Investigating the Effects of Traffic Calming on Near-Road Air Quality using Traffic, Emissions, and Air Dispersion Modelling

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ABSTRACT

This thesis focuses on the development of a microscopic traffic simulation, emission and dispersion modeling system which aims at quantifying the effects of different types of traffic calming measures on vehicle emissions both at a link-level and at a network-level and on air quality at a corridor level using a scenario analysis. The study area is set in Montréal, Canada where a traffic simulation model for a dense urban neighborhood is extended with capabilities for microscopic emission estimation and dispersion modeling.

The results indicate that on average, isolated calming measures increase carbon dioxide (CO2), carbon monoxide (CO) and nitrogen oxide (NOx) emissions by 1.50%, 0.33% and 1.45%, respectively across the entire network. Area-wide schemes result in a percentage increase of 3.84% for CO_2, 1.22% for CO, and 2.18% for NO_x. Along specific corridors where traffic calming measures were simulated, increases in CO_2 emissions of up to 83% are observed. These increases are mainly associated with a change in vehicle drive-cycles through increased accelerations and decelerations. The results for air quality modeling suggest on average NO_2 levels increase between 0.1% and 9% with respect to the base case; however, increases of up to 40% are observed under specific meteorological conditions. A high positive correlation of 0.66 between segment emissions of NO_x and concentrations of NO_2 is observed. Also, the effects of wind speed and direction are investigated in this thesis. The results show that higher wind speeds decrease NO_2 concentrations on both sides of the roadway while winds orthogonal to the road increase the difference between concentrations on the leeward and windward sides with the leeward side experiencing higher levels. The effect of different measures on traffic volumes is also investigated and moderate decreases in areas that have undergone traffic calming are observed. Finally, the results show that speed bumps result in higher emission levels and poorer near-roadway air quality than speed humps.

RESUMÉ

Cette thèse porte sur le développement d'une simulation de trafic microscopique, des émissions de véhicules ainsi qu'une modélisation de la dispersion atmosphérique qui vise à quantifier les effets de différents types de mesures d'apaisement de la circulation sur les émissions des véhicules et de la qualité de l'air. Cette analyse est conduite à la fois au niveau de liens spécifiques et au niveau du réseau à travers plusieurs scénarios de modélisation. La zone d'étude se situe dans Montréal, Canada, où un modèle de simulation de trafic pour un quartier urbain dense est étendu avec des capacités d'estimation des émissions de véhicules et modélisation de la dispersion des polluants de l'air.

Les résultats indiquent que, en moyenne, les mesures d'apaisement isolées augmentent le dioxyde de carbone (CO_2), le monoxyde de carbone (CO) et les oxydes d'azote (NO_x) de 1,50%, 0,33% et 1,45%, respectivement sur l'ensemble du réseau. Les mesures étendues sur plusieurs corridors augmentent de 3.84% les émissions de CO_2, 1.22% de CO, et 2.18% de NO_x. Le long des corridors spécifiques où des mesures de modération de la circulation ont été simulées, des augmentations d'émissions de CO_2 allant jusqu'à 83% sont observées. Ces augmentations sont principalement associées à un changement des cycles d'accélération et de décélération. Les résultats de la modélisation de la qualité de l'air, suggèrent en moyenne que les niveaux de NO_2 augmentent entre 0.1% et 9% par rapport au scénario de référence, mais des augmentations allant jusqu'à 40% sont observées sous des conditions météorologiques spécifiques. Une corrélation positive de 0.66 entre les émissions de NO_x et de concentrations de NO_2 est observée. En outre, les effets de la vitesse et direction du vent sont étudiés dans cette thèse. Les résultats montrent que des vitesses du vent plus élevés réduisent les concentrations de NO_2 des deux côtés de la chaussée alors que des vents perpendiculaires à la route d'augmentent la différence entre les concentrations des deux côtés de la route avec des niveaux plus élevés pour le côté situé en amont du vent. L'effet de l'apaisement de la circulation est également étudié sur les volumes de trafic et des diminutions modérées dans les zones qui ont subi l'apaisement sont observées. Enfin, les résultats démontrent que différents types de mesures d'apaisement ont des effets différents sur les émissions et la qualité de l'air.

DEDICATION

To
Ahmadreza, Mommy and Daddy

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LIST OF ABBREVIATIONS

CDF	Computational Fluid Dynamic
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DTA	Dynamic Traffic Assignment
HC	Hydrocarbon
HGV	Heavy Vehicles
MOVES	Motor Vehicle Emissions Simulator
NO_2	Nitrogen Dioxide
NO_x	Nitrogen Oxide
O_3	Ozone
OSPM	Danish Operational Street Pollution Model
RIT	Road-Induced Turbulence
USEPA	United States Environmental Protection Agency's
VIT	Vehicle-Induced Turbulence
VKT	Vehicle Kilometer Travelled

CHAPTER 1
INTRODUCTION

1.1 Background

Traffic calming refers to a combination of physical changes in road design and speed management aiming at improving road safety especially for users of non-motorized transportation sharing the road with drivers (Lockwood 1997). Traffic calming strategies are based on either one of two approaches: 1) black-spot approach or 2) area-wide approach. In the black-spot approach, isolated measures are installed on a specific segment of a road network, while in the area-wide approach measures are planned systematically and installed on the entire network (Elvik and Vaa 2004).

Various traffic calming measures with the means of improving road safety have been implemented all over the world for decades. They influence road safety by reducing vehicle speeds and/or the volumes of "through traffic" on street networks, reducing and/or eliminating conflicting movements, improving visibility and reducing exposure, as well as sharpening drivers' attention. Speed reduction caused by the implementation of traffic calming measures may lead to fewer fatal or serious injury accidents (Ewing 1999). It has been recognized that on average, a 1 mph reduction in mean vehicle speed results in an average accident reduction of 5 percent (Taylor *et al.* 2000).

Relatively few studies have been conducted to capture the environmental impact of traffic calming. Some studies only focused on the effects on emissions using real traffic data and on road emission measurements or employing different modeling methods to estimate them (for example, see Ahn and Rakha 2009 and Daham *et al.* 2005). Results for most of the studies showed a substantial increase in emissions while results of the studies conducted to quantify the effects on air quality demonstrated that calming measures did not significantly affect air quality and even in some cases it improved the air quality because of traffic rerouting (for instance, see Owen 2005 and Elsom 1997).

1.2 Problem Statement

Despite the beneficial effects of traffic calming on road safety, it has been associated with impacts on air quality. In fact, varying speed frequently and slowing down while driving on a calmed street, may tend to produce more air emissions due to increased accelerations and decelerations. While the safety impact of traffic calming has been studied in depth (for example, see Grundy *et al.* 2009, Hyden and Várhelyi 2000 and Huang and Cynecki 2000), relatively few studies have been conducted to capture the environmental impact of traffic calming. Most of the literature presented many advantages such as the use of real drive-cycles, traffic volumes, and air pollution measurements to quantify the effects of traffic calming on air quality. However, they lack the capability of evaluating the effects of instantaneous speed changes and traffic volumes simultaneously and in isolation.

1.3 Research Objective

1.3.1 Overall Goal

The overall goal of this research is to develop a microscopic traffic, emission and dispersion modeling system which aims to capture the effects of traffic calming schemes on vehicle induced emissions and air quality.

1.3.2 Research Tasks

Two tasks were identified to address the main goal of this research:

Task 1

This task quantifies the effects of different types of traffic calming measures on vehicle induced emissions. Using a scenario analysis, the effects of traffic calming schemes both at a link-level and at a network-level are captured. This research also investigates the effects of isolated traffic calming measures at a corridor level and area-wide calming.

Task 2

This task tries to capture the effects of range of traffic calming schemes on the ambient air quality. Again, by using a scenario based analysis, ambient air quality is measured at a corridor level.

1.4 Research Significance

This research designs and implements an integrated modelling system which includes a combination of a microscopic traffic simulation, emission and dispersion modeling and aims at quantifying the effects of different types of traffic calming measures on vehicle emissions and air quality. The developed model is capable of evaluating the effects of instantaneous speed changes and traffic volumes simultaneously and in isolation, a feature that most previous literature omits. We expect this research to have strong policy-relevance as it will assist policy makers in decisions on the types and locations of traffic calming measures to be deployed.

1.5 Organization of the Thesis

This thesis is presented in five chapters as follows. Chapter 1 defines the problem and presents the objectives of the research and structure of the thesis. Chapter 2 contains a thorough review of literature on traffic calming, its effects on traffic emissions and near-road air quality. Chapter 3 presents the methodology employed to quantify the effects of calming schemes on emissions and air quality. Chapter 4 presents the results for Task 1. This chapter demonstrates the detailed findings of the research regarding the effects on traffic emissions. In Chapter 5 the results for Task 2 of the research is presented. In this chapter the findings regarding the ambient air quality changes resulting from implementation of traffic calming are discussed. Chapter 6 presents the conclusions and limitations of the thesis and makes recommendations for future research.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

This section reviews the literature pertinent to the research questions articulated in the introduction and which form the back-bone of this thesis. As mentioned previously, two main aspects of traffic calming are explored in this thesis: 1) effect on traffic emissions, and 2) effect on near-road air quality. As such, this section presents the main findings associated with both research dimensions.

