM10 emission is detected, but for NOx the emission goes up dramatically when traffic speed is higher than 100km/h (Keuken, et al., 2010). The lowest PM10 and NOx traffic emissions have been found at average traffic speeds ranging from 60km/h to 100km/h (LAT, 2006).

Several field test have investigated this relationship in practice. For example, in 2008, a study on the effect of decreased speed limits on traffic emissions on a section of the Amsterdam ring highway found that the particulate air pollution at road side decreased by 2.20μg/m^3 (Dijkema, van der Zee, Brunekreef, & van Strien, 2008). In 2003, a study looked into how the emissions change if the maximum speed limit is reduced from 120km/h to 80km/h in Switzerland. The result was that NOx emission was reduced by 4% (Keller et al., 2008).

- Reduce traffic dynamic to reduce traffic emission

Traffic dynamics refers to the speed variation of traffic flows. Previous studies have found that traffic with high dynamics generates substantial higher emissions than traffic with low dynamics (Genseet, et al., 2001). Thus, reducing traffic dynamics is an efficient way to make traffic flow less polluting (Essen & Wilmink, 2010).

In practice, a pilot project in Rotterdam, which has a strictly enforced speed limit of 80km/h, has determined that the reduction of traffic dynamics is essential to reduce traffic emissions (Wesseling, et al., 2003).

With the successful experience of strict speed limit enforcement, four additional locations in the Netherlands with air quality problems were selected to test the 80km zone project. The result on traffic emissions was positive, with reductions of NOx of about 20-30% and PM10 reductions of about 10% (Stoelhorst, 2008).

Dynamic speed limits

A dynamic speed limit (DSL) system utilizes traffic speed and volume detection, weather information, and road surface condition technology to determine appropriate speeds at which drivers should be travelling, given current roadway and traffic conditions. Dynamic speed limits provide more flexibility than fixed speed limits (Stoelhorst & Schreuder, 2010).

Dutch researchers, De Schutter et al., conducted a study to explore the use of dynamic speed limits in traffic emission reduction in 2010. They were trying to reduce travel time, traffic emissions and fuel consumption in a balanced way. Their study was based on a model simulation, and they finally reached the conclusion that dynamic speed limits can be used to reduce the travel time, total emissions, and maximum dispersion levels at the same time (De Schutter, Zegeye, Hellendoorn, & Breunesse, 2010).

In the Netherlands, another project, named DYNAMAX, teamed up with the Dutch air quality programme. Its aim was to resolve specific traffic bottlenecks and manage traffic flows based on air quality forecasts. On a stretch of the A58 near Tilburg, the speed limit was lowered from 120 to 80 km/h when the PM10 concentration exceeded the limit. At the time of writing, the quantitative result has not been published, but it is reported that the results are promising. See Appendix B for more information.

In addition, a sufficiently low dynamic speed limit measure has been proven to be able to reduce traffic flow capacity in the affected area, as shown in Figure 4.1 below, thus leading to smaller traffic outflow (Carlson, Papamichail, & Papageorgiou, 2010). In Figure 4.1, q denotes traffic flow, ρ denotes traffic density, and b denotes the DSL rates. DSL rate refers to the DSL induced free flow speed divided by the free flow speed without DSL. If the DSL is applied before the bottleneck which is becoming active, a sufficiently low DSL could reduce the traffic flow arriving at the potential bottleneck to prevent bottleneck activation.

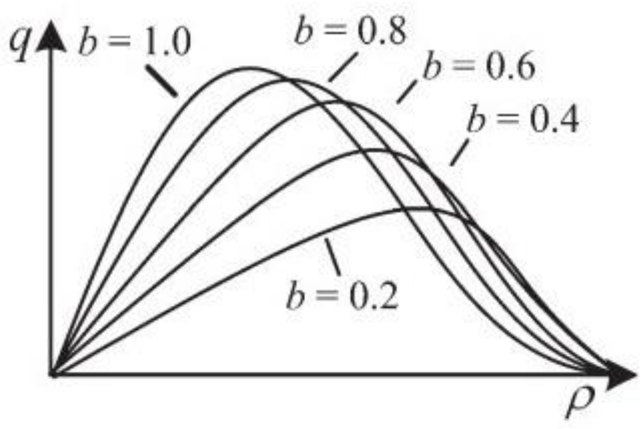


Figure 4.1: *Fundamental diagram for different values of DSL rates. Source: (Carlson, et al., 2010).*

This property is utilized by Carlson et al. in their research on mainstream traffic flow control, which may reduce traffic emissions at certain locations. This will be discussed in Section 4.1.3.

4.1.2 Ramp metering

Many ramp metering strategies exist, among which those based on real-time measures (traffic responsive) ones are preferred now due to their capability of accurately loading motorways (Papageorgiou & Papamichail, 2007).

There are several classifications of traffic responsive ramp metering strategies, like:

- **Local ramp metering strategies:** Demand-Capacity strategy, Occupancy strategy, ALINEA, etc.
- **Coordinated ramp metering strategies:** HERO, HERO ALINEA, etc. (Vreeswijk, Woldeab, de Koning, & Bie, 2011)

Local orientated strategies can be further classified into:

- **Feed forward strategies:** Demand-Capacity strategy, Occupancy strategy, RWS
- **Feedback strategies:** ALINEA (Vreeswijk, et al., 2011)

Traditionally, ramp metering has not been aimed at reducing traffic emission, but is acknowledged as an effective way to eliminate congestion caused by the on-ramps to maximize motorway traffic throughput. Here we take the Demand-Capacity and ALINEA strategies as examples to show the work process, of which the ALINEA strategy is preferred.

Demand-Capacity strategy

This strategy is based on demand-capacity theory, and is a feed forward control. The cause of capacity drop downstream of the merge area of on-ramps is that the sum of inflows from motorway and the on-ramp exceeds the bottleneck capacity. Thus by adjusting the inflow from the on-ramp based on the inflow from the motorway to ensure that the sum of inflow is under the bottleneck, the capacity drops and the congestion will be avoided (Van Lint, 2009). Figure 4.2 is a schematic represent of the demand-capacity strategy.

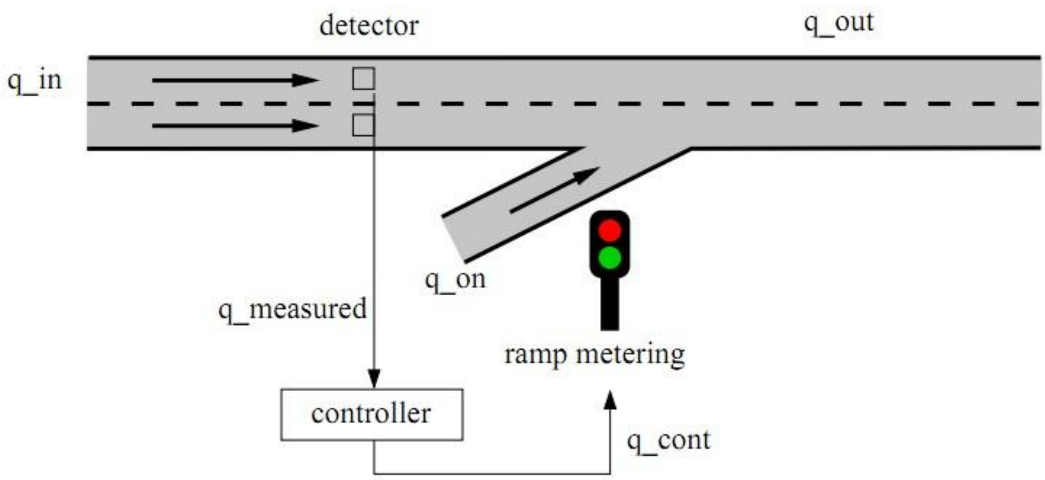


Figure 4.2: The layout of a demand-capacity ramp metering strategy. Source: (Van Lint, 2009)

As indicated in the figure above, a detector is placed upstream of the on-ramp nose to measure the inflow from motorway (q_measured), which then is sent to controller to calculate the allowed inflow from the on-ramp (q_cont). In this way, the q_out is maintained close to the motorway capacity.

ALINEA strategy

The ALINEA ramp-metering control law, which is based on feedback control theory, was proposed by Papageorgiou in the 1990s (Chu & Yang, 2005). For the ALINEA control law, the cause of the reduced outflow is formulated in terms of the occupancy downstream of the on-ramp (Van Lint, 2009). Thus, the basis of ALINEA is maintaining a suitable occupancy downstream of the on-ramp nose. The control cycle of ALINEA control law is shown in Figure 4.3:

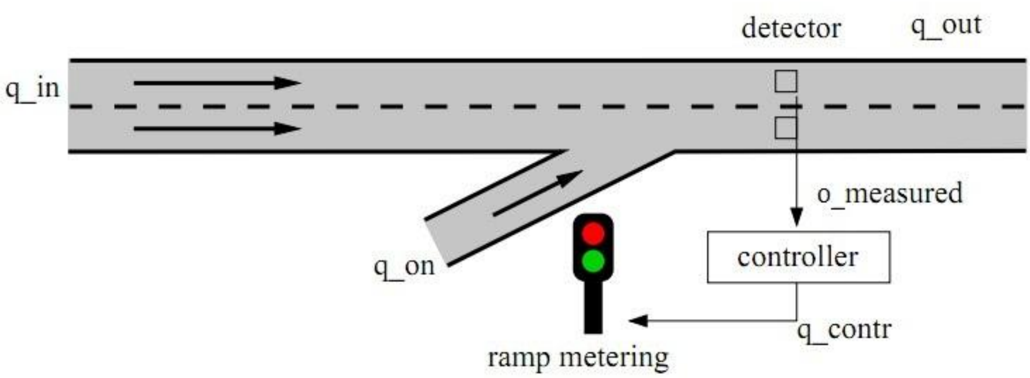


Figure 4.3: The layout of the ALINEA ramp metering strategy. Source: (Van Lint, 2009).

As can be seen from the figure above, a detector placed directly downstream of the on-ramp measures the occupancy (o_measured), which is then sent to the controller to calculate the allowed inflow from the on-ramp (q_cont). In this way, the occupancy of the traffic bottleneck is maintained close to critical occupancy to maximize q_out.

Why the ALINEA strategy is preferred over the Demand-Capacity strategy

There are three reasons to prefer the ALINEA strategy, as illustrated below:

- Motorway capacity, which the demand-capacity strategy attempts to achieve, is random because of the probabilistic character of traffic flow: the control is more likely to either overload or underload the motorway (Papageorgiou, Kosmatopoulos, Papamichail, & Wang, 2008). In contrast, critical occupancy, at which the maximum mainstream traffic flow is found, is rather stable under different traffic conditions (Papageorgiou, Kosmatopoulos, & Papamichail, 2008).
- Feedback control is simpler than feed forward control, due to no predictive model being needed.
- The feed forward control does not work properly when congestion occurs. This is because the measured motorway flow will be smaller and the controller will allow relatively high inflow from the on-ramp (Van Lint, 2009). The result is that congestion on the motorway will not be eliminated[9]. In contrast, feedback control is proven to be able to stabilize unstable traffic flow (e.g. congestion) (Van Lint, 2009). *In worldwide implementations, the ALINEA ramp metering algorithm is capable of being fine-tuned to adapt to local traffic and road conditions* (Chu & Yang, 2005).

Potential ability to reduce traffic emissions

Being capable of avoiding unstable flow and congestion on the motorway, ramp metering is considered to have the potential to reduce motorway traffic emissions (Thornton, Dixon, & Guensler, 2000). Another study suggested that the reduction of fuel consumption ranges from 15%-30% at metered on-ramps through applying strategies which are aimed at reducing traffic dynamics in the merge area (Vreeswijk, et al., 2011).

4.1.3 Mainstream Traffic Flow Control (MTFC)

The concept of MTFC

Similar to ramp metering, MTFC is a strategy that uses a stretch of motorway mainline that is upstream of the bottleneck as the storage space, instead of the on-ramps, to eliminate the congestion on downstream bottlenecks, thus

[9] A congestion override module is used in practice. When the speed of the mainline traffic flow drops to lower than 70km/h, the maximum metering is applied. However, this requires extra devices to measure the speed and extra work to determine the trigger.

maximizing the traffic throughput (Carlson, et al., 2010). The MTFC concept is explained in Figure 4.4.

Notion A, as shown in Figure 4.4, exhibits an active bottleneck at the end of the merge area downstream of an on-ramp. When q_{in} is smaller than q_{cap}^{up} but larger than q_{cap}^{down} ($q_{cap}^{up} > q_{cap}^{down}$), congestion occurs at the bottleneck and spills back to block the off-ramp upstream. The capacity drop induced by congestion results in q_{out} being decreased to be lower than q_{cap}^{down}.

Notion B shows that MTFC generates congestion before the bottleneck. The congestion outflow q_c is controlled to be almost equal to q_{cap}^{down}. Because the capacity drop is prevented, thus q_{out}, which is equal to q_c, is higher than in Notion A. If the congestion is space/time shorter than in Notion A, MTFC will lead to less blocking of upstream off-ramps.

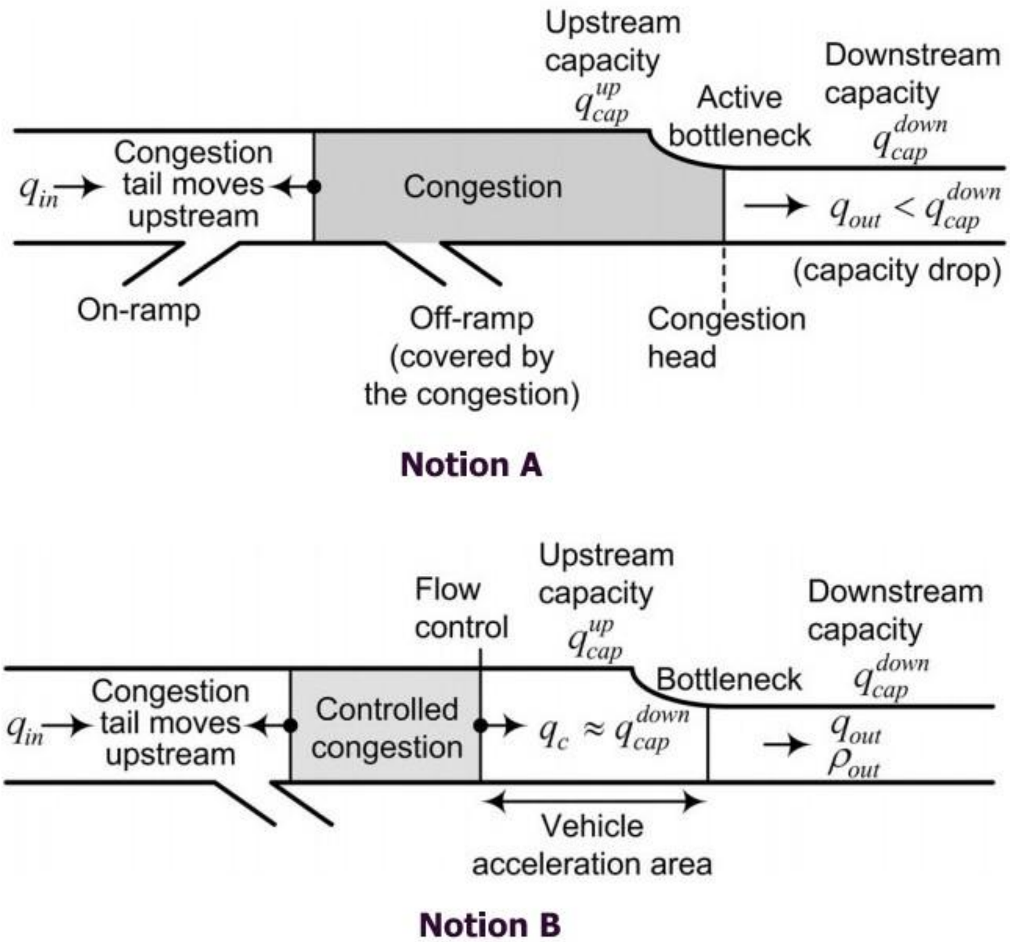


Figure 4.4: *Active bottleneck notion (Notion A) and local MTFC notion (Notion B). Source: (Carlson, et al., 2010).*

Obviously, a precondition to deploying the MTFC strategy is that the congestion is unavoidable in the case of no external control interventions. Furthermore, due to the congestion being actually relocated, rather than prevented, MTFC is less efficient than ideal ramp-metering in reducing the blocking of off-ramps, in that the relocated congestion may also block the off-ramps.

Throughout history, several MTFC traffic management measures have been studied. From the late 1950s to the 1960s, the port authority of New Yorker used a traffic control system to control the inflow into the tunnel under the Hudson River in order to neither overload nor starve-for-flow the tunnel capacity, in order to maximize the throughput (Gazis & Foote, 1969). Another example is the traffic-light based entrance control system deployed on the San Francisco–Oakland Bay Bridge, which has been used for more than 35 years and led to a throughput increase by 5% (M. S.McCalden, 1984). Recently, Carlson, et al. (2010) developed a feedback-based MTFC using dynamic speed limits to solve the capacity drop due to traffic bottlenecks on motorways.

Potential for reducing traffic emissions

Currently, there is no study or research relevant to the use of the MTFC strategy in an attempt to reduce traffic emissions. However, similar to ramp-metering, its capability of preventing the activation of bottlenecks and the induced capacity drop may be promising for traffic emission reduction at the traffic bottleneck.

4.1.4 Side-effects in terms of near-motorway livability conditions

Traffic management strategies elaborated above do have some drawbacks in terms of different aspects, which are illustrated below:

Speed limits

Strict enforcement of fixed speed limits may cause extra congestion. Particularly when there are many lane changing behaviours, the enforced speed limit reduces flexibility for drivers, which may lead to more congestion (Stoelhorst, 2008). This is because drivers are impacted by more pressure when they have to maintain speed and change lanes at the same time. Extra congestion may result in the increment of traffic dynamics which would lead to more traffic emissions.

In regards to dynamic speed limit, the DYNAMAX pilot project seems promising, however, not at all the trial locations. The study performed by De Schutter, et al. did find a positive result, but they also found that dynamic speed limits did not work well when the motorways was seriously congested (De Schutter, et al., 2010).

Ramp-metering

The ramp-metering strategy is effective to avoid congestion occurring on motorways; however, this benefit is gained at the expense of the traffic flow on the on-ramps. Traffic dynamics on motorways are reduced, but increased on the on-ramps. This may lead to higher fuel consumption and more traffic emissions on the on-ramps, due to vehicles waiting to enter the motorway and accelerating to merge into the mainstream (Thornton, et al., 2000). Because the on-ramps are more close to residential areas, the near-motorway Livability condition is still adversely impacted.

MTFC

The main side-effect of MTFC on traffic emissions is, as mentioned before, that the congestion is actually relocated, rather than avoided. Therefore, the impact on near-motorway Livability conditions is doubtful.

4.2 Multi-objective optimization of the DTM measures

Multi-objective traffic management is literally an application of multiple objectives optimization of dynamic traffic management measures.

4.2.1 Need for multi-objective optimization

Dynamic traffic management is deemed to be able to improve network performance, which not only includes travel time, but also traffic safety, environmental impacts, etc. In reality, however, these aspects of the traffic system are not isolated. This leads to the existence of different and possible competing policy objectives in dealing with one traffic problem (Wismans, et al., 2011). More and more isolated DTM measures have been developed to meet a transport problem at the local level (Taale, Westerman, Stoelhorst, & van Amelsfort, 2004). At the local level, even when a certain dynamic traffic management measure is designed to reduce traffic emissions (or any other single objective), other aspects have to be considered and weighed up in order to meet the requirements of different policy objectives (Wilmink & op de Beek, 2007). At the network level, the isolated measures may cause conflicts between one another. This is because the fact local transport problems are solved by local traffic management measures, without having an impact on the entire transport system (Taale, et al., 2004).

The DTM measures analyzed in the previous sections are usually designed to serve certain objectives, either reducing travel time or reducing traffic emissions. When there are multiple objectives to meet, an optimization process is urgently needed. In regard to near-motorway Livability, the reduction of traffic emissions obviously has impacts on travel flows, leading to negative/positive effects on travel time, traffic safety, or even climate changes, etc. These aspects need to be taken into account and weighed when implementing the DTM measures with the objective of reducing motorway traffic emissions near residential areas.

The fact that the survey results mentioned in Chapter 3 on the public acceptance of DTM measures aiming at improving local air quality being rather low, also suggests the need for a multi-objective optimization of DTM measures. This is in order to meet drivers' demands for traffic efficiency or other aspects when implementing DTM measures to reduce traffic emissions, since the result of lowered ambient air quality is usually not borne by the drivers.

In conclusion, in order to meet the different policy objectives, either at local or network level, a multi-objective optimization process is needed to optimize the use of the DTM measures to reduce motorway traffic emissions, even when only one measure is implemented.

4.2.2 Multi-objective optimization for DTM measures using generalized indicator

When dealing with the multi-objective optimization problem, a simple but efficient way is to use a generalized indicator, which is the weighted linear sum of the objectives. One could weigh the objectives against each other by taking the stakeholders' preferences or any other constraints into account, then maximize or minimize this objective function according to specific requirements.

For example, De Schutter, et al. (2010) conducted a study on the balanced trade-off between area-wide emissions and travel time, using a traffic model (METANET) and a emission model (VT-macro). They also developed a set of objective functions for every specific aspect (travel time, total emissions, total dispersion concentration, etc.), and then combined them into a generalized indicator. The result was first exhibited in two optimal solutions, which focused on reducing travel time (assign weighting factor 1 to travel time and 0 to other aspects) or total emissions (assign weighting factor 1 for total emissions and 0 to other aspects), respectively, then assign proper weighting factors to each aspect to obtain a balanced solution.

This methodology will be used in the following sections to study how to configure the DTM measures to meet certain requirements.

4.3 Conclusion

Speed limit, ramp metering and mainstream traffic flow strategies are analyzed in this chapter to examine their ability or potential to reduce motorway traffic emissions, and their shortcomings in terms of improving near-motorway Livability. Speed limits have been proven to be able to reduce traffic emissions, but fixed speed limit measures may induce extra congestion and dynamic speed limit measures do not work well in congested traffic flow. Ramp-metering is capable of reducing traffic emissions on the motorways, but its efficiency is limited by the storage ability of the on-ramp lane. In addition, ramp-metering increases traffic emissions on the on-ramps, which are also close to residential areas. The MTFC strategy is similar to the ramp-metering strategy, but it is a very new concept and its ability in reducing traffic emissions has not been sufficiently studied up until now.

Furthermore, even if the DTM measures are implemented specifically to reduce motorway traffic emissions, the improvement may be gained at the expense of other aspects, like traffic efficiency, traffic safety, etc. Thus the implementation of a DTM measure has to be optimized to meet the requirements in different aspects. A simple but efficient way is to use the generalized indicator, which is the weighted linear sum of the objectives.

5 Application of MTFC to improve near-motorway livability

In the previous chapter, several dynamic traffic management measures were examined in terms of their capability to reduce motorway traffic emissions. In this chapter, a hypothesis is considered for relocating congestion to reduce traffic emissions on motorway sections close to residential area based on mainstream traffic flow control (MTFC) strategy. More importantly, a controller will be designed to realize the control objective.

This chapter will answer the following question:

- ***How can a controller be developed for mainstream traffic flow control?***

Section 5.1 proposes a hypothesis of applying MTFC strategy using a combination of fixed/dynamic speed limit measures. Based on the hypothesis, a feedback-based controller has been developed in Section 5.2. The tunable parameters in this controller are illustrated in Section 5.3.

5.1 Applying MTFC to improve near-motorway livability

In the Netherlands, many motorways pass by/through urban residential areas, as shown by Section 2.2. Cities and motorways are connected by on-/off-ramps, which are often the causes of traffic bottlenecks on motorways. The near-motorway livability problem requires not only reducing traffic emissions on motorways, but also those on ramp lanes. This is difficult to do, particularly in zones with heavy traffic demand and traffic bottlenecks. During the research process, the following question emerged:

In cases where the unstable traffic flow and congestion, which is caused by the capacity drop at traffic bottlenecks (e.g., on-ramps), on motorways close to residential areas are difficult to improve or eliminate, particularly in cases of high-traffic demand, is it possible to relocate them to environment-insensitive areas in *order to reduce the negative impacts of the traffic emission on the ambient air quality, thereby improving near-motorway livability conditions?*

When answering this question, two aspects must be considered:

- Relocating congestion and unstable traffic flow caused by the capacity drop at traffic bottlenecks

As indicated in Section 4.1.3, mainstream traffic flow control strategy is able to relocate the capacity drop and congestion induced at the traffic bottleneck. The ramp-metering strategy performs the same function; however, as discussed in Section 4.1.3, this is achieved at the expense of the traffic flow on the on-ramps, which are usually close to residential areas. Thus, the MTFC strategy is preferred in this study. Due to the fact that no traffic lights are used on Dutch motorways, dynamic speed limit will be used to control the traffic inflow from motorways.

- Ensuring that the improved traffic flow causes less pollution

Even if the capacity drop and congestion are prevented at the traffic bottleneck, the improved traffic flow can still generate large amounts of emissions if the speed of traffic is too high. A proper fixed speed limit with strict enforcement has been proven to effectively reduce traffic emissions. In this study, 80km/h will be used since it has been proven to be effective in reducing traffic emission in a previous project in the Netherlands.

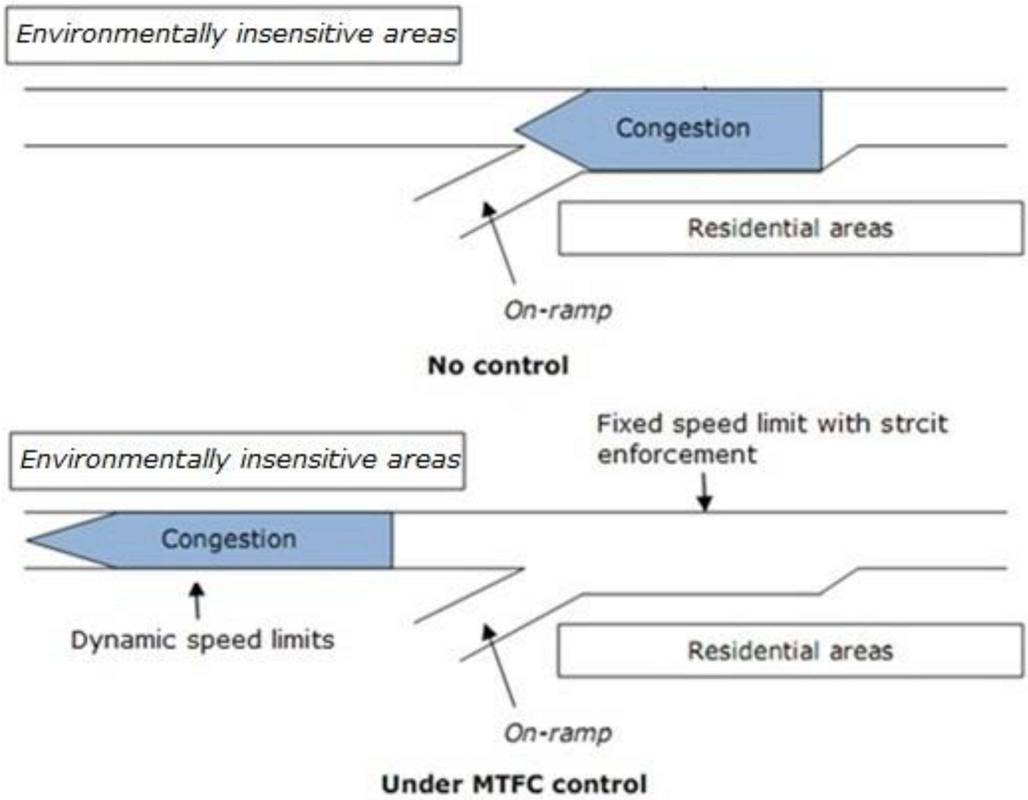


Figure 5.1: *Schematic representation of the hypothesis.*

Thus, as shown in the figure above, a hypothesis could be concluded as follows:

If the congestion or unstable traffic flow which is caused by the capacity drop at the traffic bottleneck is difficult to mitigate on the motorway stretches near the residential areas, particularly under heavy traffic demand circumstances, a mainstream traffic flow control strategy using dynamic speed limits could be utilized to relocate it. In the meantime, a fixed speed limit (e.g. 80km/h) with strict enforcement could be used to ensure that the improved traffic flow near the residential area emits less pollution. This is expected to improve near-motorway livability.

5.2 Development of a feedback-based controller

5.2.1 Control setting and control goal

The core of the proposed hypothesis is to dynamically adjust the maximum speed limits on the upstream motorway section to prevent too many vehicles from entering the target section. A controller is needed to determine the dynamic speed limit and when it should be implemented.

In this study, such a controller is formulated according to the following rules:

- This controller follows a single-input-single-output structure:

The input is the real-time measured occupancy at the target motorway section, and the output is the value of the speed limit to be implemented.

- This controller is an ALINEA-like feedback-based control algorithm:

The reason for selecting feedback control, as indicated in Section 4.1.2, is that feedback control is simpler and more effective in preventing or resolving congestion.

- The control goal is to maintain occupancy at the target section close to the desired value, i.e., critical occupancy:

Critical occupancy has been chosen, as discussed in Section 4.1.2, because it is rather stable in different traffic conditions, leading to a more reliable control action than critical traffic flow. In contrast, critical traffic flow is random in nature due to the probabilistic character of traffic flow, and thus is more likely to either over- or under-load the motorways.

Thus, a controller is created as shown below:

$V'_{in}(t)= V_{in}(t-1) + P(O_c - O_m(t-1))$

Where:

V'_{in} *= the calculated maximum speed limits on the controlled upstream section while the control action is actuated*

V_{in} *= the real-time measured average speed in the controlled upstream section*

P *= the regulator parameter, which determines how quickly the control action reacts*

O_m *= the measured real-time traffic occupancy of the target motorway section.*

O_c *= the desired occupancy (%) on the target motorway section, which acts as the trigger of control action.*

t *= time step, e.g., 30-s, 1-min or 2-min.*

5.2.2 Control cycle

Basically, the control cycle monitors the occupancy of the target motorway section. When it exceeds a pre-defined critical value, the maximum speed limit on upstream section will be lowered to a certain value, which is calculated based on the measured time mean speed on the upstream section.

The control cycle is described in a flow chart as shown below:

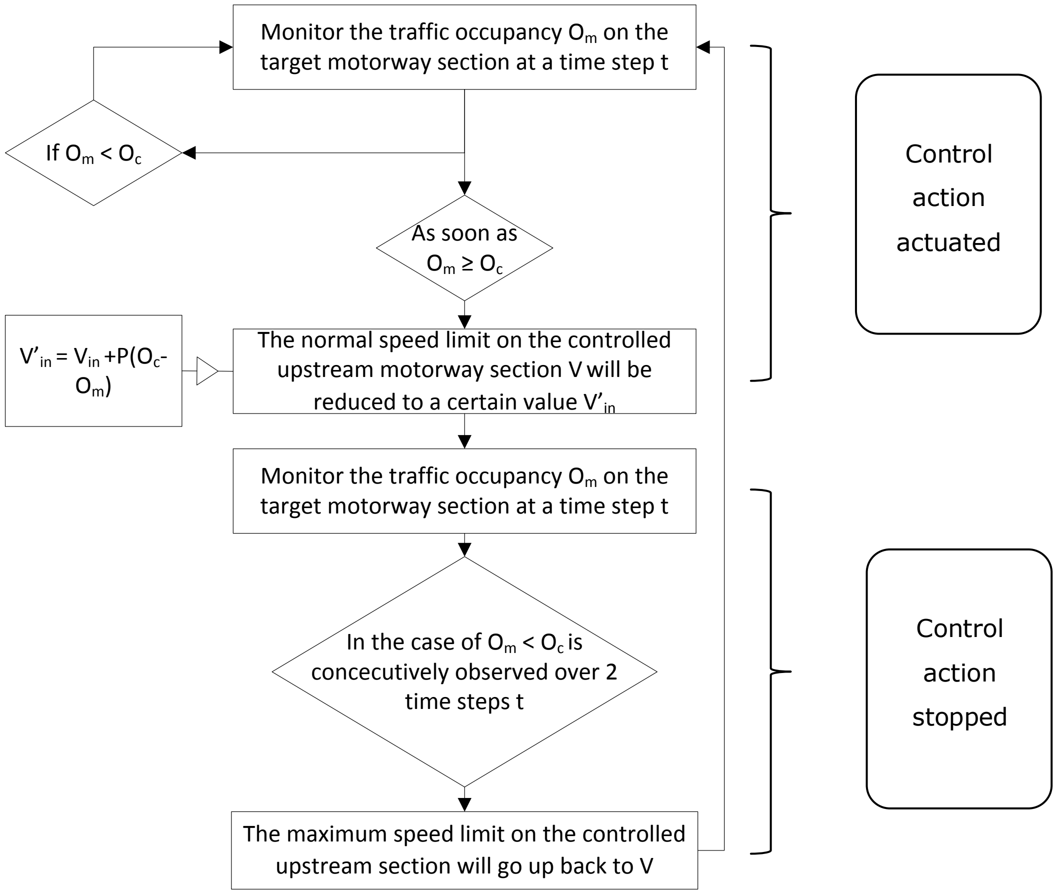


Figure 5.2: *Steps of control cycle.*

Where:

O_m = *the measured real-time traffic occupancy of the target motorway section.*

O_c = *the desired occupancy (%) on the target motorway section and acts as the trigger of the control action.*

t = *time step, e.g., 30-s, 1-min or 2-min.*

P = *regulator parameter, which determines how quickly the control action reacts.*

V = *the normal maximum speed limit in the Netherlands, i.e., 120 km/h for cars, 85 km/h for HGV.*

V'_{in} = *the calculated maximum speed limits on the controlled upstream section while the control action is actuated.*

V_{in} = *the real-time measured average speed in the controlled upstream section.*

Figure 5.3 is a schematic representation of the control cycle:

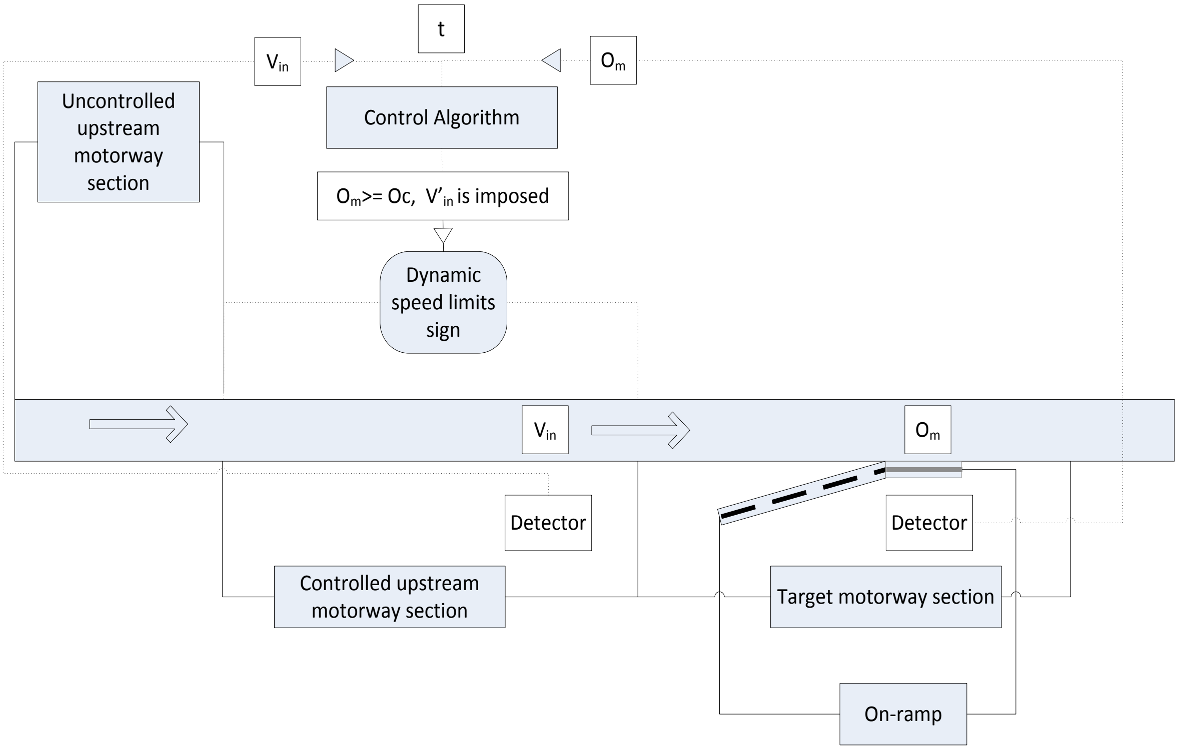


Figure 5.3: *Schematic representation of control cycle.*

Note: The on-ramp lane acts as a traffic bottleneck.

It must be noted that the upstream motorway section contains a section with the dynamic speed limit management and a section without control. Due to the implementation of dynamic speed limits, the outflow from the controller section will be reduced. In this case, if the traffic demand on motorways is larger than the reduced capacity on the controlled section, then congestion will be induced on the uncontrolled upstream motorway section, which is the so-called 'relocation of congestion'.

5.3 Tunable parameters of the proposed controller

There are two major tunable parameters – the desired occupancy O_c (trigger) and regulator parameter P, respectively.

O_c : increasing/decreasing this parameter leads to more insensitive/sensitive reactions of the control action, respectively. When the value of O_c increases, so does the chance that the control action will be actuated after congestion occurs; however, if O_c is set lower, then the motorway capacity may be underutilized.

P: increasing/decreasing this parameter contributes to stronger/smoother reactions of the regulator, respectively. In the case of an extremely high value of

P, the regulator may result in oscillatory, unstable behavior (Hadj-Salem, Blosseville, & Papageorgiou, 1990).

The rest parameter, namely the time step "t", determines the frequency of the changes in the values of dynamic speed limits. This case study will not examine the impact of different time steps; a fixed time step is used equal to 30 seconds.

5.4 Conclusion

In this chapter, a hypothesis of applying MTFC strategy is proposed with the expectation of improving near-motorway livability conditions. This hypothesis proposes to use dynamic speed limits to control the motorway mainstream traffic inflow arriving at the target section (which is assumed to contain a traffic bottleneck that leads to capacity drop and congestion) to maintain a free flow, and in the meantime, impose a proper fixed speed limit (e.g. 80km/h) with strict enforcement on the target section to further reduce traffic emissions. Implementing this combination of DTM measures is expected to reduce motorway traffic emissions near the residential areas.