2.2 Background and Definition of Traffic Calming

Studies showed that a common definition of traffic calming does not exist and traffic calming has a broad definition. For instance, in 1989, Pharoah and Russel defined traffic calming as "the attempt to achieve calm, safe and environmentally improved conditions on streets". Dr. Carmen Hass-Klau in 1990, defined traffic calming as "the combination of policies intended to alleviate the adverse environmental, safety and severance effects motor vehicles continue to impose on both the individual and society at large". The definition of traffic calming developed by the Institute of Transportation Engineers is "the combination of mainly physical measures that reduce the negative effects of motor vehicle use, alter driver behavior and improve conditions for non-motorized street users" (Lockwood 1997).

Traffic calming affects the area of safety the most. By reducing vehicle speeds, eliminating conflicting movements, and sharpening drivers' attention, traffic calming may result in fewer collisions. Also, when collisions occur, they may be less serious because of lower speeds (Ewing 1999). Speed humps, speed bumps, speed tables, raised intersection, curb extension, chicanes and bollards are commonly used traffic calming measures.

It is noteworthy that traffic calming started in the Dutch town of Delft in 1970 as an incident. A difference in elevation of eight centimeter, like a hump, built at the end of an alley followed several complaints of the neighborhood. However, this simple incident resulted in a break-through in traffic engineering. In September 1976, for the first time in Europe, minimum design standards for residential areas to lower the traffic speeds, 'woonerf', were published by Netherland. Since then, traffic calming became a popular element in road safety (Klaus 1997).

In the 1970's, influenced by the 'woonerf', several excessive designs were implemented such as wooden plant pots, soft lighting and ornamental paving in various colours, materials and shapes implemented which needed heavy maintenance. Later, in the eighties, simpler speed inhibiting measures like speed control humps were applied due to the economic recession. The nineties designs became once more a little more excessive but not as much as the early designs produced in the seventies. For instance, in the residential streets of the Netherlands the areas are demarcated by the start and end hump-like provisions on the roads. At intersections a raised area where a ramp (or half hump) is used can be found. Road narrowing, tapering, taggering shifts and speed control humps were applied on longer road sections. On access roads, there are separated cycle tracks. Roundabouts replaced intersections. Speed controls (50 km- hump) were applied (Wit and Talens 1998).

In 1977, a new code was introduced into the Danish Road Traffic Act. The code was a change of speed limits where in most cases the streets were transformed into 30 km/h streets and in few cases into 15 km/h streets. In addition to speed signs, speed reducing measures such as speed humps, lateral dislocation and narrowing of carriageway were implemented in both types of streets (Engel and Thomson 1992). Many highway networks of Denmark towns had problems caused by through traffic. Construction of a bypass road could have been a solution to this problem, but bypasses are expensive. Also, they do not solve the problems created by the town's local traffic while they just remove through traffic. Besides, it was unrealistic to imagine commercial traffic accepting 30 km/h through all Danish villages. Therefore, a speed classification system was introduced (Kjemtrup and Herrstedt 1992).

In 1981, the Danish Road Directorate published a Catalogue of Ideas, which outlined a new method of solving the problem: environmentally adapted through roads. The Catalogue of Ideas contained measures relating to road design, such as traffic islands and bicycle tracks, staggering and narrowing of carriageways, raised carriageway levels and changed road surfaces, but also planting and lighting. Moreover, it illustrated that the individual elements could be combined such as pre-warnings, gates, track crossings, intersections, and speed reducing measures to form design solutions. The Danish Road Directorate undertook a test of traffic calming measures applied to highways through the towns of Vinderup, Skrerbaek, and Ugerlose. A number of individual measures were combined and implemented in these three towns such as prewarning signs and rumblestrips, speed signs, parking sections between the lateral islands, roundabouts, path crossings and divided paths, side road closures and lighting elements placed at gateways and islands (Herrstedt 1992).

In Germany, the state of Nordrein Westfalen conducted a test on twenty-eight villages by adopting the Danish Catalogue of Ideas. These villages were traffic calmed with narrowings, roundabouts, textured surfaces and redesigned street spaces. In the 1980's, the effects of traffic calming measures were investigated in six German towns including different residential areas of Berlin-Moabit, Borgentreich, Buxtehude, Esslingen, Ingolstadt and Mainz-Bretzenheim. A 30 km/h speed limit, speed tables, chicanes, pinch points in local streets and collectors, roundabouts, textured surfaces and redesigned street spaces, conversion of one-way streets to two way operation and narrowing ring roads and arterials were some of the applied measures (Brilon and Blankeb 1993 and Ewing 1999).

A 1963 British government document, *Traffic in Towns by Colin Buchanan,* is often credited with launching the modern traffic calming movement. The Urban Safety Project, a traffic calming plan launched in 1982 to reduce accidents, included Buchanan-like volume controls. It had a quite modest impact on collision rates compared with German, Dutch, and Danish implementations. Therefore, changes in law and regulation and a new edition of the street design manual, were applied to bring Britain in line with the rest of Europe. Regulations in 1986 and 1990 permitted the use of vertical measures other than rounded 3.5 meters humps. The 1992 Traffic Calming Act and 1993 Traffic Calming Regulations expanded the range of measures to include almost any vertical or horizontal feature. The 1992 edition of *Design Bulletin 32* shifted to a hierarchical network of traffic-calmed streets (Ewing 1999).

In 1940's and 1950's, the first street closures and traffic diverters were installed to protect neighborhoods in Montclair, New Jersey and Grand Rapids, Michigan just focused on improving specific locations. Over time, instead of reacting to community concerns, local governments became more practical. Berkeley, CA, was probably first to establish a complete citywide traffic management plan in 1975. In the early 1970's, Seattle, WA, may have been first to conduct neighborhood-wide demonstrations (Ewing 1999). Today there is more emphasis on traffic calming as a neighborhood transportation problem that needs to be evaluated on an area-wide basis than on improving single locations. Now, a variety of techniques such as speed hump, traffic circles (mini-roundabouts), chicanes, bicycle boulevard, channelization change, slow streets, transit street and pedestrian zones, signing techniques and traffic diverters are being implemented.

Since the 1970's, cities like Toronto, Vancouver and Ottawa have suffered from cut-through traffic in their downtown residential areas. Early traffic calming measures included closing access points and creating maze-like streets to prevent non-resident drivers from entering neighborhoods. In 1998, the *Canadian Guide to Neighbourhood Traffic Calming* was published. Since that time, dozens of Canadian cities have applied traffic calming measures proactively (TAC 1998).

2.3 Traffic Calming and Its Effects on Traffic Emissions

While little research has been carried out to date to explore the effects of traffic calming on vehicle emissions, a few studies have focused on this issue along two different dimensions: 1) assessing the effects of isolated traffic-calming measures at a corridor level, and 2) evaluating area-wide calming schemes.

Crabbe and Elsom (1996) outlined examples of several assessments of the air quality impacts of specific traffic management measures including traffic calming in the United Kingdom. This article demonstrates that the results form a Transport Research Laboratory study (1995) in which driving patterns have been simulated (taking into consideration vehicles travelling at speeds of 23 to 30 km/h for simulating calmed areas and vehicles travelling at a constant speed of 40 km/h for non-calmed roads) show a 25-50% increase in CO, HC and CO_2 emissions and 50% decrease in NO_2 emissions. Also, results for another study summarized in Crabbe and Elsom s' article showed that two traffic calming strategies ,including a route network for pedestrians and cyclists and imposing speed limits of 30 km/h instead of 50 km/h in Buxtehude, Germany, resulted in CO, HC, and NO_x emissions reductions.

The report prepared by Cloke *et al.* (1999) for the Transport Research Laboratory highlights the evaluation of the environmental impact of area-wide traffic calming measures installed in the Leigh Park area of Havant, England. In total, 20 cars were driven through the calmed zone while their speeds were recorded. Driving cycles were established using recorded speed variations. Results from calculated air pollutant emissions by a computer model, considering a reduction in traffic volumes, indicated a decrease in CO, HC, and NO_x emissions. However, without taking into consideration traffic volume changes, CO and HC emissions were increased while NO_x emissions were decreased.

In 2001, Boulter *et al.* studied the impact of nine different traffic calming schemes on air pollutant emissions and air quality. These schemes include flat-top road hump, round-top road hump, two types of speed cushions, combined pinch point and speed cushion, raised junction, chicane, curb extension and mini-roundabout. For deriving driving cycles, actual driving speeds were measured before and after the implementation of calming measures. Exhaust emission measurements were conducted using the derived driving cycles. The results indicated that introduced traffic calming measures increase the mean emission rates of CO, HC, and CO_2 by up to 60 percent for the three types of cars (petrol non-catalyst, petrol catalyst and diesel cars). NO_x and particulate matter emissions were increased substantially for diesel cars. However, further estimations using a dispersion model showed that the increased emission rates slightly worsen the local air quality.

Várhelyi (2001) conducted a before/after study in Växjö, Sweden to evaluate the effects of the implementation of 21 mini-roundabouts, replacing signalized and yield regulated junctions, on air pollutant emissions. Diving cycles were derived from recorded distance travelled by an equipped car. Emissions were calculated using a model which considered volume change at intersections. Results of this article showed that at a roundabout replacing a signalized intersection, CO and NO_x emissions decrease following a decrease in speed variations, while at a roundabout replacing a yield regulated junction, CO and NO_x emissions increase as a result of the slowing down of traffic.

Daham *et al.* (2005) conducted a study to determine the effect of speed humps on air pollutant emissions. In this study, a car equipped with an on-road emission measurement device with a very heavy load was driven at a constant speed of 50 km/h to simulate a normal road with seven speed cushions. To simulate a calmed road with round-top speed humps, the car was slowed down to 16 km/h to go over installed speed cushions on the same road and accelerated up to 32-48 km/h. The results of the calmed road compared to the normal one showed substantial increase in CO_2, CO, NO_x and HC emissions by 90%, 117%, 195%, and 148%.

Ahn and Rakha (2009) estimated air pollutant emissions for three roads before and after installation of various types of calming measures, using a combination of global positioning system data from floating-cars and microscopic emission models. Results for the first road with a speed limit of 40 km/h showed that the installation of five speed cushions increased emissions of various air pollutants significantly. Also, for the second road with speed limit of 25 km/h where two speed bumps were installed, results indicated significant increase in emission rates. The third study corridor including three uncontrolled intersections, one four-way stop controlled intersection, four traffic circles and three intersections with three speed humps were studied. Intersections with calming measures resulted in significantly higher emission rates than intersections without calming measures or stop signs.

2.4 Traffic Calming and Its Effects on Near-road Air Quality

2.4.1 Characterization of Near-Road Air Quality

There is a recognizable amount of literature that focus on measuring and modeling near-road air quality. Several studies measured real-world air pollutant concentrations with different sampling methods.

Beckerman *et al.* (2007) measured different pollutant concentrations near a major expressway in Toronto including fine particulate matter, ultrafine particulate matter, black carbon, NO_2, NO_x and O_3 Their measurements showed that NO_2 levels are correlated with other traffic-related pollutants and decline with increasing distance from the expressway.

Two studies investigated the relationship between NO_2 concentrations and distance from the roadway. The first study, in 2003, installed several Ogawa passive samplers in different distances from a major highway in Monreal, Canada. One year later, in 2004, second study was conducted to sample NO_2 concentrations near a highway in South-west Sweden. Both studies supported the idea that NO_2 levels decrease as the distance from the roadway increases and they have a logarithmic relationship (Gilbert *et al.* 2003 and Pleijel *et al.* 2004).

Moodley *et al.* 2011 attempted to collect NO_2 concentrations at five intersections in Durban metropolis, South Africa. They used Ogawa passive samplers and an active sampler (chemiluminescence detector) and compared the samples measured from the two methods. Based on their analysis, no statistical significance between the two sampling methods was found.

Several studies used computational fluid dynamic (CFD) models to simulate the concentrations of different pollutants near the roadway. Gidhagen *et al.* (2004) compared the results of simulated NO_x concentrations using a CFD model with measurements using air intakes (Chemiluminescence analyzers and Thermo Electron) for a major street in Stockholm, Sweden. Their study concluded that simulated NO_x levels are close to the monitored levels. Another study used a CFD model and simulated carbon monoxide (CO) near two major highways in Los Angeles, USA. In their CFD model they incorporated vehicle-induced turbulence (VIT) and road-induced turbulence (RIT). This study conducted a comparison between the CFD model, field measurements, and the CALINE4 model. It was shown that considering the VIT and RIT in the CFD model results in a better simulation than CALINE4 but it is more computationally burdensome (Wang and Zhang 2009).

Another dispersion model which is commonly used and validated in various studies is The Operational Street Pollution Model (OSPM), developed by Hertel and Berkowicz (1989). In 2006, Berkowicz *et al.* modeled NO_x and CO concentrations along a road in Copenhagen, Denmark using OSPM. In their modeling process they calculated the emission factors using the European COPERT methodology. The comparison between modeled and measured concentrations showed an underestimation. They suggested that a more accurate estimation for the emission factors may result in a better agreement between the modeled and measured concentrations. While a study conducted in three street canyons of Nantes, France with statistical evaluators showed that there is a good agreement between NO_x levels measured and modeled with OSPM (Gokhale *et al.* 2005). Other studies also had similar findings regarding the good agreement between modeled and measured concentrations (Kukkonen *et al.* 2001, Berkowicz 2000 and Raducan 2008).

Also, the comparison between NO_x levels measurements and modeled concentrations with OSPM showed that the leeward concentrations are higher than the windward concentrations in a street canyon (Berkowitz *et al.* 1996). Nevertheless the assessment of air pollution for 2008 Beijing Olympic Games indicated that the street configuration and the wind speed and direction may impact the windward and leeward concentrations in a way such that the windward levels may be higher than the leeward concentrations (Wang and Xie 2009).

2.4.2 Traffic Calming and Air Quality

Elsom in 1997, gathered results of several studies conducted in European cities regarding the impacts of different calming measures on air quality. Two of these studies suggested that where drivers decelerate and accelerate aggressively across speed humps may result in increases in CO and HC emissions. Results for another study from a range of German cities showed a fall in NO_x percentage changes and a rise in CO percentage changes due to traffic calming while HC percentage changes ranged between -23% to +10%. Impacts of traffic calming measures in Exeter, UK, were measured by a diffusion tube survey and measurements showed a drop in NO_2 levels.

Oduyemi and Davidson in 1998 investigated the effects of several traffic management measures including the traffic restrictions in Dundee city centre, UK on ambient air quality. Diffusion tubes, measuring NO_2 at sites, were used in order to compare the air quality within and outside traffic restricted zones. Results of this study showed that the annual mean NO_2 concentration at two of the study sites was close to 40 $\mu gr/m^3$, indicative of effectiveness of traffic management measures in protecting the air quality.

The report by Cloke *et al.* (1999) evaluating the environmental impact of area-wide traffic calming measures installed in the Leigh Park area of Havant, England where NO_2 and benzene levels were measured using diffusion tubes at 6 different sites, demonstrated that the implemented traffic calming scheme in the area did not have a significant effect on air quality.

Boulter *et al.* (2001) studied the impact of different traffic calming schemes such as flat-top road hump, round-top road hump, curb extension and mini-roundabout on air quality using a dispersion model. Although their results showed substantial increases in emission rates, further estimations showed that the implementation of calming measures slightly worsen local air quality.

In 2005, Owen published an article evaluating the effects of traffic calming measures, such as speed humps and traffic lights, on vehicle emissions and ambient air quality of six relatively small 32 km/h zones (approximately 0.5 km x 0.5 km) in North West England before and after the installation. Ambient concentrations of NO_2 and benzene were measured using diffusion tubes and thermal desorption tubes. The results of these measurements showed that the installation of calming measures did not significantly affect air quality in the six zones. The calculations of per vehicle emissions using average driving speeds without taking into account variations of traffic volume, indicated an increase whereas, calculated emissions with consideration of traffic volume changes were decreased.

2.5 Gaps in Available Literature

Despite the beneficial effects of traffic calming on improving road safety, it has been associated with impacts on air quality. In fact, varying speed frequently and slowing down while driving on a calmed street, may tend to produce more air emissions due to increased accelerations and decelerations. While the safety impact of traffic calming has been studied in depth for several years, relatively few studies have been conducted to capture the environmental impact of traffic calming. The studies mentioned so far present many advantages such as the use of real drive-cycles, traffic volumes, and air pollution measurements to quantify the effects of traffic calming on air quality. However, they lack the capability of evaluating the effects of instantaneous speed changes and traffic volumes simultaneously and in isolation. This thesis focuses on the development of a microscopic traffic, emission and dispersion modeling system which aims to capture the effects of a range of traffic calming schemes on traffic volumes, speeds, emissions and air quality both at a link-level and at a network-level using a scenario analysis. It also investigates the effects of isolated traffic-calming measures and area-wide calming schemes at a corridor level on air quality.

CHAPTER 3
METHODOLOGY

3.1 Introduction

In this thesis, the effects of traffic calming measures on air pollutant emissions and air quality in a Montréal neighborhood are examined by employing a combination of mesoscopic and microscopic traffic models, the USEPA's Motor Vehicle Emissions Simulator (MOVES) and Danish Operational Street Pollution Model (OSPM). First, a regional traffic assignment model is used to allocate trips on the metropolitan road network. Second, O-D matrices for all trips generated from, destined to, or passing through the study neighborhood are input into a traffic simulation model operated in Dynamic Traffic Assignment (DTA) mode. Traffic simulation is then run for a range of traffic calming measures and under each scenario, second-by-second speed profiles for each link in the neighborhood are extracted. Using these instantaneous link speeds, air pollutant emissions are modeled using a version of MOVES fitted with input data describing the Montréal vehicle fleet. Later, concentration levels of air pollutants are modeled in OSPM at the corridor level.

3.2 Study Area

The study area includes the Plateau-Mont-Royal borough, more often referred to as "The Plateau", within the Montréal Metropolitan Region (FIGURE 3.1). The Plateau is a dense and lively neighborhood which recorded a population of 101,054 individuals in an area of only 8.1 km^2, according to the most recent

Canadian census report. Its residents are currently experiencing large volumes of "through traffic" due to the borough's proximity to the Montréal central business district leading to the generation of significant amounts of traffic emissions as well as safety risks. The local council of the neighborhood is actively pursuing the goal of managing increasing traffic volumes especially on local streets and improving pedestrians' and cyclists' safety.