To realize the dynamic control of the mainstream traffic inflow as proposed in the hypothesis, a controller has been developed. This controller is ALINEA-like, which adopts feedback control and uses critical traffic occupancy as the trigger. The feedback control is used since it performs better than a feed forward control to resolve or prevent congestion, and does not need an extra predictive model. Critical occupancy is used because it is robust in different traffic conditions, and thus contributes to the robustness of the control result.

6 Case study setup

In the previous chapter, a hypothesis and its controller were created with the goal of reducing motorway traffic emissions near residential areas to tackle the near-motorway livability problem. In this chapter, a theoretical case study will be performed to test the feasibility of the proposed hypothesis, by simulating the work process of the hypothesis and generating data for subsequent analysis.

In this chapter, the following question will answered:

- ***How can the feasibility of the proposed MTFC strategy be assessed?***

Section 6.1 uses simulation to perform this case study, and illustrates the work involved in the case study setup. Sections 6.2 and 6.3 elaborate on how to use VISSIM and Matlab to realize the proposed controller in simulation.

6.1 Preparing the case study

6.1.1 Microscopic simulation

To perform this case study, a simulation was chosen because when studying the impact of the proposed control algorithm, it fulfills the following requirements:

- All of the circumstances should be constant
- The variables should be under control
- A large amount of tests is required to minimize the effect of random bias

Although the results obtained by simulation do not 100% reflect the real effects, they provide an indicative way to study the real situation; furthermore, it is a much less costly approach both in time and money. Another drawback is that the driving behavior in simulation usually does not match the reality, thus simulation software calibration is necessary.

Besides, this case study will focus on a theoretical case to check whether the proposed control algorithm is capable of achieving the goal set in the hypothesis.

6.1.2 Simulation Software choice

For the simulation, three components are required: a traffic simulation model, a traffic emission model, and an external control tool.

In order to simulate real traffic flow, which is dynamic in nature, only a stochastic micro-traffic simulation model[10] is considered. Now, there exist two available traffic models – FOSIM and VISSIM.

Due to its lack of function to support an external control tool, FOSIM was abandoned. VISSIM is a microscopic/stochastic traffic simulator, which has mostly been used in the past to study urban public transportation, such as intersection design, but has been proven effective in simulating motorway traffic behavior as well (Horowitz et al., 2005). Furthermore, VISSIM is capable to communicate with an external control, like Matlab, via its Com-interface. In this way, it conveniently realizes the mainline metering control without needing other software.

Besides the capability of simulating traffic flow, VISSIM is able to generate traffic emission data using its node evaluation application. Thus, no external emission model will be used in this study.

6.1.3 Software architecture

The architecture of the chosen software and working process is shown in Figure 6.1.

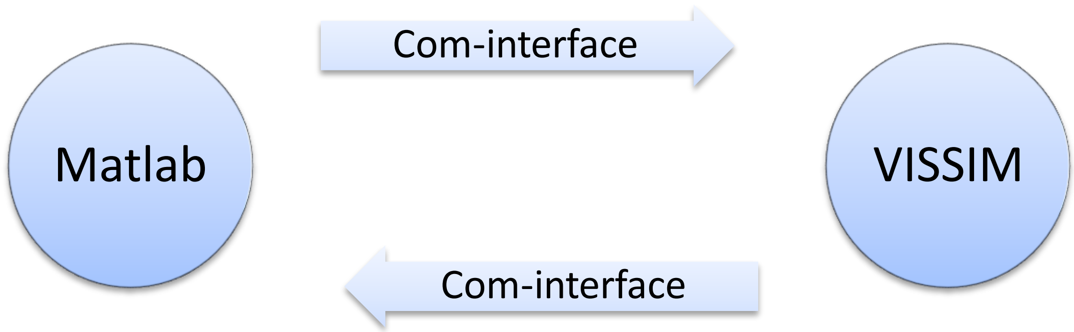


Figure 6.1: *Schematic representation of software architecture and work process.*

As mentioned before, VISSIM and Matlab are connected via a com-interface. During the simulation, VISSIM acts as a COM-server, and Matlab acts as a COM-client. Matlab can retrieve pre-defined information describing in-time traffic flow state, which is gathered in several VISSIM applications, including link evaluation, node evaluation and data collection. Based on that traffic information, Matlab can then change the properties of specific VISSIM objects, such as Desired Speed Decisions, to impact traffic state on line.

[10] Overall, traffic simulation model is divided into 3 types: a macro-, meso- and micro-simulation model. Check Appendix C for a comparison.

6.1.4 Study target

The goal of this case study is to test the feasibility of the hypothesis. A major task is to assess whether the proposed controller is able to relocate the congestion from the motorway stretch near residential areas to an upstream motorway section that is environmentally insensitive. To test whether the controller is working properly and not considering unnecessary disturbances, this case study will be based on a hypothetical motorway network, consisting of a motorway and an on-ramp as shown in Figure 6.2. Here, it is assumed that the on-ramp and its adjacent motorway section are close to a residential area, and that its upstream section is environmentally insensitive.

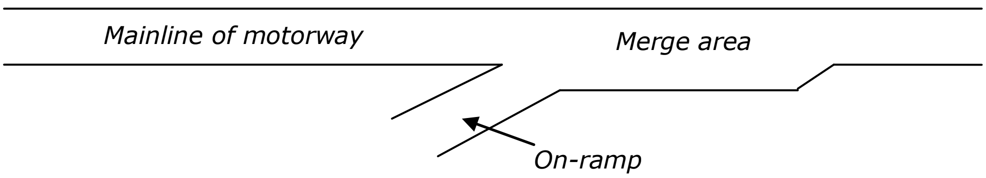


Figure 6.2: *General layout of the hypothetical motorway network.*

This section only provides a general overview of the layout of the hypothetical network. In Section 6.2.1, a more detailed view will be offered by an illustration of the motorway network built in VISSIM.

6.1.5 Initial value of the controller parameters

The proposed control algorithm as developed in Section 5.2.1 will be coded in Matlab; thus, the tunable parameter must be pre-defined to make the control algorithm work. In total, there are 2 parameters as demonstrated in Section 5.3, each of which was assigned an initial value as given below:

- Regulator parameter P = 1;
- Desired occupancy O_c = 25.

Note, as stated in Section 5.3, the time step t will not be further investigated.

6.2 VISSIM model

6.2.1 Layout of the hypothetical motorway network built in VISSIM

A motorway network is built in VISSIM with the same layout as described in Section 6.1.4. The motorway network built is a 3-lane, single-directional motorway, with only one on-ramp lane. The motorway is approximately 8 km long, and is divided into 4 sections as shown in Figure 6.3:

- Uncontrolled upstream section
- Controlled upstream section

- Target section (i.e., close to the residential area)
- Downstream section

The target section and on-ramp lane are assumed to be close to a residential area.

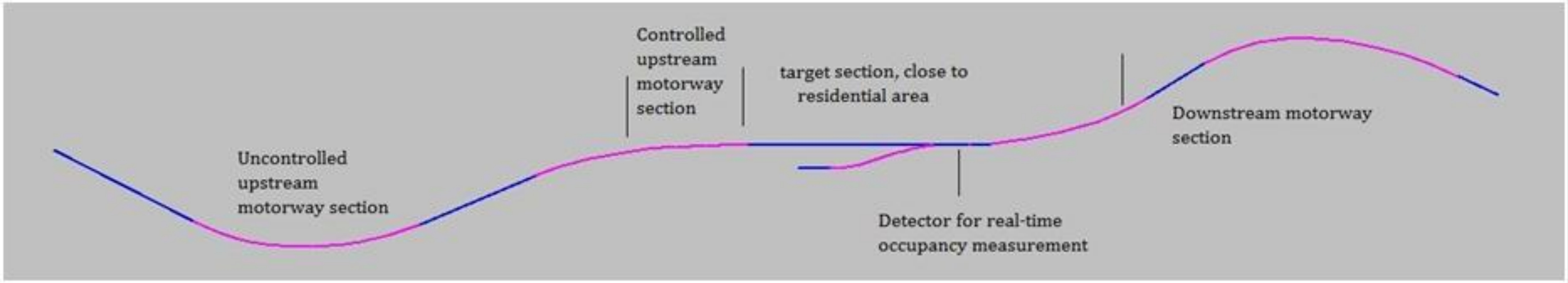


Figure 6.3: *Layout of the hypothetical motorway network built in VISSIM, viewed in centre line mode.*

Note: The length of the each section in VISSIM may differ from that shown above, particularly the two upstream motorway sections. This figure merely indicates the approximate position of the 4 sections.

In the simulation, the exact length of each section is as follows:

- Uncontrolled upstream motorway section: 4.5 km
- Controlled upstream motorway section: 0.5 km
- Target section: 2.2 km
- Downstream motorway section: 0.8 km

The detector, namely the data collection points for the measurements of the real-time occupancy, is placed in the merge area, downstream from the on-ramp nose. The detector is usually placed at the place where the congestion is first observed. In practice, congestion is often first observed downstream of the merge area; in VISSIM, however, the congestion is first observed a bit upstream of the end of merge area. According to a previous study, in simulations using a traffic model, it is acceptable to place the detector anywhere between the ramp nose and the location of the first appearance of congestion (Papageorgiou, Kosmatopoulos, Papamichail, et al., 2008).

Data collection points

Data collection points are used to gather data of traffic flow state for dynamic speed limit control and speed adaption, and for plotting contour and fundamental diagrams. A time interval of 30 s is set for all groups.

Desired speed decisions

In VISSIM, desired speed decisions (DSDs) are used as Variable Message Signs (VMS) to guide vehicles to accelerate or decelerate. When vehicles pass one DSD, they receive a pre-defined speed that they are told to follow. DSDs are used extensively in this case study because the dynamic speed limits rely heavily on them. DSDs are deployed around 400 meters apart in spacing.

Vehicle input

Traffic flow in the network could be input by function vehicle input. For each origin link, users could define different time intervals with corresponding traffic flow.

Routes

Each vehicle passing routes point will be assigned a new route decision.

Nodes

In this case study, nodes are only used to collect NOx emission and fuel consumption data. PMx and NOx are the two traffic emission related indicators of greatest concern; nevertheless, limited by time and knowledge, the Node evaluation application in VISSIM is used to generate the emission data instead of a individual traffic emission model.

Only basic emission output can be obtained through the "Node Evaluation" output. Through this evaluation, one is able to obtain basic output for CO, NOx, and VOC (in grams) as well as fuel consumption (in gallons).

Fuel consumption is calculated using the following formula:

F = VMT * k1 + Delay * k2 + Stops * k3

where:

k1 *= .075283 - .0015892 * Speed + .000015066 * Speed ^ 2*

k2 *= .7329*

k3 *= .0000061411 * Speed ^ 2*

F *= Fuel Consumption (gal)*

Speed *= node segment average speed (mph)*

VMT *= vehicle miles traveled (mi)*

Delay *= VISSIM total delay (hr)*

Stops *= total vehicle stops per hour*

The emissions calculation for NOx is a function of fuel consumption. The emission output in this case study only provides an indicative result.

In this formula, the unit of parameters differs from that in other formulas mentioned in this thesis, but this formula is only used by VISSIM itself. See Appendix D for more information.

Three nodes are set in VISSIM: one to cover the 80 km zone and on-ramp lanes, one to cover the upstream motorway section, and the third to cover the motorway section downstream of the 80 km zone.

6.2.2 VISSIM validation

The most important aspect of validating VISSIM is to check if VISSIM is able to simulate capacity drop at the location where a traffic bottleneck exists. Yuan (2008) has proved VISSIM's ability in simulating capacity drop phenomenon. Figure 6.4 provides two traffic flow and occupancy rate fundamental diagrams, which were used in his study to show the capacity drop caused by the disturbances from on-ramp traffic flows:

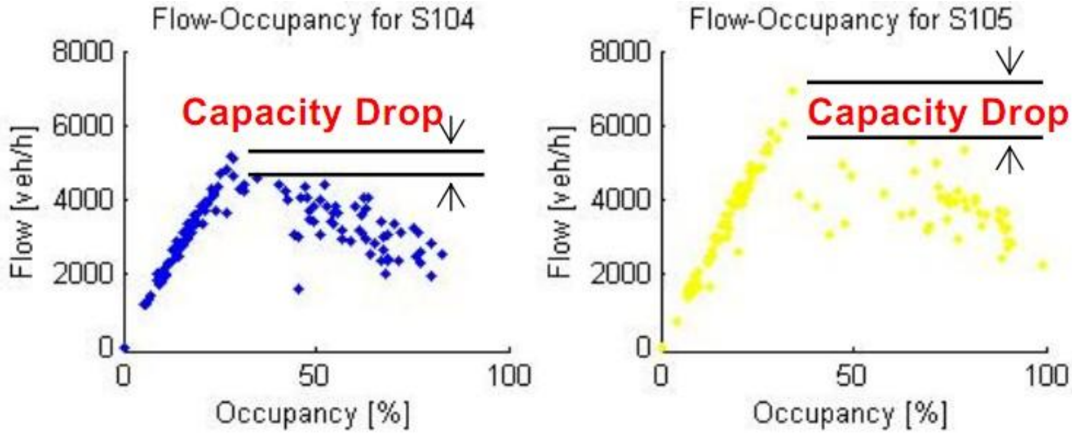


Figure 6.4: *Capacity drop phenomenon observed in previous study. Source: (Yuan, 2008).*

This capacity drop phenomenon provides a great benefit for this case study because the positive impact of the control action on the merge area could be reflected in the simulation.

6.2.3 VISSIM setting

Simulation resolution

The number of times the vehicle's position will be calculated within one simulated second ranges from 1 to 10. The higher the value of this parameter is, the smoother the vehicles move in simulation, but the longer the simulation takes. Simulation resolution 10 is used in this case study.

Simulation time

In total, simulation time is 11,400 seconds. The first 600 s are devoted to network filling, while the last 600 s are for network clear-up.

Vehicle input

Vehicle input is used to define traffic demand. Since this is a mainstream traffic flow control strategy, the simulation focuses on studying the effects of controlling the mainline flow. Thus, the traffic demand from on-ramp origin will be low and consistent, and the traffic demand from mainline origin will be larger and fluctuating. The exact traffic demand used in this simulation is as given below:

Table 6.1: *Vehicle input*

Time (s) / Origin	0-900	900-2,400	2,400-3,600	3,600-4,800	4,800-6,000	6,000-7,200	7,200-8,400	8,400-9,600	9,600-10,800
Mainline (veh/h)	4,700	5,100	5,500	5,700	5,400	5,000	4,500	4,000	3,600
On-ramp (veh/h)	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000

Routes

Here, route points are used to guide traffic flow from on-ramp to drive across the merge area, rather than disappearing at the end of the acceleration lane.

80-km zone

To simulate the enforced 80 km/h speed limit, a new desired speed decision is created, which is given below:

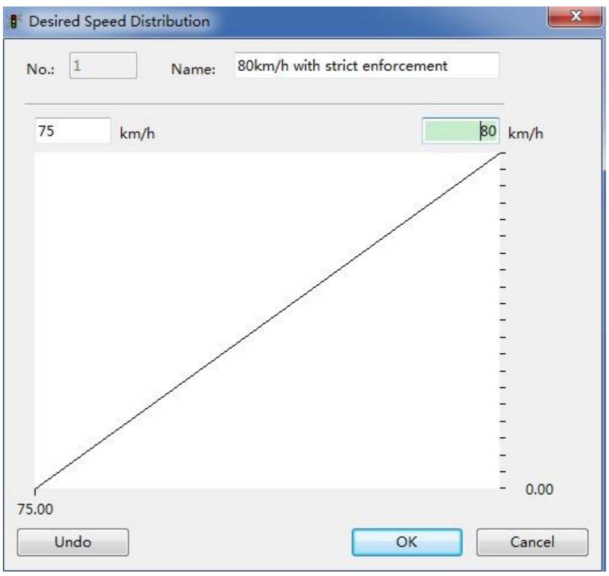


Figure 6.5: *New created speed distribution for strictly enforced 80 km/h speed limit.*

Vehicles assigned to this speed distribution are expected to run between 75 km/h and 80km/h. A small-scale motorway stretch built in VISSIM has been used to validate the created speed distribution, and it was found that the maximum speed is maintained well under 80 km/h as shown in the figure given below:

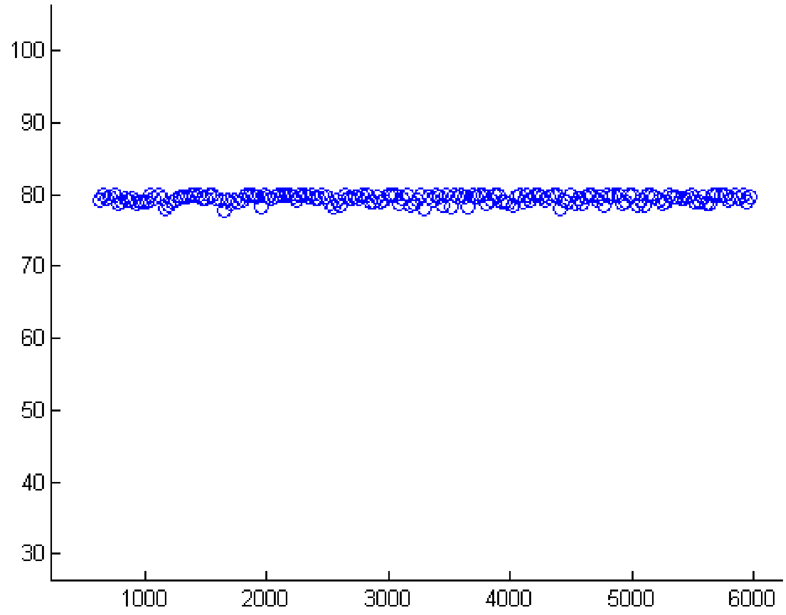


Figure 6.6: *Maximum speed under the created speed distribution.*

Traffic fleet composition

Only cars and HGV fleets are considered in the case study. For traffic flow from motorway origin, the fraction of HGVs is set to 2.5%, while the fraction of cars is 97.5%. For traffic flow from on-ramp origin, the proportion is 1% for HGVs and 99% for cars.

Desired Speed decisions (DSDs)

In the Netherlands, vehicles running on the motorways are subject to a maximum speed limit, which is as follows:

Table 6.2: *Speed limits for passenger cars and HGVs on motorways in the Netherlands.*

Vehicle class	**Motorway (dual carriageway)**
Passenger cars	120/100 km/h
HGVs	80 km/h

In this case study, the following DSDs are placed:

In general, cars and HGVs from motorway origin are assigned a desired speed of 120 km/h and 85 km/h, respectively; vehicles from on-ramp origin are given a desired speed of 50 km/h, and then when they are approaching the merge area, cars and HGVs are given desired speeds of 120 km/h and 85 km/h, respectively.

For the 80-km zone, 3 DSDs (one for each lane) are placed in the beginning of the target section to assign a customized speed distribution (80 km/h with strict enforcement) to vehicles passing by. At the end of the 80-km zone, 3 DSDs are deployed to assign normal speed limits to cars and HGVs.

For dynamic speed limits, several DSDs are placed 400 meters apart on the controlled upstream section to dynamically assign the speed distribution ordered by the controller.