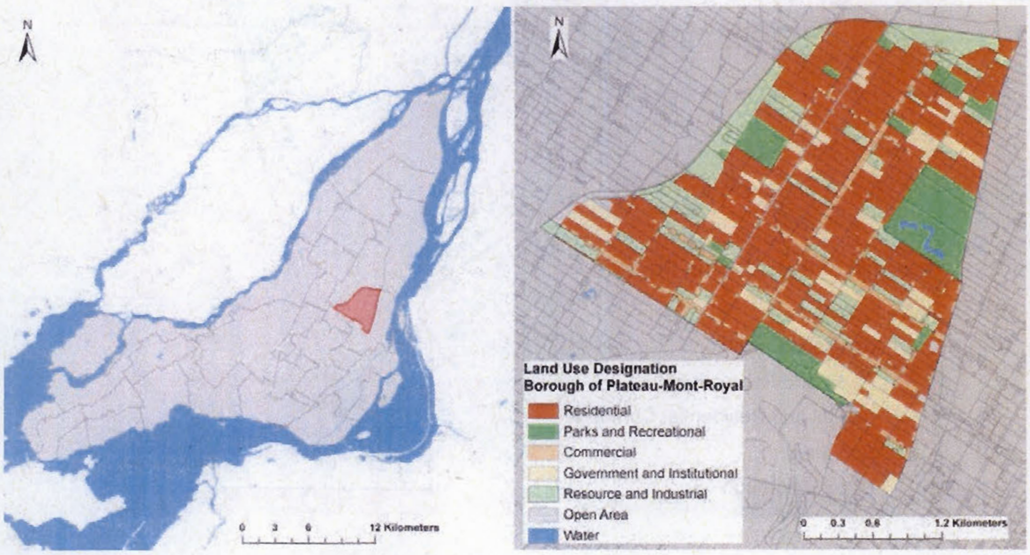

FIGURE 3.1 The Plateau borough in the context of the Montréal region.

Within the Plateau, this thesis focuses on a small sub-area that has recently been the subject of much debate due to the increasing traffic volumes and speeds witnessed along several residential streets with a large number of daycares, schools, churches, and community centers. This area is bound by four main arterial roads: Rue St Gregoire to the North, Rue Rachel to the South, Rue St. Denis to the West, and Avenue Papineau to the East (FIGURE 3.2). It is important to note that while the traffic simulation model will be run at the level of the entire Plateau borough, our main focus will be on the traffic calming measures and link-evaluation in this sub-area, in particular, the four residential and school corridors (Marquette, Chambord, Garnier, and Fabre) highlighted in FIGURE 3.2.

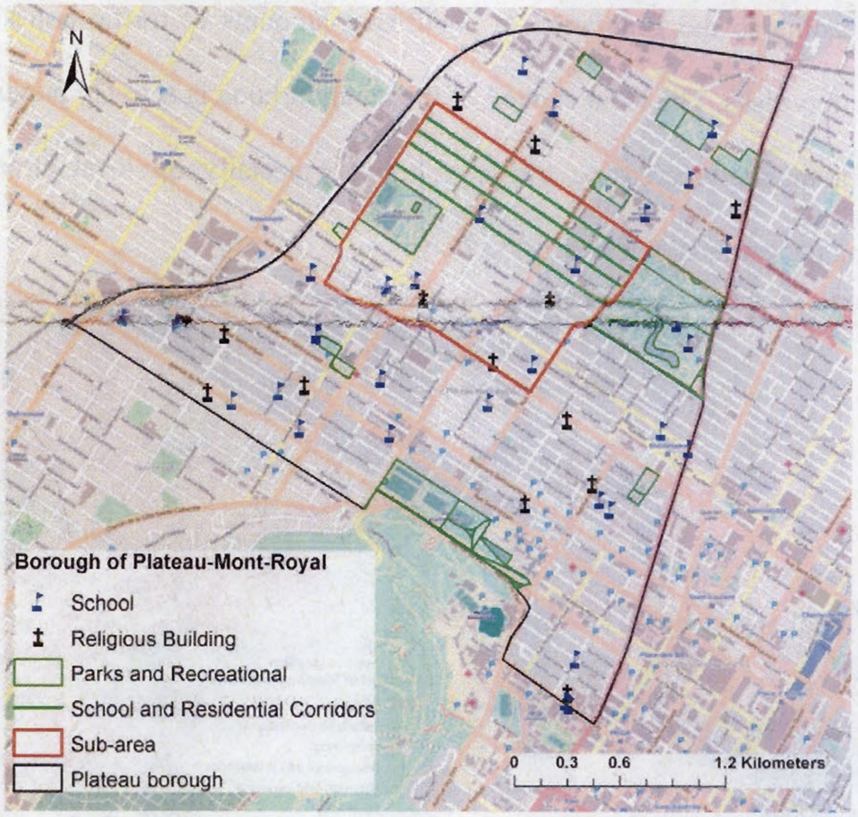

FIGURE 3.2 Sub-area featuring highlighted residential and school corridors.

3.3 Traffic Simulation

In order to analyze emission levels properly one must consider the accelerations and instantaneous speeds for individual vehicles; therefore, for this study a microsimulation model of the road network in The Plateau is developed to achieve the sensitivity necessary to analyze the effects of different policy interventions. A model at the meso scale cannot capture such effects.

In order to do this, first a regional traffic assignment model is developed for the Montréal Metropolitan Area using the PTV VISUM platform. This model takes the 2008 Origin-Destination trip data for the Montréal region provided by the Agence Métropolitaine de Transport. The regional network consists of 127,217 links. VISUM runs under a stochastic user equilibrium traffic assignment for the 6-7AM period and for the 7-8AM period. The regional traffic assignment output becomes the main driver for the micro-simulation model and is used to generate a matrix containing the numbers of trips between every two traffic analysis zones for all the following trips: (1) generated outside the Plateau and destined to the borough, (2) generated in the borough and destined to an outside zone, (3) generated and destined within the Plateau, and (4) "through" traffic.

For the development of the micro-simulation in VISSIM, a database of all intersections in the study area is created. For every intersection, traffic light signal phases, turning restrictions, and traffic counts are input. Traffic counts are obtained from the City of Montréal automatic counters and through manual counts. The VISSIM network is developed using a combination of orthophotos, topographic maps, cartographic maps, and field visits. All stop signs, traffic lights, and the changes in speed limit between arteries, local roads and school zones are included. In total, the VISSIM network has 8,656 links and connectors and 576 intersections. The matrix of the number of trips from VISUM is used and VISSIM runs under dynamic traffic assignment to assign vehicles on a very detailed road network within The Plateau. On the boundaries, each link acted as an abstract parking lot to remove vehicles from or generate vehicles onto the network. Also, an origin link and a destination link for each zone centroid within the borough are added to include vehicles that originated from or were destined to the Plateau. In multirun mode with the volume initially set at 10% of the total, increasing by 10% for the next nine iterations, the convergence reached its criterion after 39 iterations in the base case. In order to generate the instantaneous link speeds and volumes, one final iteration after convergence is run and data for every second between 7-8AM is recorded. Note that link speeds and volumes are extracted only for the sub-area in The Plateau where traffic calming measures will be tested, while the VISSIM is run for the entire borough.

3.4 Emission Modeling

The Motor Vehicle Emission Simulator (MOVES) was developed by the U.S. Environmental Protection Agency's (EPA) in order to estimate link-based emissions from mobile sources under a variety of user-defined conditions. MOVES requires information about the link length, road grade, traffic volume, traffic composition, and vehicle speed. Speed can be input as an average "per link" speed or second-by-second speed that captures acceleration, deceleration, cruising, and idling, commonly referred to as the drive-cycle. By including the drive-cycle in emissions estimations, the model becomes much more representative of actual driving conditions (see EPA 2012 for a full description). Instantaneous speeds, hourly drive-cycles (full 3600 seconds), for each link in the sub-area are extracted from VISSIM.

Other required information for emission simulation, including link length, link grade, meteorological data, fleet composition, and fleet age distribution for Montréal, are input to reflect local conditions. Link length and grade are extracted from AutoCAD maps of the area. The meteorological data are collected for October 2011. The vehicle type and model year information are obtained from the Société de l'assurance automobile du Québec (SAAQ), also for October 2011. MOVES is used to calculate hourly carbon dioxide (CO_2), carbon monoxide (CO), and nitrogen oxide (NO_x) per link.

3.5 Dispersion Modeling

The Danish Operational Street Pollution Model (OSPM) is a street pollution model, developed in Denmark. Concentrations of exhaust gases from road traffic are calculated using a combination of a plume model for the direct contribution and a box model for the recirculating part of the pollutants in the street. Several different inputs such as street configuration, meteorological data and background concentrations, emission factors and traffic data are required in OSPM. Vehicle speed is also required to consider the effects of traffic turbulence. In this thesis, OSPM runs under special mode to calculate the NO_2 concentrations.

The required data for street configuration including average height of buildings, and width and orientation of the street are gathered through field visits. The emission factors estimated from MOVES are used. Hourly meteorological data such as wind speed, wind direction, global radiation and temperature are collected for October 2011 from Environment Canada. A total of 30 days meteorological data are used for dispersion modelling. Considering each day conditions, different wind speed and wind direction combinations, the two most critical variables for dispersion are input. The hourly urban background concentrations of NO_2, NO_x and O_3 and the percentage of emitted NO_2 for October 2011 are gathered. Traffic volumes and vehicle speeds extracted from VISSIM are used. The NO_2 concentrations for three study corridors (Marquette, Chambord and Garnier) are modeled for different wind speed and directions combinations using OSPM and the results are presented for every segment of the study corridors in Chapter 5. The summary of corridor specifications and meteorological data are shown in Table 3.1.

Table 3.1 Corridor Specifications and Meteorological Data

		Chambord	Garnier	Marquette
	Average Width (m)	11	10	11
	Direction	130°	130°	130°
	Average Building Height (m)	11	12	10
	Average Temperature (°C)	10		
	Global Radiation (W/m2)	140		
Background Levels	NO_x (ppb)	18		
Background Levels	NO_2 (ppb)	10		
Background Levels	O_3 (ppb)	17		

3.6 Traffic Calming Scenarios

A total of eight different traffic calming scenarios including single, isolated, and network-wide measures have been identified and simulated within the traffic simulator, microscopic emissions model and dispersion model. Besides the base-case scenario which has a network-wide speed limit of 50 km/h, the eight simulated scenarios are identified and described in Table 3.2. In general the identified measures include speed humps, speed bumps, and speed limits:

- Speed bumps are defined as raised areas in the roadway pavement surface that are less than 0.3 m in width and are crossed at very low speeds: 5-10 km/h. Within VISSIM, we simulated them by defining an area of 0.3 m in width with a speed of 5 km/h.
- Speed humps are also similar to speed bumps, but are broader, typically 3 to 4 m in width, and are crossed at higher speeds (25- 30 km/h). Within VISSIM, we simulated them by defining an area of 3 m in width with the speed of 25 km/h.
- A network-wide speed limit of 30Km/h was implemented in VISSIM by defining the desired speed of every residential street as 30 km/h. This includes most streets in the study area except for the major arteries.

All the scenarios summarized in Table 3.2 are analysed for the estimation of emissions of greenhouse gases and the results are presented in Chapter 4. For studying the effects of traffic calming on air quality, scenario 4 is not included in the modeling process and scenario 1, 2 and 3 are presented in one scenario called speed bumps on roads. Chapter 5 presents the results of the air quality analysis.

Table 3.2 Description of Scenarios

Scenarios	Descriptions
Scenario 1	Entails the implementation of 17 speed bumps (necessitating a speed reduction to 5 km/h) along Rue Marquette, a major residential street in the neighborhood
Scenario 2	Entails the implementation of 17 speed bumps (necessitating a speed reduction to 5 km/h) along Rue Chambord, a major residential street in the neighborhood
Scenario 3	Entails the implementation of 17 speed bumps (necessitating a speed reduction to 5 km/h) along Rue Garnier, a major residential street in the neighborhood
Scenario 4	Entails a network-wide speed limit of 30 km/h
Scenario 5	Entails the implementation of 17 speed bumps along each of the following streets: Marquette, Chambord, Garnier, and Fabre. This scenario essentially captures the simultaneous effects of scenarios 1-3, including an additional street.
Scenario 6	Entails the implementation of 17 speed humps along each of the following streets: Marquette, Chambord, Garnier, and Fabre. This scenario essentially replaces speed bumps in scenario 5 with speed humps
Scenario 7	Entails the implementation of 17 speed humps along each of the following streets: Marquette, Chambord, Garnier, and Fabre including a network-wide speed limit of 30 km/h. This scenario essentially merges scenarios 4 and 6.
Scenario 8	Entails the implementation of 17 speed bumps along each of the following streets: Marquette, Chambord, Garnier, and Fabre including a network-wide speed limit of 30 km/h. This scenario essentially merges scenarios 4 and 5

CHAPTER 4
RESULTS FOR THE EFFECTS OF TRAFFIC CALMING ON EMISSIONS OF GREENHOUSE GASES

4.1 Introduction

In order to evaluate the effects of the different traffic calming measures, two categories of measures are proposed and presented in this chapter: (1) *network level measures* – the total Vehicle Kilometers Traveled (VKT) within the network, total vehicle emissions on the network, and total emissions per VKT (2) *link level measures* - the total emission percentage change on each link with respect to the base case scenario. The network level measures provide a sense of the overall performance within our sub- area. The link level measures allow us to investigate the effects of different measures in the immediate vicinity of the change.

4.2 Network Level Evaluation

The network-level emissions computed for all the scenarios are presented in Table 4.1. As expected, because traffic flows are reduced, the imposed traffic calming measures decrease the total VKT in the area under all of the scenarios compared to the base case except for scenario 5 (which introduces speed bumps along four different roads). In scenario 5, total volumes on the network are lower, although the total VKT is higher. This might be due to the fact that a significant number of vehicles avoided the calmed corridors which resulted in traveling longer distances. Indeed, Scenario 5 makes calmed corridors most unattractive compared to neighboring corridors thus inducing the search for alternative paths.

In terms of emissions, in general, total emissions are higher under all scenarios with respect to the base case. More important however are emission rates (in gr/VKT) which also increase thus indicating that vehicles on the network are generating higher emissions due to the resulting changes in drive-cycles. Scenarios 1, 2, and 3 which introduce calming measures along individual corridors generate smaller increases in emission rates than Scenarios 7 and 8 which combine lower speed limits and traffic calming along four different streets at the same time. Scenario 8 yields the highest increase in emissions of CO_2 by 7.60 %, CO by 4.54%, and NO_x by 4.62%, this is because speed bumps (which necessitate a slowing down to 5 km/h) lead to higher emissions than speed humps (which only necessitate a reduction to 25 km/h). Both speed humps and bumps lead to higher emissions when combined with lower speed limits. This could be the effect of lowering network-wide average speeds.

For comparative purposes, the average speed of each link on the network is calculated and MOVES in average-speed emission estimation mode is used in order to estimate the average-speed emissions and compare them to the second by second emissions presented in Table 4.1. Table 4.2 presents the results of this comparison. It is observed that average-speed emissions are systematically higher than instantaneous speed emissions. This is due to the fact that the average speeds on the network, even in the base-case scenario, are already fairly low (10-40 km/h). Indeed, when MOVES is operated with average speeds, it tends to overestimate emissions when speeds are low due to the embedded drive cycles that do not necessarily represent local driving conditions. Using instantaneous speeds derived for the entire hour of simulation (3,600s) ensures that a more reasonable treatment of emissions is obtained. It is also observed that the difference between emissions estimated using average vs. instantaneous speeds is higher along links with lower average speeds.

While the network-wide evaluation shows small to moderate changes in emissions (up to 7.6%), it is important to recognize that our sub-area comprises 352 links of which only 30 will undergo traffic calming. It is important to investigate link-level effects in order to identify whether certain links will undergo significant changes in drive-cycles and emissions.

Table 4.1 Effects of Traffic Calming on Total Air Pollutant Emissions and Total VKT

Scenarios	CO_2 (ton)	CO (kg)	NO_x (kg)	VKT	CO_2 (gr/VKT)	CO (gr/VKT)	NO_x (gr/VKT)
Base case	2.80	50.35	3.57	9751	287.41	5.16	0.366
Sc 1: Bumps on Marquette	2.83	50.45	3.61	9690	291.51	5.21	0.372
Sc 2: Bumps on Chambord	2.84	50.51	3.62	9744	291.33	5.18	0.372
Sc 3: Bumps on Garnier	2.85	50.16	3.61	9739	292.36	5.15	0.371
Sc 4: Speed limit	2.84	50.66	3.53	9738	291.45	5.2	0.362
Sc 5: Network-wide speed bumps	2.98	51.15	3.78	9775	305.14	5.23	0.387
Sc 6: Network-wide speed humps	2.83	49.51	3.62	9733	291.04	5.09	0.372
Sc 7: Network-wide speed humps and speed limit	2.84	50.13	3.53	9683	293.39	5.18	0.364
Sc 8: Network-wide speed bumps and speed limit	3.02	52.63	3.74	9691	311.18	5.43	0.386

Table 4.2 Comparison between Network-Wide Emissions Derived Using Instantaneous and Average-Speeds

Scenarios	Second by second emissions			Average speed emissions		
	CO_2 (ton)	CO (kg)	NO_x (kg)	CO_2 (ton)	CO (kg)	NO_x (kg)
Base case	2.80	50.35	3.57	3.40	51.72	4.11
Sc 1: Bumps on Marquette	2.83	50.45	3.61	3.40	51.70	4.09
Sc 2: Bumps on Chambord	2.84	50.51	3.62	3.41	51.83	4.11
Sc 3: Bumps on Garnier	2.85	50.16	3.61	3.44	52.18	4.13
Sc 4: Speed limit	2.84	50.66	3.53	3.44	52.42	4.13
Sc 5: Network-wide speed bumps	2.98	51.15	3.78	3.51	52.90	4.16
Sc 6: Network-wide speed humps	2.83	49.51	3.62	3.41	51.89	4.11
Sc 7: Network-wide speed humps and speed limit	2.84	50.13	3.53	3.43	52.19	4.11
Sc 8: Network-wide speed bumps and speed limit	3.02	52.63	3.74	3.57	53.67	4.16

4.3 Link Level Evaluation

The base case scenario has a network-wide speed limit of 50 km/h. FIGURE 4.1 shows the generated CO_2 emissions per kilometer of roadway in the sub-area. Of the 16.147 tons of CO_2 generated in the Plateau borough over the 7-8 AM period, 2.803 tons occur in the study area. As shown in FIGURE 4.1, arterial roads have the highest CO_2 emissions especially boulevard Saint-Joseph, going across the study area and avenue Papineau, on the Northeast side of the network. Other residential and school corridors are experiencing CO_2 emissions of less than 100 kg/km.