Discrete values of dynamic speed limits displayed

In order to make it convenient for drivers to adapt their speeds, the values of dynamic speed limits need to be calibrated to ensure that drivers can easily read and follow them. One way to do that is to round the calculated values to a set of discrete values. The table below shows the calculated rates and their corresponding speed distributions in VISSIM.

Table 6.3: *Speed distribution selection for traffic flow affected by dynamic speed limits*

Calculated V'in (unit: km/h)	**Speed distribution***
V'in ≥ 85	85
85 ≥ V'in ≥ 75	80
75 ≥ V'in ≥ 65	70
65 ≥ V'in ≥ 55	60
55 ≥ V'in ≥ 45	50
45 ≥ V'in ≥ 35	40
35 ≥ V'in ≥ 25	35**

*This set of discrete speed distributions is as a test scheme used in the simulation.

**This distribution is also a customized speed distribution, which does not exist in the default desired speed distribution in VISSIM.

6.2.4 VISSIM calibration

Capacity

The default-built motorway in VISSIM has a higher capacity than motorways in the Netherlands (Yuan, 2008). Thus, road-capacity-related parameters ought to be calibrated. In VISSIM, road capacity is not given directly, but influenced by car following behavior. VISSIM uses Wiedemann cars following 99 for motorways, which has several parameters. CC1 parameter defines the time headway, which impacts road capacity most as mentioned in the VISSIM user manual. Thus, the value of CC1 increased from 0.9 to 1.2, which results in a more reasonable road capacity.

Lane change behavior

During simulation, some unrealistic lane change behaviors were observed. In the merge area, vehicles from the on-ramp are often found stopping at the end of the acceleration lane, failing to find an acceptable gap to merge into mainline traffic flow. This caused a queue to form in the acceleration lane and on-ramp lane, while allowing a free flow in the mainline lanes. In reality, drivers will become aggressive (reduce their acceptable gap) when attempting to merge into mainline flow, while drivers in the mainline traffic flow will decelerate when faced with merging traffic flows.

To correct this unrealistic lane change behavior, researchers usually calibrate the lane change parameters in VISSIM according to the characteristics of their study site. In this study, lane change parameters will be calibrated according to previous studies conducted by Yuan (2008) and Stanescu (2008) in ITSEDULAB, who found that the SDRF [11] parameter in VISSIM has a large impact on lane change behavior.

The exact changed parameter values are listed as follows:

Table 6.4: *Modified lane change parameters*

Parameters	**Own vehicles**	**Trailing vehicles**
Maximum deceleration	-6.0 m/s^2	-6.5 m/s^2
Deceleration increment with -1 m/s^2 per distance to the end of the merge area	200 m	150 m
Accepted deceleration	-2.5 m/s^2	-2.5 m/s^2
Waiting time before diffusion	30 s	30 s
Minimum headway (front/rear)	1.5 m	N/A
Safety distance reduction factor	0.01 or 0.6*	N/A
Maximum deceleration for cooperative breaking	-6.0 m/s^2	N/A

*0.01 for merge area; 0.6 for other sections

Speed adaption

Except for the lane change parameter, Stanescu (2008) found another phenomenon that makes lane change behavior in VISSIM unrealistic, particularly when traffic flow transitions into congestion from free flow:

- When traffic flow in mainline lanes tends to slow down and generate congestion, traffic flows from on-ramp still run into the acceleration lanes at a high speed. This leads to them drive to the end of acceleration lane, then stop, unable to merge into the main traffic flow. These vehicles gradually form a queue in the acceleration lane.

[11] SDRF: safety distance reduction factor, which temporarily reduces the safety distance by a factor to let drivers accept shorter gaps while making a lane change.

- As the disturbance from on-ramp traffic flow decreased, mainline traffic flow tended to transition to free flow again at high speed; however, as a result, traffic flow from the on-ramp waits in a queue, making them unable to find an acceptable gap to merge into main flow, resulting in a longer queue even in the on-ramp lane.

This is not in line with reality, where drivers from the on-ramp will adjust their speed to the speed of the main flow to make lane change easier; however, in VISSIM, the vehicles from the on-ramp do not realize the speed difference between them and the main flow until they enter the acceleration lane. To solve this problem, an additional DSD point will be placed on the on-ramp lane before the acceleration lane to command vehicles to adjust their speed. This function is done by using Matlab. The desired speed distributions assigned to the on-ramp traffic flow in order to adapt the measured main flow speed are listed in the table below:

Table 6.5: *Speed distribution selection for speed adaption of on-ramp traffic*

Measured time average speed on mainline	**Speed distribution for vehicles from on-ramp**
Speed ≥ 85 km/h	Enforced 80
85 km/h ≥ Speed ≥ 75 km/h	80
75 km/h ≥ Speed ≥ 65 km/h	70
65 km/h ≥ Speed ≥ 55 km/h	60
55 km/h ≥ Speed ≥ 45 km/h	50
45 km/h ≥ Speed ≥ 35 km/h	40
35 km/h ≥ Speed ≥ 1 km/h	35

Lane change decision distance and emergency stop distance

Yuan (2008) also found some other parameters which influence lane change behavior – lane change decision distance and emergency distance – both of which are properties of connector.

By making lane change decision distance longer, vehicles will start the lane change earlier, thus they get more chance to complete the lane change; if the emergency distance is moved backwards, which defines the last position for a vehicle to make a lane change, vehicles will avoid driving to the end of the acceleration lane which is less likely in reality.

Extra DSD to compensate for the DSDs incapability of showing the rates of speed limits

In reality, drivers accelerate/decelerate in advance when they observe changes in speed limits shown on the VMS panels around 20-50 meters ahead. In VISSIM, the DSDs, which are used as the VMS, are incapable of showing visible rates of dynamic speed limits; thus, drivers will not respond to the changed rates until they drive past the DSDs. To compensate for this shortcoming, an extra DSD will be deployed 30 meters upstream of the beginning of the motorway section affected by dynamic speed limits to guide drivers to respond in advance.

6.3 Matlab Coding

Without Matlab, VISSIM can only run according to the pre-defined settings. During simulation, almost no changes can be made, except for a limited set of simulation parameters, like simulation speed, etc. This is insufficient for this case study, which aims to test dynamic speed limits control responding to real-time traffic flow state. As an external control tool, Matlab could initiate and control simulation running in VISSIM via the Com-interface.

This section explains how to realize dynamic speed limit control in VISSIM with the help of Matlab, as well as the speed adaption for on-ramp traffic flow mentioned in Section 6.2.4. The complete Matlab coding has been saved in the CD attached to this report.

6.3.1 Dynamic speed limits

Collecting data of traffic flow state and changing its desired speed are two basic tasks that are required. The first can be completed by data collection points, while the latter can be completed by setting different DSDs.

The following three values are related:

- TIMEFROM and TIMETILL value of DSDs
- Desired speed distribution of DSDs
- Traffic occupancy rate on the target motorway section

The process of realizing the dynamic speed limit is described as follows, in which horizontal arrows indicate the movement of the information and vertical arrows indicate the process order:

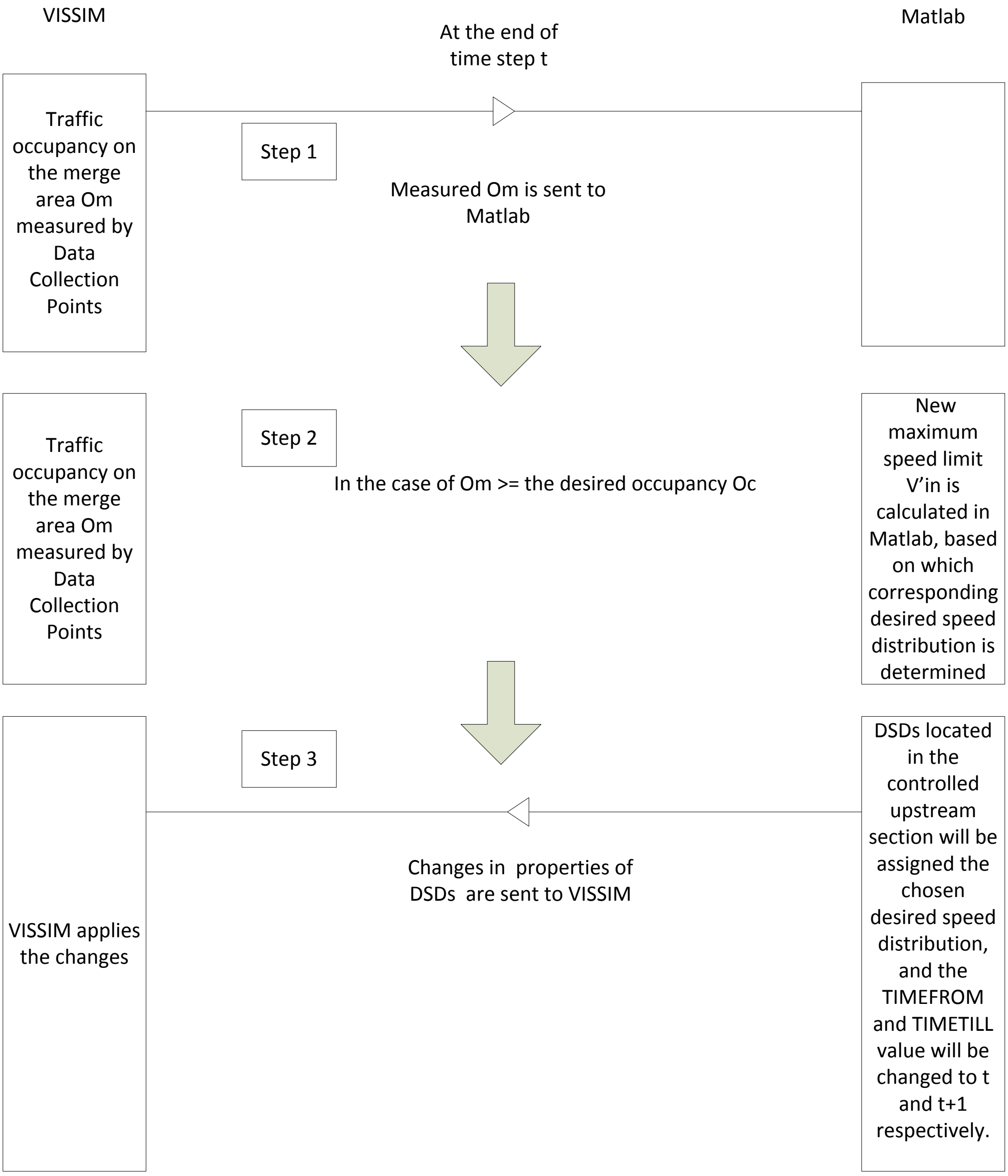


Figure 6.7: *Work process of dynamic speed limit control using VISSIM and Matlab*

The left side indicates work done in VISSIM, while the right side indicates work done in Matlab, and the arrows between refer to the movement of information. See Table 6.3 for the matches of measured V'in and speed distribution.

6.3.2 Speed adaption

The process of adjusting the speed is described as follows:

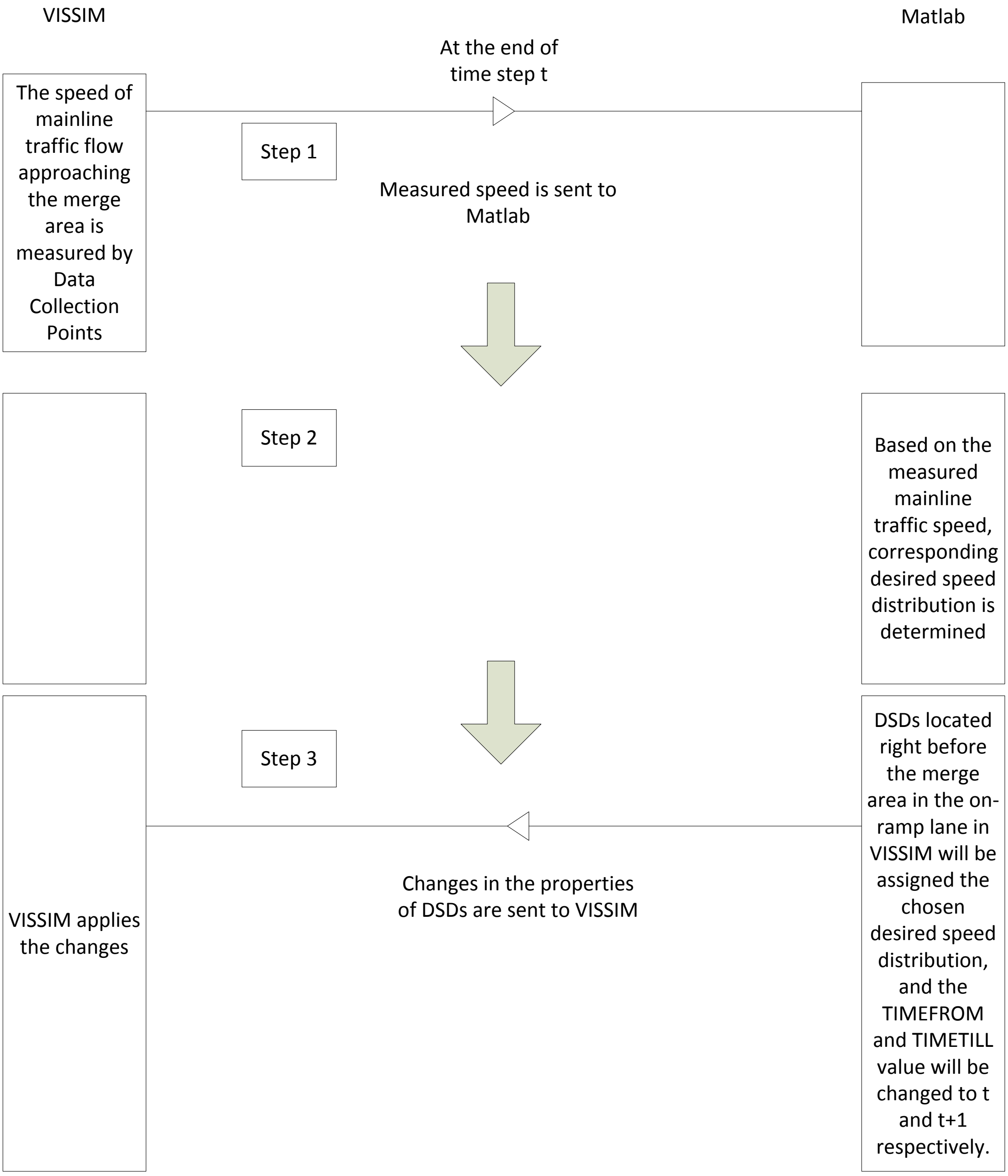


Figure 6.8: *Work process of speed adaptation using VISSIM and Matlab*

The process is similar to that of dynamic speed limit control, but without any triggers. See Table 6.5 for exact matches between measured mainline traffic speed and speed distribution.

6.4 Conclusion

This chapter illustrates the setting up of a theoretical case study to examine the feasibility of the proposed hypothesis and the impacts of its controller. The case study chose to use simulations with VISSIM and Matlab. VISSIM has been chosen due to its connection with external control tool, i.e., Matlab, which will be used to realize more complex control in VISSIM.

For the sake of simplicity, a hypothetical motorway network has been built in VISSIM. The created motorway network contains a motorway mainline and one on-ramp that acts as a traffic bottleneck. The on-ramp and its adjacent motorway section are assumed to be near the residential area. Four sections are defined on the network, as follows:

- Target area, including the on-ramp and its adjacent motorway section, which is assumed to be close to residential areas
- Dynamic-speed-limit-controlled motorway section upstream of the target area
- Uncontrolled motorway section upstream of the dynamic-speed-limit-controlled section
- Motorway section downstream of the target area

Then, the exact settings and calibrations in VISSIM are illustrated. Finally, the steps involved in the realization of the dynamic speed limit control and speed adaption for on-ramp vehicles is illustrated with Matlab and VISSIM.

7 Simulation results

In this chapter, the results from the VISSIM simulation will be exhibited and analyzed. Does the proposed controller succeed in relocating congestion and emissions? To what extent will the traffic efficiency (travel time) be affected? Does the MTFC strategy have side effects on the traffic system?

The following question will answered after reading this chapter:

- ***What are the impacts of the proposed MTFC strategy in terms of traffic efficiency, traffic emission, traffic safety, driver acceptance, and climate?***

Section 7.1 introduces the scenario setting. Section 7.2 determines the performance indicators to evaluate the simulation results. Section 7.3 analyzes the impacts of the proposed MTFC strategy on the traffic emission near residential areas and traffic efficiency. Section 7.4 examines the impacts of tuning controller parameters. Section 7.5 analyzes the side effects of the proposed MTFC strategy on traffic emission on other motorway sections, climate, driver acceptance and traffic safety.

7.1 Simulation scenario

To test the feasibility and the impacts of the proposed controller, four scenarios will be simulated in VISSIM:

- Reference scenario without any traffic management:

This scenario is simulated to generate a benchmark result, based on which any improvement of the proposed controller can be qualified and quantified.

- MTFC control scenario using a combination of fixed/dynamic speed limits.

The second scenario aims to test the effectiveness of the proposed control algorithm, and the impact on the traffic system, including travel time, traffic emission, traffic safety, climate and social acceptance.

- Modification scenario 1, with varying values of the regulator parameter P.
- Modification scenario 2, with varying values of desired occupancy O_c.

These two scenarios aim to test the impacts of tuning the parameters of the formulated controller.

In order to eliminate the impact of the random nature of simulation and thereby generate more accurate results, the first two scenarios will be simulated 10 times, each of which will be run at different random seed. See Figure 7.1.

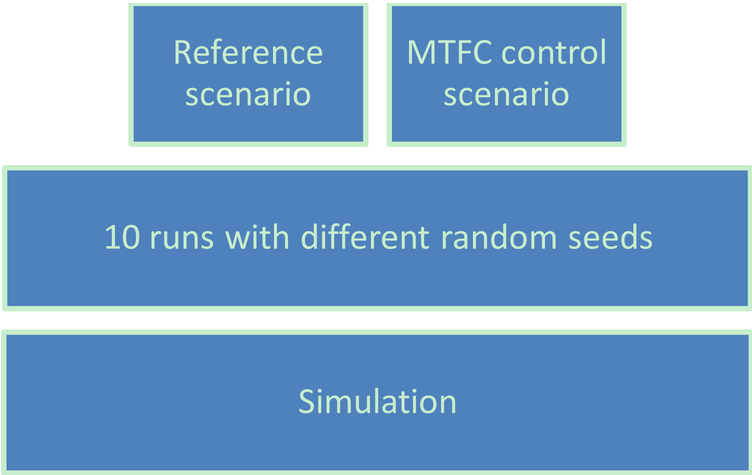


Figure 7.1: *Simulation setup for reference case and MTFC control case*

The random seed is calculated with the formula given below (Stanescu, 2008):

$$Randomseed_i = |15*i - 15^{0.2*i}|$$

where i is the number of simulations run for a specific scenario. The calculated value of each random seed is given below:

Table 7.1: *Value of random seeds.*

i	1	2	3	4	5	6	7	8	9	10
Random seeds	13	27	40	51	60	64	61	44	4	75

Source: (Stanescu, 2008).