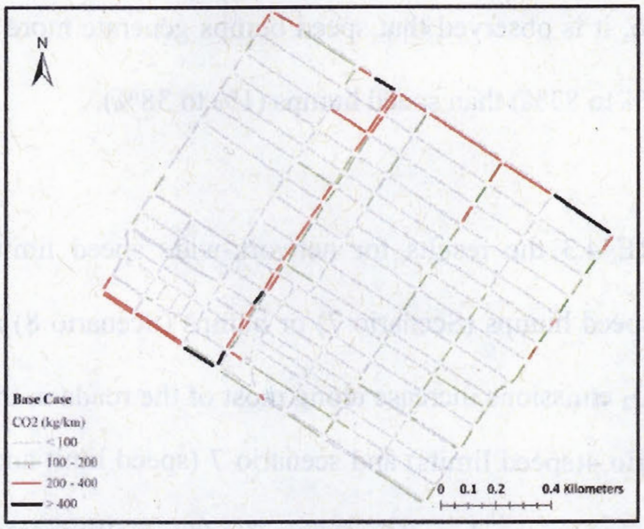

FIGURE 4.1 CO_2 emissions in the study area under the Base Case scenario.

The link level evaluations for isolated measures (Scenarios 1, 2, and 3) are presented in FIGURE 4.2. We observe that implementing speed bumps along isolated corridors (Marquette, Chambord, and Garnier) increases total CO_2 emissions along the corridor itself by 15-81% compared to the base case. The rest of the network does not experience a significant change in emissions. Note that the VKT on these links decrease but they still experience a rise in CO_2 emission rates (in g/VKT) by 35-74% therefore indicating that the increase in emissions is associated with changes in drive-cycles.

Generally, area-wide calming measures introduced in scenarios 5 and 6, including humps and bumps along four different streets at the same time, not only increase emissions along calmed roads but also worsen emissions across the network (FIGURE 4.3). We observe that calmed streets shift some of the traffic to alternative routes thus worsening their emissions. Comparing the results of scenarios 5 and 6, it is observed that speed bumps generate more acute increases in emissions (10% to 83%) than speed humps (1% to 38%).

Also, in FIGURE 4.3 the results for network-wide speed limits (Scenario 4) combined with speed humps (Scenario 7) or bumps (Scenario 8) are shown. It is observed that CO_2 emissions increase along most of the roads in the network. The results for scenario 4(speed limits) and scenario 7 (speed limit and speed humps) follow almost the same trend, with scenario 7 additionally increasing emissions along the calmed roads (1-23% change in CO_2 g/VKT). In scenario 8 (speed limit and speed bumps), we note a substantial increase in CO_2 emission rates with respect to the base case scenario, mostly along roads on which bumps were simulated (37-96% change in CO_2 g/VKT). Clearly, lowering network-wide speed has led to a deterioration of emissions as vehicles move at lower average speeds. Again by comparing the results of scenarios 7 and 8 for calmed roads, the difference between emissions induced by bumps and humps becomes more apparent.

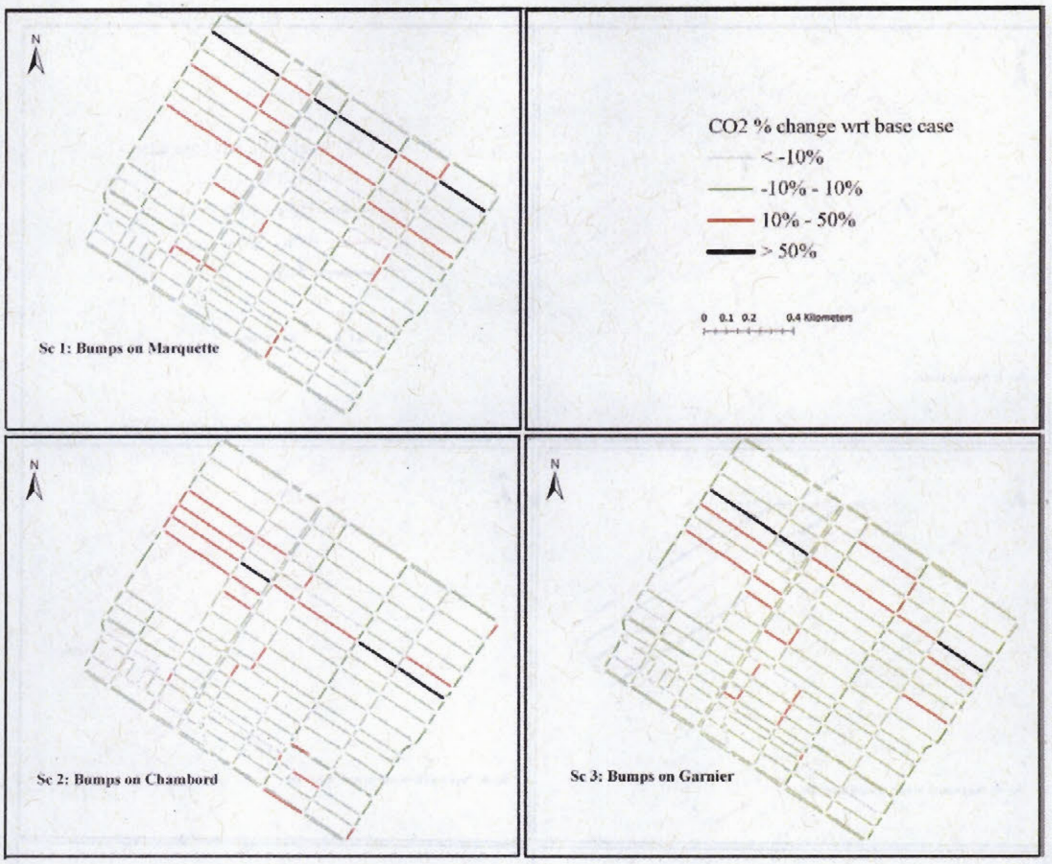

FIGURE 4.2 Link level emissions for isolated calming measures.

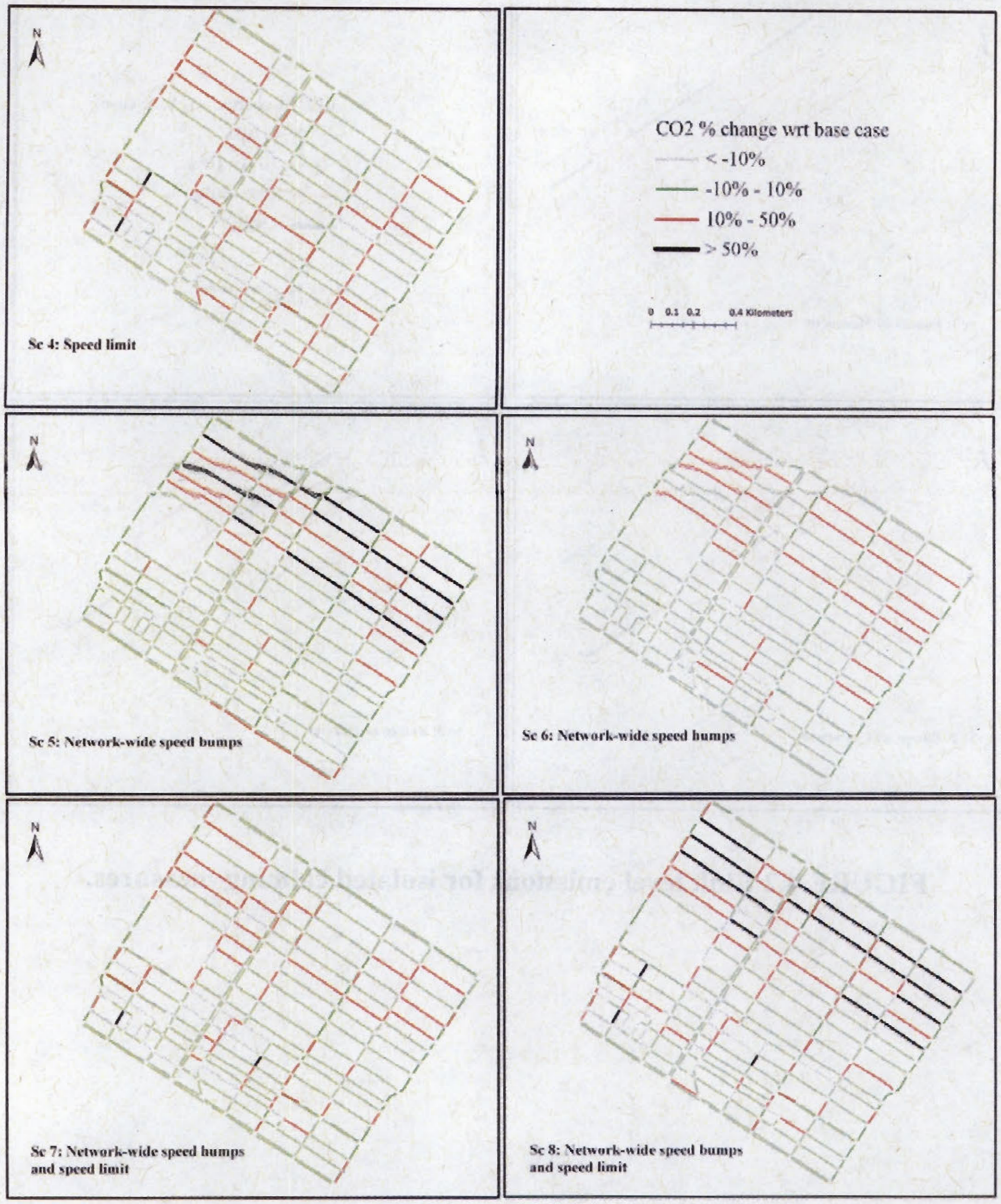

FIGURE 4.3 Link level emissions for area-wide calming measures.