The simulation process for the last two scenarios, as indicated in Figure 7.2, is different from that of the reference scenario and MTFC control scenario. The modification scenarios will be simulated in 1 single run for each value of the parameter, using the same seed. In total, there will be 12 different values for each tunable parameter. See Table 7.2 for the exact values of P and O_c to be tested.

Table 7.2: *Varying values of parameter P and O_c to be tested.*

Parameters												
P	*0.01*	*0.05*	*0.07*	*0.1*	*0.4*	*0.7*	*1*	*2*	*5*	*100*	*200*	*300*
O_c	*13*	*17*	*20*	*23*	*25*	*27*	*32*	*35*	*40*	*50*	*80*	*100*

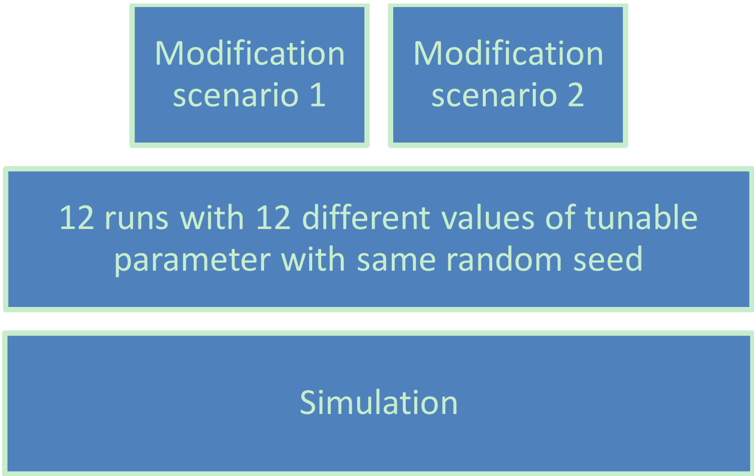


Figure 7.2: *Simulation setup for modification cases.*

7.2 Performance indicators

A set of performance indicators has been chosen to assess the impacts of the proposed controller on traffic efficiency and traffic emission.

Traffic efficiency performance indicators

The performance of a controller on traffic efficiency can be relative to its impacts on traffic delay and travel time. Given the availability of measured data, the following indicators were selected to assess the controller performance on traffic efficiency:

Average traffic delay (s) *= average delay per vehicle experienced in the entire network*

Total travel time (veh/h) *= total travel time spent in the entire network*

'Traffic delay' is defined as the additional travel time experienced by a driver due to the circumstance that hinders the desired movement. It is calculated as the time difference between the actual travel time and the free-flow travel time (AASHTO Glossary, 2011). It is deemed as the main indicator of network performance. In VISSIM, the free-flow travel time is measured as the travel time of one vehicle in a network without other vehicles or traffic lights (PTV AG, 2009). It is possible that given different traffic management measures, the decreased traffic delay would not lead to increased travel time.

Traffic Emission performance indicators

The performance of the controller on traffic emissions can be relative to its impacts on the NOx emission and fuel consumption on each section of the network. Thus, the following indicators are used:

NOx.tar (g) *= total NOx emission in the target area, which includes the on-ramp and the motorway section near the residential area*

NOx.ups (g) *= total NOx emission on the motorway section upstream of the target area*

NOx.down (g) *= total NOx emission on the motorway section downstream of the target area*

Fuel.ups (gal) *= total fuel consumption on the motorway section upstream of the target area*

Fuel.entire (gal) *= total fuel consumption on the entire motorway network*

7.3 Analysis of base scenario and MTFC scenario simulation results

Qualitative and quantitative results have been obtained from the simulation:

- 'Qualitative results' refers to the speed contour diagram, traffic flow-time diagram, and traffic flow-occupancy diagram, all of which are based on one single simulation in each scenario.

A group of data collection points, which are deployed every 300 meters throughout the hypothetical motorway network in VISSIM, were used to collect the time averaged traffic speed, time and position data. These data were collected after the simulation finished and were then sent to Matlab to plot speed contour diagrams.

The DC group located downstream of the merge area was used to measure the traffic outflow from the traffic bottleneck. Again, Matlab was used to plot the traffic flow-time diagram and the traffic flow-occupancy diagram. The related Matlab code has been saved in the CD attached to this report).

- Quantitative results will be presented in terms of the performance indicators listed in Section 7.2.

Those related data are collected with the VISSIM applications Network performance evaluation and Node evaluation. To get reliable quantitative results, each scenario has been simulated for 10 runs with random seeds as listed in Table 7.1.

7.3.1 Qualitative result

Speed contour diagrams

Figure ***7.3*** exhibits the speed contour diagrams from the base scenario (left) and the MTFC scenario (right), respectively. The y-axis indicates the varying positions in the motorway network, and the x-axis indicates the time of simulation. The color bar at the right exhibits the different colors used to signify different speeds. The motorway section from around 5 km to around 7.2 km is assumed to be surrounded by residential areas, and the location at around 6.5 km is where the traffic bottleneck (merge area downstream from the on-ramp lane) is located.

In the left diagram of

Figure ***7.3***, it can be seen that the congestion (orange and red parts) in the traffic bottleneck gradually spilled back to the upstream section, and even reduced the average speed in the downstream section (inside the black circle).

In the right diagram of

Figure ***7.3***, it is clear that the congestion in the merge area has been relocated to its upstream section, though a few tiny orange parts remain. The congestion, however, seems more severe than that in the reference scenario. Especially the part enclosed within the black circle, which reflects a rather low traffic speed, is under the control of the minimum speed limit (35 – 40 km/h) of the dynamic speed limit control. For motorway traffic, this speed limit may be too low; however, under high traffic demand circumstances, only a sufficiently low DSL can ensure that the traffic flow arriving at the bottleneck will not cause congestion. Yet, this may induce extra safety risk, which will be analyzed in Section 7.5.4.

From the speed contour diagrams, only a qualitative result demonstrated that the proposed control algorithm is effective in relocating the congestion from the target section to the upstream section; however, the quantitative result of the extent to which traffic efficiency is impacted and the changes of traffic emission cannot be derived from these figures. This will be shown in section 7.3.2, where deeper insight into the effect of MTFC strategy will be provided.

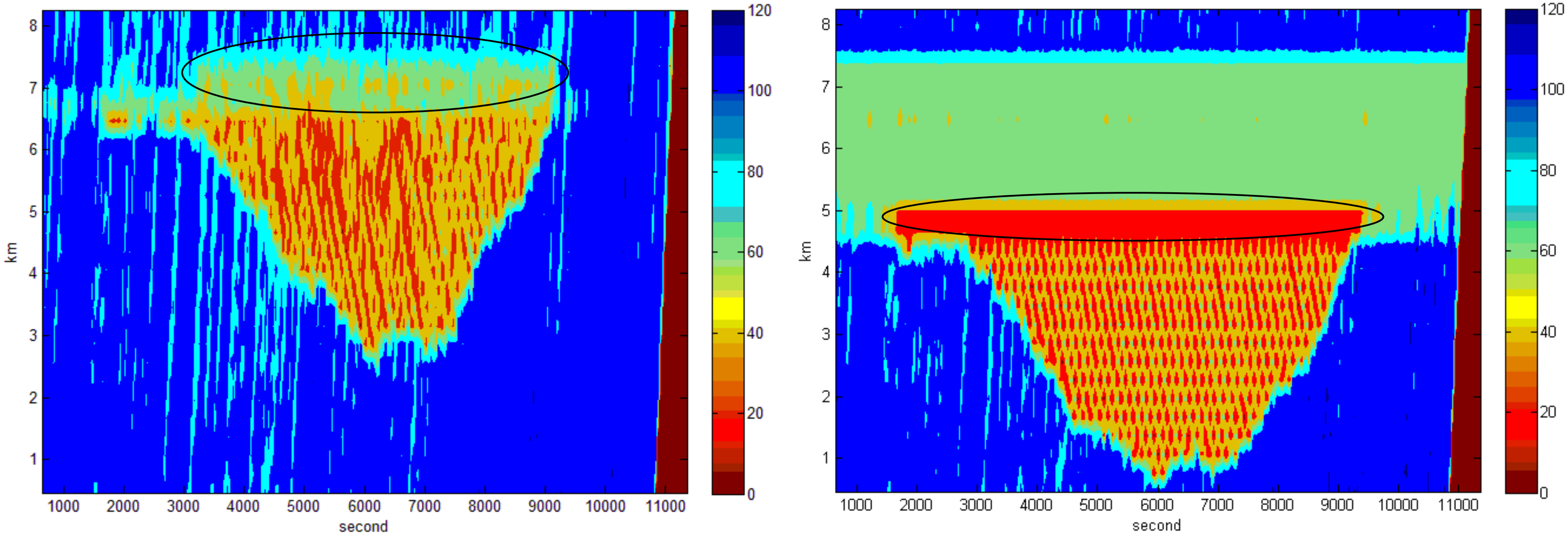
Note, in each diagram, a dark red area can be seen at the right side. This dark red part indicates that the network is empty, rather than congested. This is because no vehicles were input during the last 600 s of simulation for network clear-up. With no vehicles detected, the speed value at those locations and times is shown as zero.

Traffic flow-time diagrams

To check the impacts of the hypothesis on the capacity of the motorway section downstream of the merge area (traffic bottleneck), the outflow-time diagrams have been drawn as shown in Figure 7.4, and the outflow-occupancy diagrams have been drawn as shown in Figure 7.5.

In Figure 7.4, the traffic flow is more stable downstream of the traffic bottleneck in the MTFC scenario; however, the capacity seems to be less improved. Thus, it cannot be concluded from the traffic flow-time diagram that the MTFC strategy would prevent the capacity drop at the traffic bottleneck (the merge area downstream of the on-ramps).

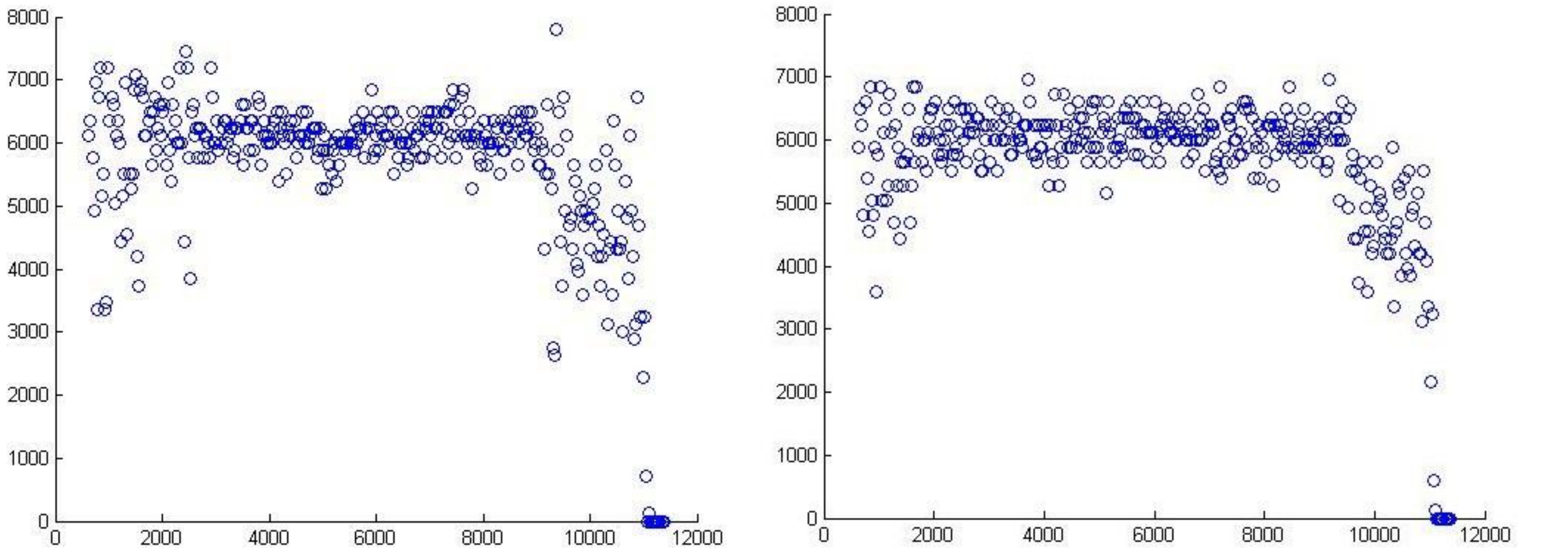
In Figure 7.5, it is clear that the capacity drop is almost prevented in the MTFC scenario; however, it seems that the motorway capacity is not fully utilized under the MTFC scenario, since the highest traffic flow observed in the traffic flow-occupancy diagram in the base scenario is higher than in MTFC scenario. This is probably due to the 80-km zone used in the MTFC scenario, due to the fact that lower traffic speed leads to lower capacity.



Speed contour diagram from reference scenario

Speed contour diagram from MTFC scenario

Figure 7.3: *Speed contour diagrams from reference scenario and MTFC scenario.*



Traffic outflow and time diagram, in base scenario

Traffic outflow and time diagram, in MTFC scenario

Figure 7.4: *Flow-time diagrams of the area downstream of the merge area, in base scenario and MTFC scenario.*

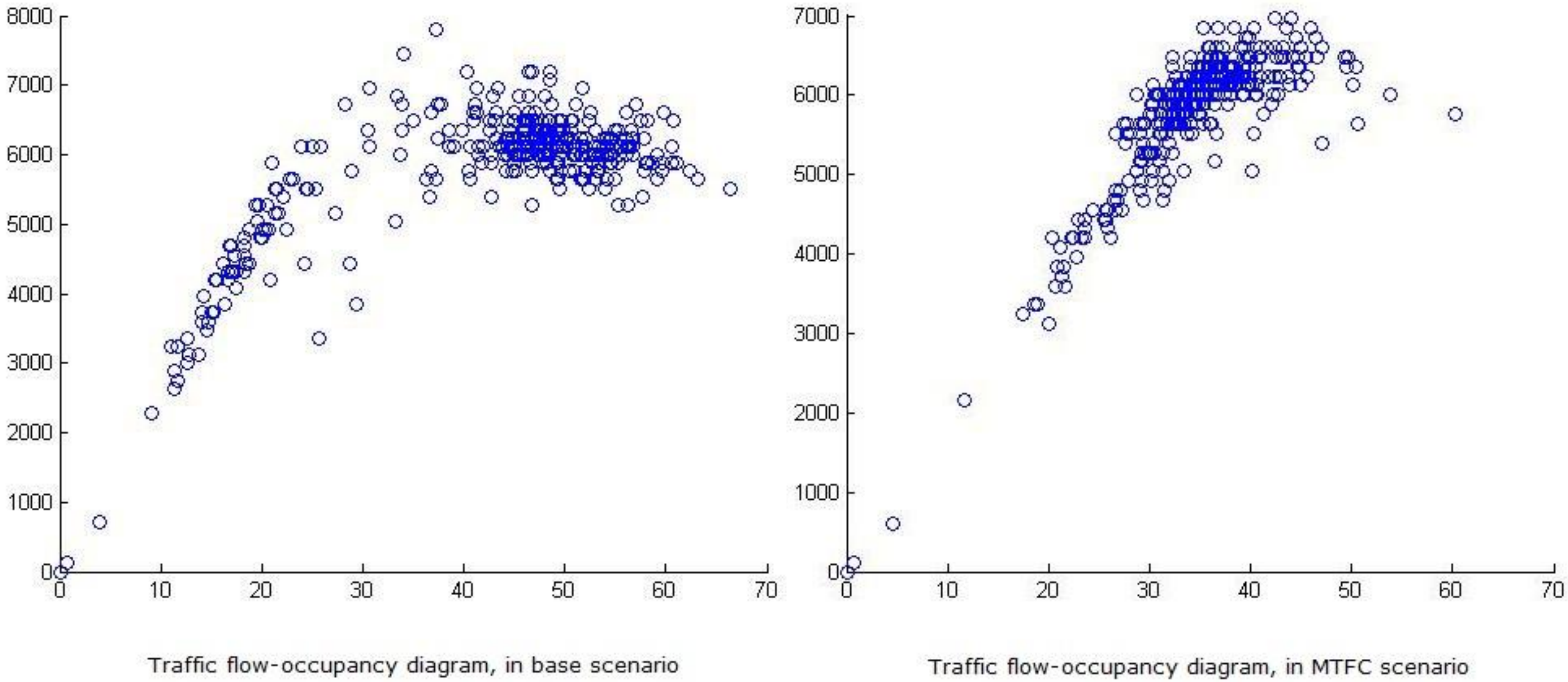


Figure 7.5: *Traffic flow and occupancy diagrams in base scenario and MTFC scenario.*

7.3.2 Quantitative analysis

Table 7.3 lists the total travel time spent in the entire network, average delay per vehicle experienced, and the NOx emission in the target area derived from the simulation of the two scenarios. The figures are averaged results from the 10 runs of the two scenarios. Check Appendix E for complete results.

Table 7.3: *Simulation results of reference scenario and MTFC scenario.*

	Reference scenario	MTFC scenario	Deviation (%)
Total travel time (veh/h)	1888.366	2092.414	+10.81%
Average delay (s)	152	142	-6.58%
$NOx._{tar}$ (g)	22659.50	19646.11	-13.30%

Table 7.3 indicates that, compared with the reference scenario, the MTFC scenario performs better in the NOx emission in the target area by a reduction of 13.30%, but worse in total travel time by an increment of 10.81%. This is in line with the results shown in the speed contour diagram, i.e., that in the MTFC scenario, congestion in the merge area has been relocated out of the target area, but the congestion on the upstream motorway section seems more severe.

One notable fact is that the average delay in the MTFC scenario is reduced by 6.58% compared to that in the reference scenario; however, the travel time in the MTFC scenario actually increases. This is attributable to the different traffic management measures that influence the free-flow performance implemented in the MTFC scenario and reference scenario. The lowered speed limit is an essential factor. Thus, although travel time in the MTFC scenario is increased, the network performance is still deemed to be improved in terms of traffic delay.

The speed contour diagrams and the quantitative results both prove that the MTFC strategy using a combination of fixed and dynamic speed limits is capable of reducing traffic emissions on the on-ramp and the motorway section near the residential area, which further contributes to the improvement of near-motorway livability conditions.

The initial parameters, namely the regulator parameter P and the desired occupancy Oc, that were used in the controller will be tuned in order to find the Pareto optimal solutions.

7.4 Effects of tuning parameters

This section investigates the impacts of tuning parameters on the traffic efficiency (average traffic delay experienced per vehicle) and traffic emission (NOx emission on the motorway section and on-ramp near the residential area), in order to find the optimal values in terms of different conditions.

The analysis will be based on:

- Generalized indicator, which is developed in Section 7.4.1; and
- Speed contour diagrams.

The full figures will be listed in Appendix F, and will not be shown in this section.

7.4.1 Generalized indicator

The following generalized indicator has been developed to assess the impacts of tuning parameters.

$J = a*E_{tar}/E_{tar.nom} + b*AVD_{entire}/AVD_{entire.nom}$

where

J = the generalized indicator

a.b = weighting factors

$\boldsymbol{E_{tar}}$ ***(g)*** = NOx emission on the target motorway section and on-ramp in modification case

$\boldsymbol{E_{tar.nom}}$ ***(g)*** = NOx emission on the target motorway section and on-ramp in reference case

$\boldsymbol{AVD_{entire}}$ ***(s)*** = average delay per vehicle experienced on the entire motorway network in modification case

$\boldsymbol{AVD_{entire.nom}}$ ***(s)*** = average delay per vehicle experienced on the entire motorway network in reference case

$\boldsymbol{AVD_{entire.nom}}$ and $\boldsymbol{E_{tar.nom}}$ are obtained from the simulation of reference scenario, while $\boldsymbol{AVD_{entire}}$ and $\boldsymbol{E_{tar}}$ are from the simulations of the two modification scenarios. For those simulations, the random seed will be consistent and equal to the default value 13.

The varying values of tunable parameters in the controller will lead to different $\boldsymbol{AVD_{entire}}$ and $\boldsymbol{E_{tar}}$. Based on those data, along with the different weighting factors, the generalized indicator will yield a group of scores, which can be used to examine the impacts of varying parameters on traffic efficiency and traffic emissions. In general, a smaller score indicates a better result.

7.4.2 Impacts of tuning regulator parameter

View from generalized indicator

In total, the regulator parameter has 12 different values, as listed in Table 7.2. Three conditions are examined by modifying the weighting factors:

- Balanced condition: weighting factor a = b = 0.5, namely
  $J = 0.5*E_{tar}/E_{tar.nom} + 0.5*AVD_{entire}/AVD_{entire.nom}$
- Traffic efficiency optimized: weighting factor a = 1, b = 0, namely
  $J = 0*E_{tar}/E_{tar.nom} + 1*AVD_{entire}/AVD_{entire.nom}$
- Traffic emission optimized: weighting factor a = 0, b = 1, namely
  $J = 1*E_{tar}/E_{tar.nom} + 0*AVD_{entire}/AVD_{entire.nom}$

The best performance in the traffic efficiency and traffic emission optimized condition are the optimal solution for traffic efficiency and traffic emission. Note, only a series of discrete value parameters were tested. This means the actual optimal solution for each parameter may differ from the results obtained in this study.

Thirty-six (36) scores were yielded, which are illustrated in Figure 7.6. For all of the three conditions, the scores decrease as the P increases, and reach the bottom at P = 0.4 or P = 1. From then on, the scores start to increase in direct proportion to the increase of P until P = 5, and then decrease again. The scores stop decreasing and keep steady since P ≥ 100.

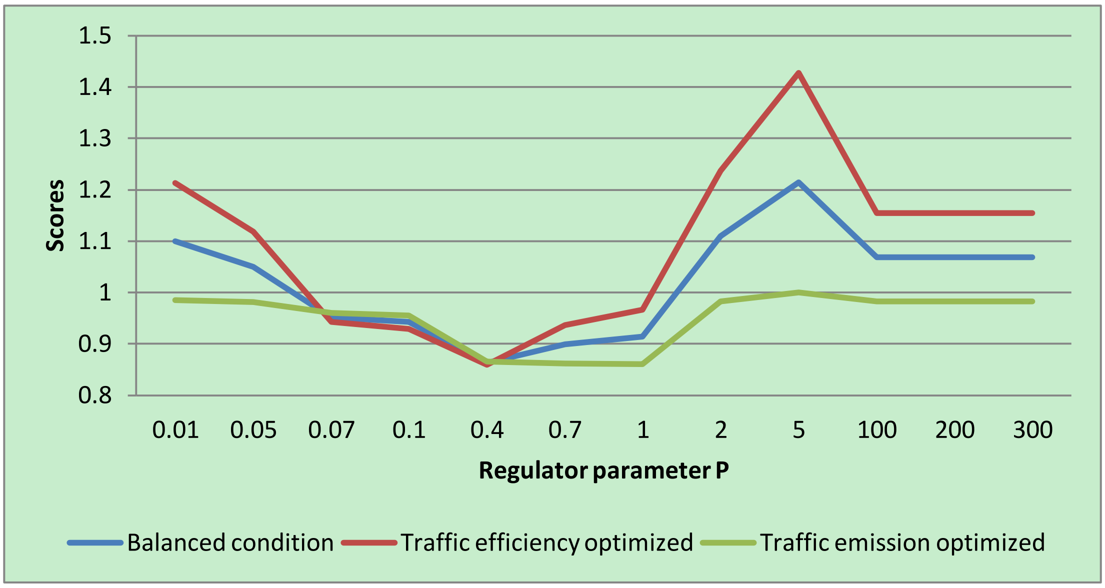


***Figure 7.6:** Impacts of tuning regulator parameter P.*

The lowest score is found approximately at:

- P = 0.4 in the balanced condition
- P = 0.4, when the objective function is optimized in terms of traffic efficiency
- P = 1, when the objective function is optimized in terms of traffic emission in the target area.

The best performances of certain objectives in every condition are as listed below:

Table 7.4: *Best performance in different conditions, and deviation from that in reference scenario.*

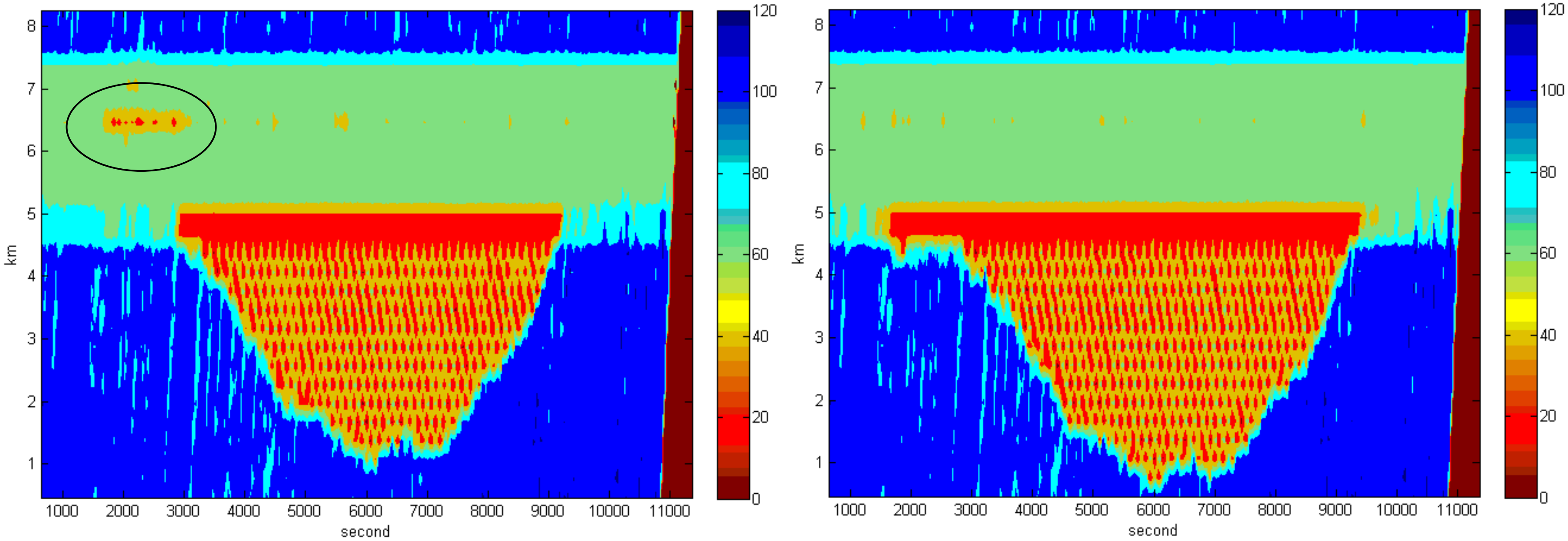
Conditions	**Performance indicator**		**Deviation from the reference (%)**
Traffic efficiency optimized	AVD_{entire} (s)	124.036	-14.04%
	E_{tar} (g)	19480.22	-13.46%
Traffic emission optimized	AVD_{entire} (s)	139.454	-3.35%
	E_{tar} (g)	19371	-13.95%
Balanced condition	AVD_{entire} (s)	124.036	-14.04%
	E_{tar} (g)	19480.22	-13.46%

As the table shows, when the controller is optimized in terms of traffic efficiency, the traffic emission reduction is also remarkable; however, while the controller is optimized in terms of traffic emission reduction, much smaller benefits are gained in traffic delay reduction.

View from speed contour diagram

As indicated in Section 5.3, increasing/decreasing the regulator parameter P contributes to stronger/smoother reactions of the regulator, respectively. This is evidenced by the speed contour diagrams, as shown in Figure 7.7. In the case of P = 0.4, the control action is actuated at around time 3000 s, which is later than in the case of P = 1, which leads to an earlier actuation (i.e., at time 2000 s). The smoother reaction of the controller in the case of P = 0.4 results in small-scale congestion as indicated inside the black circle.

It is quite clear in the case of P = 0.4, however, that the congestion (i.e., orange and red part) on the upstream motorway section is temporally/spatially shorter than in the case of P = 1. This is consistent with the result shown in Figure 7.6 that using P = 0.4 in the controller leads to lower traffic efficiency than in the case of P = 1.



Speed contour diagram, P=0.4

Speed contour diagram, P=1

Figure 7.7: *Speed contour diagram for P = 0.4 and P = 1.*

7.4.3 The impacts of tuning desired occupancy

View from generalized indicator

In total, there are 12 different values of desired occupancy O_c, as listed in Table 7.2. And again, three conditions are examined by modifying the weighting factors:

- Balanced condition: weighting factor a = b = 0.5, namely
  $J = 0.5*E_{tar}/E_{tar.nom} + 0.5* AVD_{entire}/AVD_{entire.nom}$
- Traffic efficiency optimized: weighting factor a = 1, b= 0, namely
  $J = 0*E_{tar}/E_{tar.nom} + 1* AVD_{entire}/AVD_{entire.nom}$
- Traffic emission optimized: weighting factor a = 0, b = 1, namely
  $J = 1*E_{tar}/E_{tar.nom} + 0* AVD_{entire}/AVD_{entire.nom}$

This also yields 12 * 3 = 36 scores, which are visualized in the figure below:

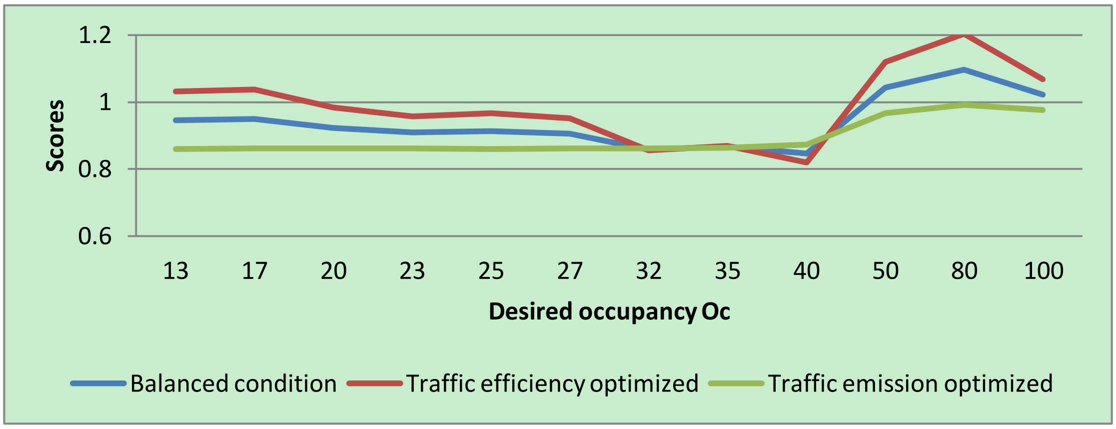


Figure 7.8: *Impacts of tuning desired occupancy O_c.*

For the traffic efficiency optimized condition, the score decreases as the P increases, and reaches a low point at O_c = 40. From then on, the score starts to increase in direct proportion to the increase of O_c until O_c =80, and then decreases again. A similar trend holds for the balanced condition. In regards to the traffic emission optimized condition, the score almost remains constant as O_c increases, and dramatically increases after O_c = 40. The score reaches a peak at O_c = 80, and then falls again.

In addition, the lowest score in each condition is found approximately at:

- O_c = 40 in the balanced condition;
- O_c = 40, when the objective function is optimized in terms of traffic efficiency;
- O_c ranges from 13 to 32 when the objective function is optimized in terms of traffic emission in the target area.

The best performances of certain objectives in every condition are as listed below:

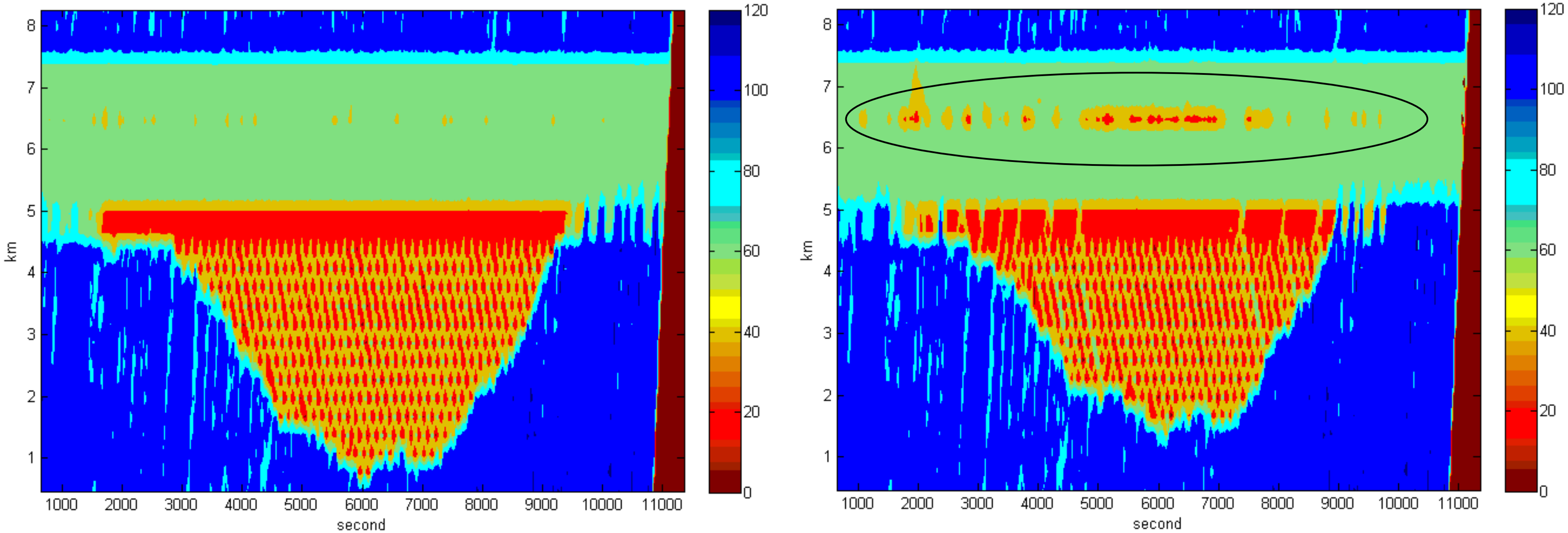
Table 7.5: *Best performance in different conditions, and deviation from that in reference scenario*

Conditions	Performance indicator		Deviation from the reference (%)
Traffic efficiency optimized	AVD_{entire} (s)	118.267	-18.04%
	E_{tar} (g)	19651.76	-12.70%
Traffic emission optimized	AVD_{entire} (s)	138.073	-4.31%
	E_{tar} (g)	19374.65	-13.93%
Balanced condition	AVD_{entire} (s)	118.267	-18.04%
	E_{tar} (g)	19651.76	-12.70%

A similar result could be found from the table above, compared with that in Table 7.4. As the table shows, when the controller is optimized in terms of traffic efficiency, that also leads to a large reduction in traffic emission; however, while the controller is optimized in terms of traffic emission reduction, much smaller benefits are gained in traffic delay reduction.

View from generalized indicator

As indicated in Section 5.3, increasing/decreasing this parameter leads to more insensitive/sensitive reactions of the control action, respectively. Similarly, this can also be evidenced with the speed contour diagrams as shown in Figure 7.9. In the case of O_c = 40, there is a light congestion as circled in the merge area (at the location around 6.5 km). In contrast, in the case of O_c = 27, almost no congestion occurred in the merge area. This means that using a higher value for desired occupancy in the controller results in insensitive actuation of control action, and a higher possibility of the appearance of congestion; however, in the case of O_c = 40, congestion on the upstream motorway section is temporally and spatially shorter than in the case of O_c = 27.



Speed contour diagram, Oc=27

Speed contour diagram, Oc=40

Figure 7.9: *Speed contour diagrams for O_c = 27 and O_c = 40.*

7.5 Side effects of the improvement on livability

Improvements in livability conditions in the MTFC scenario may be gained at the expense of other aspects, such as the emission of air pollutants on other motorway sections, emission of climate-related pollutants, and traffic safety. In addition, drivers may not accept new traffic management measures that damage their welfare. This section investigates the impacts of the controller on those aspects.

7.5.1 Air-pollutant emission on other motorway sections

The implementation of MTFC strategy relocates congestion to the motorway section upstream of the target area. This may result in more air pollutant emission on the upstream section, and less on the target section and its downstream section. The benefits on the target section have been evidenced in Section 7.3; thus, this section will examine the loss in the upstream section and gains in the downstream section. Similarly, the NOx emission data is used to represent the traffic emission.

Table 7.6: *NOx emission on motorway section upstream (downstream) of the target area in reference scenario and MTFC scenario*

Reference scenario			**MTFC scenario**		
$NOx._{ups}$ (g)	*$NOx._{down}$ (g)*	*$NOx._{entire}$ (g)*	*$NOx._{ups}$ (g)*	*$NOx._{down}$ (g)*	*$NOx._{entire}$ (g)*
46315.8	21526.51	90501.81	49334.26	21430.23	90410.6

As can be seen from the table above, the NOx emission on the upstream section is increased in the MTFC scenario by 6.5%, while the NOx emission on the downstream section is reduced slightly by 0.45%. In total, the NOx emission in the MTFC scenario is almost the same as in the reference scenario.

This suggests that the implementation of MTFC strategy has few impacts on traffic emissions in the entire network. In this study, improvements in livability in the target area are gained at the expense of air quality in its upstream section, which is acceptable if the upstream section is environment-insensitive.

7.5.2 Impacts on climate

The MTFC strategy does have positive impacts on the near-motorway livability, but what about its impact on climate change, e.g., CO_2 emissions? Since the Node evaluation application is unable to output CO_2 emission data, the fuel consumption in the entire motorway network will be used to assess this issue, for the emission of CO_2 is directly proportional to the fuel consumption (Beek, et al., 2007).

Table 7.7: *Fuel consumption in the entire motorway network in the reference scenario and MTFC scenario*

	Reference scenario	**MTFC scenario**
$Fuel._{entire}$ *(gal)*	6654.545	6647.837

Similar to the emission of air pollutants, the fuel consumption in the two scenarios is almost the same. As a whole, the MTFC strategy does has no obvious impact on fuel consumption. It could be concluded that, in this study, the improvement in near-motorway livability leads to few impacts on CO_2 emission of traffic. The objective of improving air quality and the objective of reducing greenhouse gas are not mutually exclusive.

7.5.3 Driver acceptance

The MTFC strategy relocates the congestion of the merge area to its upstream section, thus its impacts on drivers from motorway origin and from on-ramp origin are different. The congestion in the merge area downstream from the on-ramp nose is removed in the MTFC scenario. Furthermore, no ramp metering measures are implemented. These definitely bring positive impacts for drivers from the on-ramp origin, enabling them to experience more comfortable driving on the on-ramp lanes and the merge area. Thus, this section will investigate driver acceptance by analyzing the changes in fuel consumption on the upstream section to see how the drivers from motorway origin are affected.