4.4 Conclusion

In this chapter, results for estimating the effects of isolated traffic calming measures at a corridor level and area-wide calming schemes on vehicle induced emissions are presented. In general, the results show that total VKT on the network are slightly lower due to the implementation of traffic calming. In spite of this decrease, network emissions are higher. While both isolated and area-wide measures lead to modest increases in network-wide emissions (on average, 1.50% in CO_2, 0.33% in CO, and 1.45% in NO_x under isolated measure and 3.84% in CO_2, 1.22% in CO, and 2.18% in NO_x under area-wide measures) compared to the base case, link-level emissions along roads that have experienced traffic calming and proximate alternative routes increase by up to 83% in CO_2 indicating that localized air quality impacts are inevitable especially in the Plateau which is characterized by dense urban canyons. Under both isolated and area-wide calming measures, speed bumps result in higher increases in emissions than speed humps.

CHAPTER 5
RESULTS FOR THE EFFECTS OF TRAFFIC CALMING ON AIR QUALITY

5.1 Introduction

Near-road air quality results from a range of factors including traffic volumes, wind and temperature, dispersion characteristics of the road (e.g. urban canyon effects). In this chapter, first the results for validation of a dispersion model using a case study will be presented. Next, an evaluation of traffic calming measures on NO_2 levels along selected roadways is presented. The analysis presented in this section mostly follows the same scenarios as those used for emissions evaluation.

5.2 Case Study and Validation of Dispersion Model

The case study presented in this section is used to test the agreement between estimated and measured NO_2 concentrations. This case study is set along the Papineau corridor located within The Plateau. The NO_2 levels are estimated using a combination of traffic simulation, emission and dispersion modeling. The details for the modeling process are presented in the following sections in this chapter. The estimated NO_2 concentrations are compared to the data for NO_2 levels from a land-use regression model previously developed for Montreal in which passive diffusion samplers were used to measure NO_2 levels (Crouse *et al.* 2009).

5.2.1 Study Corridor and Field Data Collection

The case study is set along the Papineau corridor. Avenue Papineau is a major road experiencing high traffic volumes every day. The study corridor is a two way street bound by Avenue Mont-royal and Boulevard Saint Joseph with approximately 500 meters length and 17 meters width. Traffic volumes including volumes of passenger cars, vans, SUVs, trucks and buses on the corridor were manually counted for three days in November 2012 during 8-9AM and 4-5PM peak and 10-11AM off peak period. The manual counts were then used for the traffic simulation in VISSIM.

The concentrations of NO_2 from Crouse *et al.* (2009) are used for validating the modelled NO_2 levels along the Papineau corridor. In this study, Crouse *et al.* (2009) measured NO_2 concentrations using two-sided Ogawa passive samplers (Ogawa and Co., USA) for two weeks in November/December 2005. The samplers were installed at 133 locations in Montréal. Also, a land use regression model was developed to estimate the variability of NO_2 concentrations across the city as well as a "pooled" model to estimate the NO_2 annual average. The resulting model explains 80% of the variability in the concentrations of NO_2.

5.2.2 Traffic Simulation

In order to analyze NO_2 levels properly considering the accelerations and instantaneous speeds for individual vehicles; a microscopic traffic model of the Papineau corridor is developed. The corridor platform is modeled in VISSIM using a combination of orthophotos, topographic maps, cartographic maps and field visits. Traffic lights and signal timings are included. Vehicles are assigned to the network using the static routing decision which allocates vehicles on routes from a defined point to a defined destination relying on static percentages for each destination calculated from the manually counted traffic volumes. The model includes three types of vehicles: cars/vans/SUVs, heavy vehicles (HGV) (trucks) and buses. Traffic volumes are modeled for 8-9AM and 4-5PM peak hours and 10-11AM off peak hour. Results for the validation of the traffic simulation are presented in Table 5.1. Although there are some underestimations in terms of heavy vehicles and overestimations in terms of buses, the overall simulated traffic volumes are acceptable. Based on VISSIM output, the instantaneous link speeds and volumes are generated for emission and dispersion modeling.

Table 5.1 Results for Validation of The Traffic Simulation

	Street	Cross 1	Cross 2		Car\Van\SUV	HGV	BUS
AM	Papineau	Mont-royal	Gilford	Simulated	1533	51	20
				Traffic counts	1538	60	22
				Percentage difference	**-0.3**	**-14.8**	**-11.3**
	Papineau	St. Joseph	Gilford	Simulated	1554	48	26
				Traffic counts	1482	132	30
				Percentage difference	**4.9**	**-63.8**	**-12.9**
OP	Papineau	Mont-royal	Gilford	Simulated	1262	91.7	12
				Traffic counts	935	79	11
				Percentage difference	**35.0**	**16.1**	**9.1**
	Papineau	St. Joseph	Gilford	Simulated	1241	92	12.8
				Traffic counts	1290	158	12
				Percentage difference	**-3.8**	**-41.8**	**6.7**
PM	Papineau	Mont-royal	Gilford	Simulated	1175	54	23
				Traffic counts	1015	51	14
				Percentage difference	**15.8**	**5.9**	**64.3**
	Papineau	St. Joseph	Gilford	Simulated	1186	56	26
				Traffic counts	1431	49	25
				Percentage difference	**-17.9**	**14.3**	**4.0**

5.2.3 Emission Modeling

The Motor Vehicle Emission Simulator (MOVES) is employed to model the NO_x emissions along the Papineau corridor. A more detailed model description is presented in section 3.4. The instantaneous link speeds and volumes extracted from VISSIM are input for estimation. Other required input data include link length, link grade, meteorological data, fleet composition, and fleet age distribution for Montréal, which are input to reflect local conditions. Links lengths are extracted from AutoCAD maps of the corridor. The meteorological data are collected for November 2012. The vehicle type and model year information are obtained from the Société de l'assurance automobile du Québec (SAAQ) and Statistics Canada, also for November 2012. MOVES is used to calculate NO_x emission factors for all vehicle types (cars, heavy vehicles and buses) for each segment of the study corridor. The results for emission modeling are presented in Table 5.2. The results for emission factors are consistent with the results from the literature (see for example John et al., 1999 and Wang et al. 2010).

Table 5.2 Emission Modeling Results

Vehicle type	Distance Traveled (VKT)			Total NO_x (gr)			Emission Factor (gr/VKT)		
	AM	OP	PM	AM	OP	PM	AM	OP	PM
Car/Van/ SUV	633.9	517.9	485.4	234.5	191.9	176.2	0.37	0.37	0.36
HGV	20.7	30.5	22.5	374.3	556.5	387.7	18.09	18.23	17.25
Bus	8.8	5.0	9.8	63.2	34.9	65.1	7.16	6.95	6.64

5.2.4 Dispersion Modeling

The Danish Operational Street Pollution Model (OSPM) is used for modeling the concentrations of NO_2 along the Papineau corridor. OSPM runs under special mode to calculate the NO_2 concentrations. The description of the model is presented in section 3.5. The vehicle volumes and speeds extracted from the

VISSIM model and emission factors derived from MOVES are used as input in OSPM. It should be mentioned that for dispersion modeling heavy vehicles and buses are combined into one group of heavy vehicles. Other required data include street configuration (average height of buildings and width and orientation of the street) gathered through site visits, meteorological data (wind speed, wind direction, global radiation and temperature) collected for the three days in November 2012, background concentrations of NO_2, NO_x and O_3 and the percentage of NO_2 emitted directly by vehicles. Table 5.3 and Table 5.4 present the summary of street configuration and meteorological data, respectively. FIGURE 5.1 shows the wind speed and directions for which the concentrations are modeled. These include meteorological data for November 12, 13 and 14 2012. FIGURE 5.2 illustrates street configuration for one segment along Papineau as it is expressed in OSPM.