Table 7.8: *Fuel consumption on the motorway section upstream of the target area and in the entire network in the reference case and the MTFC case*

	Reference scenario	**MTFC scenario**
$Fuel._{ups}$ *(gal)*	3,408	3,628
$Fuel._{entire}$ *(gal)*	6,654	6,647

It can be seen that, in the MTFC scenario, the fuel consumption on the upstream section is increased. The increment is around 6.5%. In addition, the fuel consumption in the entire network is hardly impacted by the MTFC strategy. This means that if the drivers travel across the entire motorway, their vehicle will not consume more fuel than in the reference scenario. Thus, these drivers may accept the MTFC strategy.

In

Figure *7.3*, it has been observed that the congestion induced by the MTFC strategy spills back spatially further than in the reference scenario. This means that, in some segments of the upstream sections, drivers will encounter congestion earlier than in the reference scenario. If some of those drivers exit the motorway through off-ramps,[12] they will not benefit from the improved traffic condition downstream; in other words, their vehicles will consume more fuel and experience more travel time than usual. There is a high possibility that these drivers will be against the MTFC strategy.

7.5.4 Impact on traffic safety

Traffic speed impacts traffic safety. The MTFC strategy is implemented by using speed control measures. Thus, it is necessary to study how traffic safety is impacted. Higher speed leads to higher crash rate and crash severity, and it has been proven that reduced speed and homogenized speed has a positive on traffic safety (Beek, et al., 2007). Besides the traffic speed, Beek et al. (2000) also mentioned that speed differences between vehicles also affect the crash rate. Since the target area is regulated to 80 km with strict enforcement, it is believed that traffic safety in the target area has been improved. Thus, this section will focus on the motorway section affected by the dynamic speed limit, namely that section upstream of the 80-km zone (target area).

The notion of speed difference denotes the difference of 5-minutes averaged speed in one section and its adjacent section. Speed difference is of importance at the location where the maximum speed limit is reduced. The equation given below can be used to calculate the speed difference (Abdel-Aty, Haleem, Cunningham, & Gayah, 2008):

$$\text{Speed difference (F)} = \text{Average Speed}_E - \text{Average Speed}_F$$

where

F: stands for the section of interest;

E: stands for the section upstream of the section of interest.

Cunningham (2007) concluded that if the speed difference is larger than or equal to 7 mph (around 11.3 km/h), then there will be an explosive increase of crash risk. The speed differences (i.e., difference of 5-minutes averaged speed), between the dynamic-speed-limit-controlled section (which is the section of interest, around 500 m) and the section 400 m upstream of it, are collected. Then,

[12] This is not simulated in this case study, but is quite common in reality.

each difference of 5-minutes averaged speed between those two sections minus 11.3 km/h, the lines in the figure given below, shows the final result.

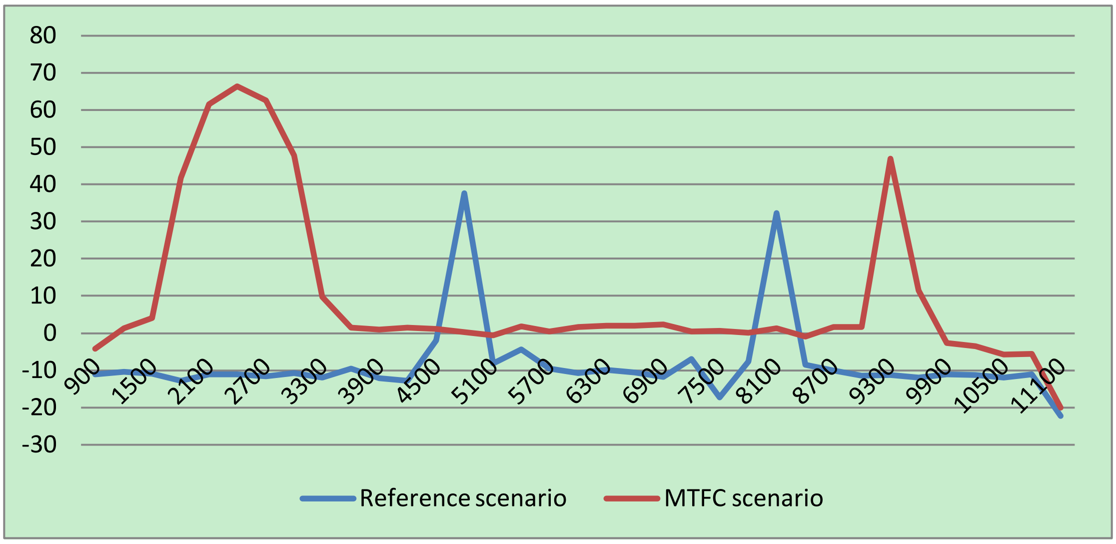


Figure 7.10: *Absolute speed difference between dynamic speed limits controlled section and its upstream section, in reference scenario and MTFC scenario*

The lines above 0 indicate that the speed difference is greater than 11.3 km, i.e., at the corresponding periods, traffic flows are at high risk of crash. It is ambiguous that, in the MTFC scenario, the speed differences often exceed 11.3 km/h, particularly during the periods of time 1500 to 3000 s and 9300 to 9900 s. From the speed contour diagram of MTFC scenario in

Figure ***7.3***, it can be seen that these two periods are the congestion formulation and dissolving stages, respectively. As a whole, it can be concluded that the MTFC strategy using dynamic speed limits leads to a higher crash risk for drivers.

7.6 Conclusion

The simulation results exhibited in this chapter proved the feasibility of applying MTFC strategy to relocate congestion and emission in order to improve near-motorway livability. The NOx emission on the target section (which is assumed to be close to residential areas) is lower in the simulation of the MTFC scenario then in the reference scenario. What's more, it has been proven that setting proper regulator parameters and triggers for the proposed controller is important. The most important finding is that, for road authorities, it would not be impossible to improve traffic efficiency and near-motorway livability at the same time.

In conclusion, viewed from either the perspective of near-motorway livability or traffic efficiency, fine-tuned mainstream traffic flow control strategy leads to a large reduction of traffic emission near residential areas, while leading to higher traffic efficiency. However, this strategy relocates the traffic risk as well as the congestion and emission, and it may be unfavorable to a few drivers if they leave the motorway halfway. In addition, no harm will be brought about by the MTFC strategy on the climate.

8 Conclusions and recommendations

The main objective of this graduation project is to find a promising way to improve near-motorway livability conditions without compromising the current traffic efficiency. In this chapter, the conclusions related to the research objective and questions will be summarized, and recommendations for further study are given.

8.1 Summary of the research process

This section will provide a summary of the work done in this study. The answers to the sub-questions proposed in Section 1.2.2 will be presented, and will be used in Section 8.2 to support the answers to the three main research questions.

- *What is the near-motorway livability problem?*

The near-motorway livability problem in the Netherlands has been formulated as being that the motorway traffic flow emits a large amount of air pollutants that harm the ambient air quality. People, particularly those that are sensitive, like children, elderly people, and unhealthy people, who live near or spend a substantial amount of time near these motorways are observed to have a higher risk of getting lung disease, cancer, heart disease, respiratory disease, etc. The result of the worsened air quality is usually not borne by the drivers, but by the population nearby.

Many factors influence the near-motorway livability problem, including the total amount of traffic emission, air pollutant dispersion, distance from the motorway, and population attributes. This thesis aims to intervene at the source of this issue, that is, reducing the total amount of traffic emission.

- *What is the promising solution to the near-motorway livability problem?*

Numerous approaches exist to reduce traffic emissions, and they generally fall into two categories: (1) reduction of total vehicle travel; and (2) reduction per unit emission. Another classification is as follows: (i) technique approaches, (ii) systemic approaches, and (iii) behavioral approaches, which are actually in line with the first classification. In general, five approaches are most sound: dynamic traffic management; clean fuel and vehicles; energy-efficient vehicle technology; demand management; and public transport.

Those approaches, regardless of which type they are, all have advantages and disadvantages. Based on the factors that influence motorway traffic emissions, dynamic traffic management seems to be the best choice, since it can be used to (a) reduce traffic volume, (b) restrain the heavy emitting vehicles, (c) maintain traffic speed at optimal level, and (d) reduce traffic dynamics; however, it would be unwise to simply state that DTM is better than other alternatives, since the total potential reduction of traffic emission is difficult to assess.

If the time scale of implementation is taken into account, DTM is often preferred in practice, since it is a short-term option. Thus, in this study, DTM is deemed a promising way to reduce the traffic emissions and thus contribute toward the improvement of near-motorway livability.

However, in the long run, the capability of DTM is limited in meeting the explosively increasing amount of vehicles. At that time, other approaches will have tremendous potential to contribute to the reduction of traffic emission.

- *Which dynamic traffic management measures may reduce motorway traffic emission?*

Proper fixed speed limit, particularly when strictly enforced, has been proven to effectively reduce traffic emissions by maintaining the traffic speed at a level of less emissions, e.g., 80 km/h. But the strictly enforced fixed speed limit is highly location-specific. Dynamic speed limits are capable of dealing with complex traffic conditions, and several studies have proven their capacity to reduce traffic emissions, but it has been found to be less efficient in congested traffic flow.

Ramp metering aims toward maximizing traffic throughput the motorway by limiting the traffic inflow from on-ramps. Several studies have suggested that the ramp metering strategy can be adapted to serve the objective of reducing traffic emissions on the motorways, for it eliminates congestion on the motorways. But the efficiency of ramp metering is limited by the storage space of the on-ramp lanes. In addition, improvement on the motorways is gained at the cost of the traffic flow on the on-ramps. This will lead to more traffic emission on the on-ramps, which are even closer to residential areas.

Mainstream traffic flow control is similar to the ramp metering strategy. The advantage of MTFC is that it has a larger storage space, and will not pose negative impacts on the traffic flows on the on-ramps. MTFC strategy is a rather new concept, though, and although its capacity to maximize traffic throughput has been proven, few studies have paid attention to the use of MTFC to reduce traffic emission.

- *What multi-objective optimization methodology could be used?*

When dealing with the multi-objective optimization problem, a simple but efficient way is to use the generalized indicator, which is the weighted linear sum of the objectives. One could weigh the objectives against each other by taking the stakeholders' preferences or any other constraints into account, then maximizing or minimizing this objective function according to specific requirement.

- *How can a controller be developed for the mainstream traffic flow control strategy?*

A hypothesis of applying mainstream traffic flow control strategy to relocate the congestion and emission on the motorway section near the residential area is established. A controller is needed to realize the proposed hypothesis. The developed controller, as given below, is an ALINEA-like one: (1) it is based on the feedback control theory; (2) it uses critical occupancy as the trigger of the control action.

$$V'_{in}(t) = V_{in}(t - 1) + P(O_c - O_m(t - 1))$$

where

$\boldsymbol{V'_{in}}$ = *the calculated maximum speed limits on the controlled upstream section while the control action is actuated.*

$\boldsymbol{V_{in}}$ = *the real-time measured average speed in the controlled upstream section.*

$\boldsymbol{P}$ = *regulator parameter, which determines how strongly the control action reacts.*

$\boldsymbol{O_m}$ = *the measured real-time traffic occupancy of the target motorway section.*

$\boldsymbol{O_c}$ = *the desired occupancy (%) on the target motorway section, acts as the trigger of control action.*

$\boldsymbol{t}$ = *time step, e.g., 30 s, 1 min or 2 min.*

The feedback control is used because it could stabilize the unstable traffic flow, and does not need an extra predictive model. Critical occupancy is used because it is robust in different traffic conditions, and thus contributes to the robustness of the control result.

- *How can the feasibility of the proposed MTFC strategy be assessed?*

The feasibility of the proposed controller has been examined in a theoretical case study using simulation. The microscopic traffic model VISSIM and an external control tool, Matlab, were used in the simulation. Four scenarios were simulated: (1) Reference scenario; (2) MTFC control scenario; (3) Modification scenario 1 (tuning regulator parameter P); and (4) Modification scenario 2 (tuning desired occupancy O_c).

The reference case is simulated to output traffic and emission data as a benchmark for further comparison. The MTFC control case is simulated to examine the feasibility of the proposed hypothesis and the impacts of its controller. The modification cases are simulated in order to find the approximate optimal values of the controller-tunable parameters with the aim of optimizing the MTFC control to meet the requirements for traffic efficiency and traffic emission reduction.

A hypothetical motorway network is comprised of a mainline and an on-ramp, built in VISSIM. The on-ramp and its adjacent motorway section are the target area, which is assumed to be near the residential areas. The objective of the controller is to reduce the NOx emission in the target area without compromising traffic efficiency in the entire network.

- *What are the impacts of the proposed MTFC strategy in terms of traffic efficiency, traffic emission, traffic safety, driver acceptance, and climate?*

The simulation results are presented in three parts:

➢ *The impacts of the controller on the NOx emission in the target area, and the average traffic delay experienced per vehicle in the entire network.*

Compared with the results from the reference case, the NOx emission in the target area is reduced by 13.30%, while the average traffic delay is reduced by 6.58%.

➢ *The impacts of the tuning controller parameters.*

A generalized indicator as given below has been developed to assess the impacts of tuning parameters:

$J = a*E_{tar}/E_{tar.nom} + b*AVD_{entire}/AVD_{entire.nom}$

where

J = generalized indicator

a.b = weighting factors

E_{tar} (g) = NOx emission on the target motorway section and on-ramp in modification case

$E_{tar.nom}$ (g) = NOx emission on the target motorway section and on-ramp in reference case

AVD_{entire} (s) = average delay per vehicle experienced in the entire motorway network in modification case

$AVD_{entire.nom}$ (s) = average delay per vehicle experienced in the entire motorway network in reference case

If the generalized indicator is optimized in terms of traffic efficiency (a = 0, b = 1), the approximate optimal values are found at P = 0.4, or O_c = 40. If it is optimized in terms of traffic emission reduction (a = 1, b = 0), P = 1, or O_c ranges from 13 to 32, the best result are obtained. If it is optimized in the balanced condition (a = b = 0.5), the approximate optimal value of P and O_c are 0.4 and 40, respectively.

- *The side effects of the controller on the NOx emission on the other motorway sections, traffic safety, climate, and driver acceptance.*

The NOx emission on the upstream section is increased in the MTFC scenario by 6.5%, while the NOx emission on the downstream section is reduced slightly by 0.45%. In total, the NOx emission in the MTFC scenario is almost the same as in the reference scenario.

As a whole, the MTFC strategy does has no obvious impact on fuel consumption, i.e., no obvious impacts on CO_2 emission, which is considered a greenhouse gas.

Drivers from the on-ramp are benefited by the improved traffic flow in the merge area, and thus are expected to welcome the MTFC strategy; however, the drivers from the motorway origin may be of different opinions. If the drivers travel through the entire motorway, their vehicle will not consume more fuel than in the reference scenario. These drivers may accept the MTFC strategy. In contrast, if drivers confront the spilled-back congestion, and leave the motorway via off-ramps (this is not included in the simulation, but is common in reality), then they will consume more fuel than in no control scenario and may be against the MTFC strategy.

The traffic safety in the merge area is improved due to the homogenized traffic speed and the eliminated congestion; however, in the dynamic controlled section upstream of the target area, a higher risk of crash is observed through the analysis on the speed difference.

8.2 Conclusions

Answers to the three main research questions comprise the conclusion and the discussion.

- **How can the near-motorway livability problem be solved?**

The near-motorway livability problem is caused by the heavy traffic flows on motorways close to residential areas. Air pollutants are emitted from vehicles, then dispersed to the ambient areas, posing threats to human health. Several factors influence this process, such as the emission amount, the wind direction, the weather, distance from the motorway, and the given attributes of the exposed populations. The dispersion of the air pollutants is difficult to interrupt, and the impact on human health is complicated. Thus, this study is focused on ways to reduce the total amount of traffic emission.

Approaches such as dynamic traffic management, demand management, public transportation, clean fuel and vehicles, and energy-efficient vehicle technology, have all been applied in the field of air quality improvement. It has been found that proper implementation of DTM could reduce traffic emissions in short-term, but will encounter a limit when the traffic demand increases explosively in the future. Clean fuel, like bio-fuel and hydrogen, will be promising measures in future, due to advances in technology. Clean vehicles, like electric vehicles and hybrid vehicles, will help prevent or reduce emission of traffic pollutants, but the high cost is a barrier to large-scale market penetration. Demand management, especially road pricing, is effective to reduce congestion and traffic emission, and it improves equity in the transport sector, since it can internalize the external cost. Public transportation could reduce the amount of vehicle trips, contributing toward emission reduction; however, it needs to become more attractive and popular, in the meantime, if it is to help cut costs by a significant amount.

It is difficult to definitively point out which approach is better than the others, since their potential effectiveness is difficult to assess, given with different background. Among the many approaches, dynamic traffic management is preferred in this study, in light of the time-scale of its implementation. DTM is deemed as a promising solution to the near-motorway livability problem in the short term. In the long term, DTM is limited in its ability to meet the explosive increase in vehicles; at that time, other alternatives will play a role and be used together with DTM to contribute toward improving the livability conditions in the vicinity of motorways.

- **How can multi-objective optimization of the dynamic traffic management measures be achieved in order to improve near-motorway livability without compromising the traffic efficiency?**

Several dynamic traffic management strategies are considered to be capable of, or have potential for, reducing motorway traffic emissions, including speed control, ramp metering, and mainstream traffic flow control.

However, those strategies are usually applied for one specific objective, such as reducing traffic emission or maximizing the traffic throughput. When multiple objectives are involved, like maintaining traffic efficiency and reducing traffic emission in this case, those DTM measures have to be optimized to meet different and possibly competing objectives.

A popular way to deal with the different objectives is to use a generalized indicator with a linear sum of weighed objectives. The weightings given to each objective could be weighed against each other to meet certain policy requirement.

- **How can mainstream traffic control strategy be applied to deal with the near-motorway livability problem in the Netherlands?**

In this study, a MTFC strategy using a combination of fixed/dynamic speed limits is proposed to solve the near-motorway livability problem. The MTFC strategy created congestion on the motorway section that is environment-insensitive and upstream of the target area. With this strategy, the congestion and emission on the critical motorway section near the residential area is relocated. Apart from that, the improvement on the critical motorway section is not achieved at the expense of the traffic flow on the on-ramps, which are usually close to residential areas too.

A theoretical case study using simulation was conducted. The positive result was that the proposed MTFC strategy succeeded in reducing traffic emission in the target areas, while also reducing the average traffic delay per vehicle experienced in the entire network. By tuning the controller parameters, more promising results were achieved.

However, the negative result is due to the implementation of a 80-km zone, the motorway capacity seems not fully used. What's more, the side effects of the MTFC strategy have to be noted, particularly the increased crash risk in the dynamic-speed-controlled motorway section.

Above all, the most important finding from the case study is that the improvement in traffic efficiency when traffic flow is congested and unstable does not conflict with the reduction of traffic emission. More studies are required to further investigate the impacts of the MTFC strategy and eliminate its side effects.

In a nutshell, this study meets the research objective. The near-motorway livability in the Netherlands was investigated. A promising DTM strategy to improve near-motorway livability condition was found and evaluated. The result was positive in terms of meeting the requirements of the road authorities in traffic emission reduction and maintaining traffic efficiency. The research is promising, but further studies are required in order to gain deeper insight into this issue.

8.3 Recommendations

This section lists the recommendations for further studies based on this graduation work.

Focus on the four main principles to improve near-motorway livability conditions by using DTM at the network level.

In brief, the way to improve near-motorway livability by using DTM centers around reducing air pollutant emission in the vicinity of motorways. Four main principles were highlighted for further study:

1. Improve traffic flow

Maintaining traffic speed at optimal level (e.g., 60–100 km/h) and homogenizing traffic flow to reduce traffic dynamics

2. Restrain heavy-polluting vehicles

e.g., by restricting access of heavy-polluting trucks into zones where the concentration of air pollutants exceeds set thresholds

3. Reduce the traffic flow arriving at the traffic bottleneck which is close to become active

e.g., route guidance or cooperative ramp metering

4. Relocate the congestion and emission

e.g., restraining traffic inflow into the environmentally sensitive area by using MTFC strategy

At the network level, those approaches could be integrated like the examples listed below:

- Ramp metering could be implemented in the environmentally insensitive area, to increase the storage space of the MTFC strategy. An essential benefit of this combination would be a higher capacity in the MTFC affected area, and higher traffic safety.
- The combination of route guidance and cooperative ramp metering could partly solve the shortage of storage space in the on-ramp lanes. A possible benefit would be the prevention of long queues on some on-ramps while other on-ramps lanes remained empty, namely the storage space of on-ramps would be more efficiently utilized.

It must be noted that motorways are often long enough to pass several cities. Thus, the integrated network management should take into account the preferences of different municipalities.

Improve the simulation of the MTFC strategy

In reality, at times, the congestion induced by the traffic bottleneck downstream of the on-ramps will spill back and block the off-ramps. Those vehicles that are planning to leave motorway via off-ramps will wait on the upstream section and block the mainstream traffic flow, leading to more congestion. The MTFC strategy stores the vehicles on the motorway, and may lead to blocking the off-ramp too.

In this simulation, the hypothetical motorway network only consists of one on-ramp. The effect of the MTFC strategy on the upstream off-ramps was not studied. This should be studied in further research. A study focusing on a real motorway network would also be preferred in the future.

Demand management for traffic flow from on-ramps

In contrast to the drivers from motorway origin, the drivers from urban streets via on-ramps would benefit much from the MTFC strategy. They would experience less congestion and no need to wait before the merge area. This may induce an increasing amount of traffic demand entering the motorway via on-ramps, resulting in more negative impacts on motorway traffic flows. Thus, a demand management for the traffic flow from on-ramps is necessary in long term.

Improve traffic safety

As found in Section 7.5.4, the traffic safety in the dynamic-speed-limit-controlled motorway section was lowered. Particularly during the congestion formation caused by the MTFC strategy, a much higher risk of crash was observed. This is due to the greater speed difference between the controller section and its upstream section. A transit area or buffer area could be established on the motorway section upstream of the controlled section to guide vehicles and gradually reduce their speed.

Deep insight into the impacts of the MTFC strategy on air pollutant emission

In this study, no external traffic emission model was used, and only NOx emission has been output and used to study the impacts of MTFC strategy on the air quality. It seems that the result is quite promising in terms of NOx emission reduction; however, attention should also be directed toward the impacts on other air pollutants, such as PMx, SO_2, CO, O_3, etc. Thus, a more functional traffic emission model should be involved in further study.

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Appendix A: Complex nature of human-health issue

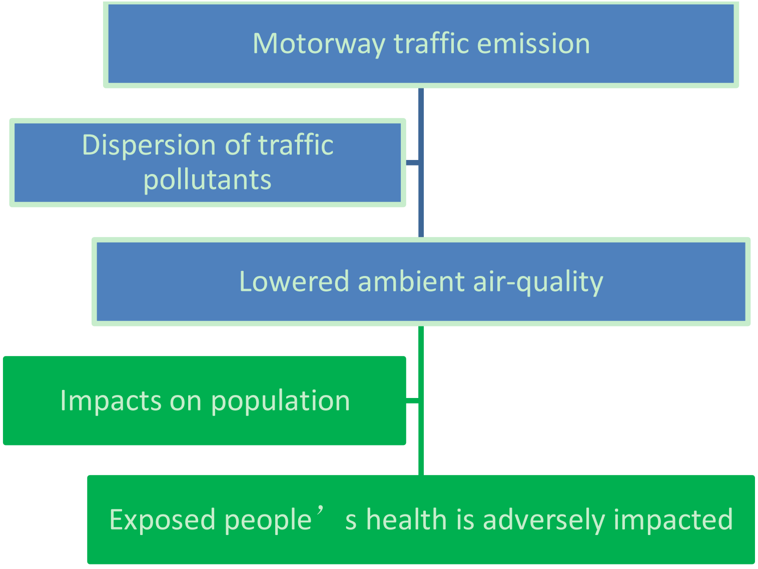

Figure A.1: The pictorial representation of the near-motorway livability problem

Generally, it is believed that worsen air-quality is responsible for the negative impacts on human health in part. As indicated in section 2.1 and 2.2, traffic pollutants have been associated with numerous diseases, such as cardiac and pulmonary diseases, asthma, cancer, low-birth rate and other respiratory diseases, etc. It is believed that the gradients of pollutions near motorways result in the elevated health risks that may be higher than in general areas (Brugge, et al., 2007).

In response, European Union (EU) has developed an extensive range of health-based standards for numerous pollutants in the air as partly shown in Table 2.3. Actually, it is quite difficult to give the threshold values of air pollutants, in terms of their harms on human-health. This is due to the complexity nature of human-health. Some additional factors to be considered when evaluating the impacts of traffic pollutants on human health can be found in *Table A.1*:

Table A.1: Additional factors affecting human health

Factors groups	
Personal factors	Social status, drinking/ smoking, family composition, if at home during the peak hour, if open window often, etc.
Other factors	Weather, distance from motorways, place of buildings (upwind or downwind), type of filtration system installed in the home,

	etc.

This complexity determines that the adverse impacts of traffic pollutants on the populations, given with different ages or health conditions, are disputed or unclear in terms of the pollutants concentration.

For example, the effect of NOx (and specifically, NO2, for which European commission has set a limit of 40 ug/m3) on health is not clear. This is because NOx is more a conservative indicator of pollution rather than a cause of bad health. Very high concentration of NO2 is determined to be negative on health but around 40 ug/m^3 is not so clear.

What's even more important, the adverse impact on human health resulted from traffic pollution starts with low concentrations, and especially PMx can already affect health before European norms of air-quality are reached, like the case in Overschie. PMx has been associated with the cardiovascular health and lung function. Besides, Hoek et al. (2002) stated that PMx pollution may be the greatest potential threat to health.

Lebowitz (1996) revealed that the lowest effect level of ozone (O_3) for asthmatic can happen with levels as low as 0.08 parts per million. This value is approximately equal to 169 μg/m^3, which is lower than the ozone standard defined by European Union (200 μg/m^3). Lebowitz (1996) also found that the sulfur dioxide start to do human harm from as low as 200 μg/m^3, for which the EU standards are 350μg/m^3 hourly and 125μg/m^3 daily. Although the daily standard is lower than 200 μg/m^3, but the hourly standard is much higher. Asthmatics may get worse even in a brief exposure to sulfur dioxide (Koren, 1995).

Appendix B: Detail of DYNAMAX project

Although cars are becoming less polluting, road traffic though is still a major source contributing to air pollutants emission. The situation along motorways is even more severe, against which in the Netherlands the so-called Air-quality Innovation Program has been established. IPL investigated lots of promising measures, including modified roadside noise barriers, cleaning of road surfaces, catalytic coatings, motorway canopies with air treatment, roadside vegetation and Dynamic Traffic Management. For the first time in Europe, theories about air-quality have been tested in large-scale practical trials. Promising DTM measures have been implemented on the motorways around Rotterdam, and then their impacts on air-quality were modeled. DYNAMAX is a contributing and representative project of IPL. Its aim was to resolve specific traffic bottlenecks and manage traffic flows based on air-quality forecasts. Thus it could be viewed as a practical multi-objective traffic management measure using DTM technology, in order to prove the practical feasibility of solving near-motorway livability problem with traffic management.

DYNAMAX project is a dynamic traffic management measure featuring managing maximum traffic speed limits on the basis of specific factors, such as environmental harmful emission, weather etc. The promising result of DYNAMAX project has proved that suitable DTM, particularly the speed control, is capable of reducing traffic emissions, congestion and routing the heaviest polluters around critical locations (Rijkswaterstaat, 2010).

Evolvement from 80km zones project to Dynamax

In the Netherlands, the previous 80km projects have proved its positive effectiveness on the reduction of emission. At five locations of Netherlands, a project called 80 km zone to test the effect of fixed speed limits was launched in 2005. The test result was promising that local traffic emission reductions of NOx were about 20-30%, and the PM10 traffic emission reductions were about 10% (Stoelhorst & Schreuder, 2010). In the meantime, however, 80 km zone project resulted in other side effects, like increased congestion observed where A13 highway enters Rotterdam (Pel, 2009). Following research has found out the reason for this capacity drop that the drivers tended to drive at a lower speed than limit on the most right lane and confront difficulty when they were trying to change lanes, namely drive behavior was changed (Stoelhorst & Schreuder, 2010). But at some test locations, the road capacity was not influenced, or even improved. Obviously, without taking the different characteristics of traffic zones into account, 80 km zone is failed to realize the objective of improving local air-quality along motorways while not or imposing less negative impact on traffic performance.

In this case, Dutch government has started to extend and upgrade the existing measure of dynamic speed limits attempting to serve multiple objectives, not only implemented when accident happens or confronting extreme bad weathers. As a result, DYNAMAX project emerged. It is expected to increase traffic performance under varying adverse conditions, and being capable to enhance road safety and local environment.

Road Side Infrastructure of the Dynamax System

Dynamax is a system that monitors the variable road signs placed above the roads to determine the maximum speed limits to be enforced in a certain section. It is a kind of ITS based DTM measure, thus its core is as same as other ITS applications which are based on the information and communication technology. Its information process center is located in the transport centers where irrelative people have less chance to see. Its road side infrastructure can be found at the test road stretches and may interest drivers most. In the following text, a short description on the road side infrastructure of Dynamax system will be made.

Figure B.1: 3 road signs consist the enforcement part of the Dynamax system.

Above figure is a picture taken on a stretch of A13 near Rotterdam, showing the speed limits enforcement system which is the major composition of the road side infrastructure. As the figure depicts, the system consists 3 road signs with 3 red circles and numbers against the black background. Each road sign contains a lamp with glass fibers to show the images, and each lamp is comprised of 3 bulbs. 3 road sign are attached on a long slim rectangle frame made of metal, and are lifted above the road at a sufficient height. In this manner, drivers can see the signs at a distant place and receive the message easily in advance.

How does Dynamax System Work

The variable maximum speed limits enforcement is done through the monitoring on the light bulbs that display a number referring to the speed limit value on the road sign. Taking the Figure B.*1* as an example, 3 lamps are turned on showing 3 numbers, all of which are 80, and 3 red circles constantly. For each lamp, the number is generated by only one bulb, as opposed to the red circle which is generated by 2 bulbs in order to keep the red circle remain visible in the event of one bulb unexpectedly failed to be on. Only if the 3 generated numbers are constant, same as the situation reflected in the picture, the system will order the road section speed meter to enforce the speed limits corresponding with the numbers shown on the road signs.

The speed limits will stop as soon as the road signs are not constant, for instance, all numbers change from "80" to "100". This is in order to ensure drivers to have time to react to the new speed limit. In addition, the system only acts on the consistent images, because the road signs serve other purposes as well, like being a warning system for traffic congestion or road work or adverse weather which might result in a difference between the content displayed on the road signs.

The Result of Field Trials

In total there were 5 experiments on four locations, running for 6 to 9 months. Table B.*1* lists the exact location and corresponding objectives and manners.

Table B.1: An overview of the field trials of DYNAMAX project

Location	Objective	Manner
A1 near Naarden	Throughput: reduce travel time	The speed limit arises to 120 from 100 km/h during quite period of the day.
A58 near Tilburg	Environment: improve air-quality	The speed limit was lowered to 80 from 120 km/h when the PM10 concentration tends to exceed the limitation.
A12 Bodegraven-Woerden	Throughput: resolving shockwaves	The speed limit was lowered to 60 from 120 km/h to resolve a shockwave.
A12 Bodegraven-Woerden	Traffic safety	The speed limit was reduced from 120 to 100 or 80 km/h during the heavy rain.
A12 near voorburg	Throughput: reduce congestion and travel time without changing air-quality (improved)	The speed limit arises from 80 to 100 km/h at the start and end of the evening traffic peak time (during the peak time, the value may be reduced due to congestion).

Because the quantitative effects of the field trials are still confidential, only a rough result can be found which shows a quite promising result. It is said the dynamic speed limit did changed the driver behavior and has been proved to be capable to serve multiple policy objectives such as enhanced traffic throughput, traffic safety and improved environment.

Appendix C: Traffic models classification

This part is from Weng's (2010) study:

"*Traffic models may be classified according to the level of details with which they represent the traffic system. Considering the distinguished traffic entities and the description level of these entities in the respective flow models, three main types are generally accepted: microscopic, mesoscopic to macroscopic (Hoogendoorn, 2008).*

Macroscopic simulation models depict the traffic entities at high levels of aggregation in flow, speed and density on a statistic basis without having to explicitly represent vehicles. The model may assume that the traffic stream is properly allocated to the roadway lanes, and may employ an approximation to this end. The simulation performed in high speed for networks of large scale, especially suitable of urban traffic network planning and management study.

On the other side, a microscopic simulation models are aimed at describing detailed information on both the space–time behavior of the systems' entities. The models distinguish and trace single cars and their drivers for each time step. From which, an individual driver's adjustment of speed or lane position in reaction to other lead or adjacent vehicles, or roadway conditions can be observed.

Mesoscopic models combine properties of both microscopic and macroscopic simulation models. The mesoscopic models' unit of traffic flow is the individual vehicle, and they assign vehicle types and driver behavior, as well as their relationships with the roadway characteristics.

Their movement, however, follows the approach of macroscopic models and is governed by the average speed on the travel link. As such, mesoscopic models provide less fidelity than microscopic simulation tools, but are superior to travel demand models, in that, mesoscopic models can evaluate dynamic traveler diversions in large-scale networks."

Appendix D: Emission model used in Node evaluation

The following information was obtained from an Email from Dörthe Müller, who is working for PTV Company, providing technical support to customers.

"Node evaluation (since VISSIM Version 4.10-05):
+ Simplified Synchro-compatible emission model in the node evaluation, providing fuel consumption and CO, NOx and VOC emissions (configurable) per movement, based on the default formulas for fuel consumption used by TRANSYT 7-F and on an unpublished letter regarding emission rates to the Federal Highway Administration from Oak Ridge National Labs.

The basis for these calculations are the same as for Synchro and TRANSYT7-F. It is a very simple model that allows to compare scenarios. Vehicle types are not considered and it is assumed that the truck percentage is a standard 3-5% and transit is not present. (It somehow releate to the American vehicle fleet, i.e. your input data of traffic composition does not affect emission calculations.)

The calculations are for fuel consumption, CO, NOx, and VOC.

Fuel Consumption is calculated using the following formula:

$F = VMT * k1 + Delay * k2 + Stops * k3$

where:

$k1 = .075283 - .0015892 * Speed + .000015066 * Speed ^ 2$
$k2 = .7329$
$k3 = .0000061411 * Speed ^ 2$

F = Fuel Consumption (gal)
Speed = node segment average speed (mph)
VMT = vehicle miles traveled (mi)
Delay = VISSIM total delay (hr)
Stops = total vehicle stops per hour

The emissions calculations for CO, NOx, VOC are functions of fuel consumption. Only basic emissions output can be obtained through the "Node Evaluation" output. Through this evaluation, you are able to obtain basic output for CO, NOx, and VOC (in grams) as well as Fuel Consumption (in gallons). In line with the origin the fuel consumption is in US gallon. The node evaluation based on the American vehicle fleet."

Appendix E: Complete results of reference and MTFC scenario

Table E.1: Full results from the 10 simulations of the reference scenario and the MTFC scenario

	Reference scenario					**MTFC scenario**				
Iteration*	***TTT (veh/h)***	***NOx.$_{tar}$ (g)***	***NOx.$_{ups}$ (g)***	***NOx.$_{down}$ (g)***	***Fuel.$_{entire}$ (gal)***	***TTT (veh/h)***	***NOx.$_{tar}$ (g)***	***NOx.$_{ups}$ (g)***	***NOx.$_{down}$ (g)***	***Fuel.$_{entire}$ (gal)***
1	1851.086	22510.52	45986.48	21539.62	6620.35	2081.492	19371.3	49408.42	21427.56	6632.89
2	2015.829	23153.78	47093.38	21539.55	6749.02	2138.173	19420.21	50068.95	21438.31	6685.85
3	1812.53	22433.11	45829.03	21516.89	6601.39	2034.183	19400.24	49054.01	21422.52	6608.59
4	1896.839	22612.18	46452.5	21552.89	6663.06	2137.23	21522.46	47682.12	21500.67	6669.5
5	1842.868	22414	46045.77	21450.45	6611.05	2069.896	19585.45	49019.98	21361.04	6615.18
6	1894.953	22602.94	46396.6	21517.88	6655.69	2084.322	19419.14	49512.85	21426.65	6644.02
7	1916.309	22813.72	46575.69	21579.53	6688.89	2071.003	19469.6	49440.56	21446.83	6643.89
8	1907.148	22777.39	46401.32	21519.16	6668.96	2167.546	19441.48	50347.26	21442.68	6708.19
9	1847.359	22661.65	46000.08	21531.12	6631.83	2064.624	19439.21	49404.5	21431.14	6637.85
10	1898.735	22615.73	46377.12	21518.05	6655.21	2075.672	19391.99	49403.95	21404.92	6632.41
Mean	1888.366	22659.5	46315.8	21526.51	6654.545	2092.414	19646.11	49334.26	21430.23	6647.837

*all iterations are of the P=1 and Oc=25.

Appendix F: Complete results of the modification scenarios

Table F.1: Full results from the simulations of the two modification scenario

	Modification scenario 1 (regulator parameter P)			**Modification scenario 2 (desired occupancy Oc)**	
Values*	***TTT (veh/h)***	***NOx.tar (g)***	**Values***	***TTT (veh/h)***	***NOx.tar (g)***
0.01	2227.195	22181.02	13	2131.096	19371.34
0.05	2161.643	22084.52	17	2133.154	19376.76
0.07	2038.096	21607.92	20	2094.231	19383.14
0.1	2031.025	21515.03	23	2074.717	19374.65
0.4	1994.228	19480.22	25	2081.492	19371.30
0.7	2056.625	19409.49	27	2069.854	19380.69
1	2081.492	19371.00	32	1990.519	19404.68
2	2245.226	22116.42	35	1989.329	19453.40
5	2332.148	22523.38	40	1951.598	19651.76
100	2145.026	22123.94	50	2166.328	21771.15
200	2145.026	22123.94	80	2152.849	22306.69
300	2145.026	22123.94	100	2059.678	21971.11
Mean	2133.563	21388.40	**Mean**	2074.570	20068.06

*all simulations are run with the default random seeds