Table 5.3 Papineau Corridor Configurations

	Papineau Gilford&Mont-Royal	Papineau St.Joseph&Gilford
Length (m)	300	110
Width (m)	17	17
Direction	130°	130°
Building height (m)	11	11

Table 5.4 Meteorological Data

		AM	OP	PM
	Global Radiation (W/m2)	140	140	140
	Temperature (°C)	-1	4.4	10.9
Background levels	**NO_x (ppb)**	10	10	8
	NO_2 (ppb)	8	8	7
	O_3 (ppb)	19	19	25

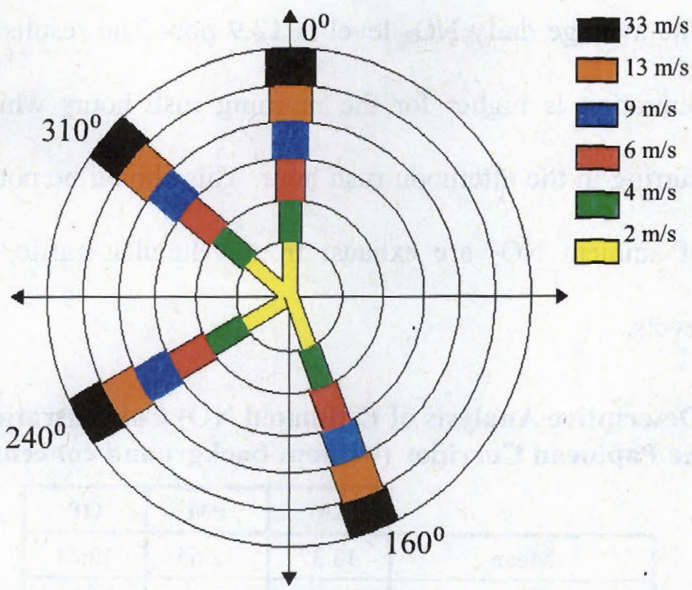

FIGURE 5.1 Wind directions and speeds.

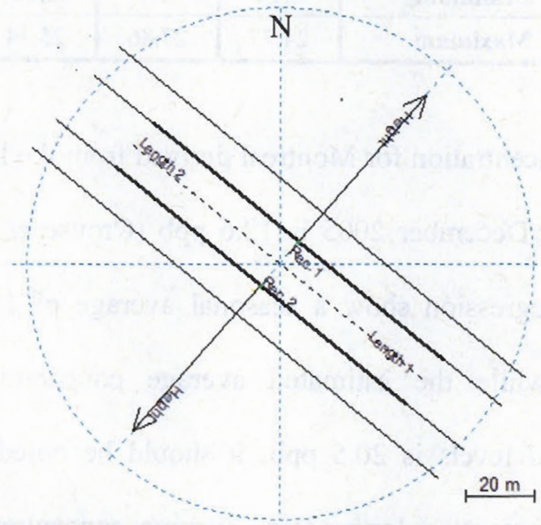

FIGURE 5.2 Street configuration for one segment along Papineau as it is expressed in OSPM.

5.2.5 Comparison of the Dispersion Model Results with Data from a Land Use Regression Model

The results of dispersion modeling and its comparison with land-use regression output are presented in this section. Table 5.5 shows the descriptive analysis of estimated NO_2 concentrations along the Papineau corridor using OSPM for three time spans. The average daily NO_2 level is 12.9 ppb. The results show that the average concentration is higher for the morning rush hours while the highest levels are occurring in the afternoon rush hour. This should be noted that OSPM estimations of ambient NO_2 are exhaust from vehicular traffic, excluding the background levels.

Table 5.5 Descriptive Analysis of Estimated NO_2 Concentrations (in ppb) along the Papineau Corridor (without background concentrations)

	AM	PM	OP
Mean	13.32	12.65	12.81
Median	12.01	10.81	11.38
Standard Deviation	4.10	5.48	4.57
Minimum	9.10	7.10	8.10
Maximum	24.77	27.86	25.34

The average NO_2 concentration for Montreal derived from the land-use regression model for November/December 2005 is 12.6 ppb (Crouse *et al.* 2009). Results from the land use regression show a seasonal average of 18.1 ppb along the Papineau corridor while the estimated average concentration with OSPM including background levels is 20.5 ppb. It should be noted that the land-use regression model expresses a longer-term average concentration (two months) than the one obtained in OSPM (three days of emissions and of meteorological data) and therefore a slightly lower concentration is expected compared to the dispersion model output. In addition, the land-use regression model was developed for 2005/2006 while traffic counts were conducted in 2012. It is therefore not uncommon to expect increased traffic volumes along such a major corridor and as a result, higher near-road air pollutant levels. Looking at the monthly average NO_2 levels for November/December 2005 to 2011 obtained from a permanent monitoring station in Montréal close to study area shows a low variation over time with standard deviation of 1.65 (Table 5.6). Note however that this station is not located near-road and therefore levels are expected to be higher closer to the roadway.

Table 5.6 Monthly Average NO_2 Levels for November/December 2005 to 2011 for a Permanent Monitoring Station in Montréal

Year	Avg. NO2 (ppb)
2005	24.38
2006	21.91
2007	23.4
2008	21.4
2009	21.13
2010	21.44
2011	19.26
Standard Deviation	1.65

5.3 Analysis of Near-Road Air Quality under Traffic Calming

This section presents the results of evaluation of traffic calming measures on NO_2 levels along the roadways. The analysis presented in this section follows the same scenarios as those used for emissions evaluation except for the scenario with the imposed speed limit (scenario 4). Also, scenarios 1, 2 and 3 (which stand for Scenario 1entailing the implementation of 17 speed bumps (necessitating a speed reduction to 5 km/h) along Rue Marquette, Scenario 2 entailing the implementation of 17 speed bumps (necessitating a speed reduction to 5 km/h) along Rue Chambord and Scenario 3 entailing the implementation of 17 speed bumps (necessitating a speed reduction to 5 km/h) along Rue Garnier) are presented under one scenario entitled speed bumps on the roads. Concentrations of NO_2 are estimated for different combinations of wind speeds and directions representing the Fall 2012 conditions for each segment of the study corridors in the sub-area highlighted in FIGURE 3.2 (Chambord, Marquette, Garnier).

5.3.1 Base-Case Conditions

The average, maximum and minimum NO_x emissions and NO_2 concentrations for the base case with the speed limit of 50 km/h along the study corridors are presented in FIGURE 5.3. The average NO_2 levels (without taking into account background concentrations, i.e. only considering the contribution of traffic) range between 10 and 12 ppb. The maximum NO_2 concentrations, exceeding 25 ppb, are recorded on one segment along the Chambord corridor. This segment is characterized by the highest traffic volumes and therefore illustrates the association between traffic flow and near-road air quality. FIGURE 5.3 illustrates that while the averages on all segments are close in magnitude, the maxima have a much higher variability and occur under different combinations of wind speed and direction (depending on the orientation of every segment). The minima do not fall below 10 ppb indicating the effect of traffic under the most dispersive wind conditions. We also observe a very high variability in NO_x emissions which vary between less than 5 grams to more than 35 grams per segment. The pearson correlation coefficient for NO_x emissions and average NO_2 levels is 0.95 while the correlation between NO_x emissions and maximum NO_2 levels is 0.74.

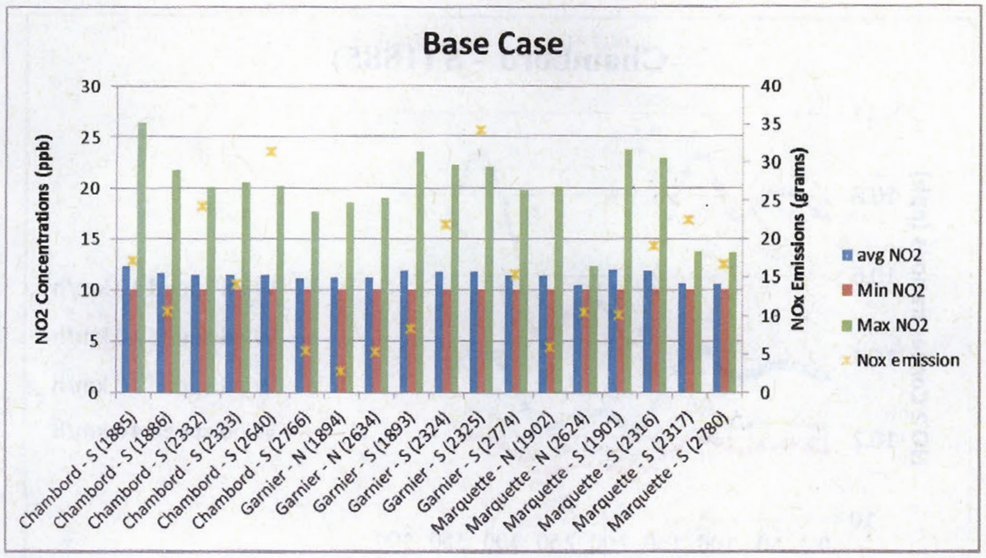

FIGURE 5.3 Average, maximum and minimum NO_2 concentrations (ppb) and NO_x emissions (grams) for the base case along the study corridors.

In order to investigate the effects of wind speed and wind direction on NO_2 levels, for various wind speeds and directions, concentrations were modelled along both sides of each road segment. FIGURE 5.4 illustrates the effects of wind speed on the NO_2 concentrations along a road segment pertaining to the Chambord corridor (the busiest corridor in terms of traffic flow). It illustrates the average NO_2 concentration on both sides of the segment. Clearly, we observe a negative association between wind speed and NO_2 levels: as the wind speed increases the NO_2 concentrations decrease. The largest effect of increasing wind speed is seen when transitioning between a speed of 10 km/h to a speed of 20 km/h. Beyond 20 km/h, the decrease in NO_2 levels is maintained but becomes less drastic.

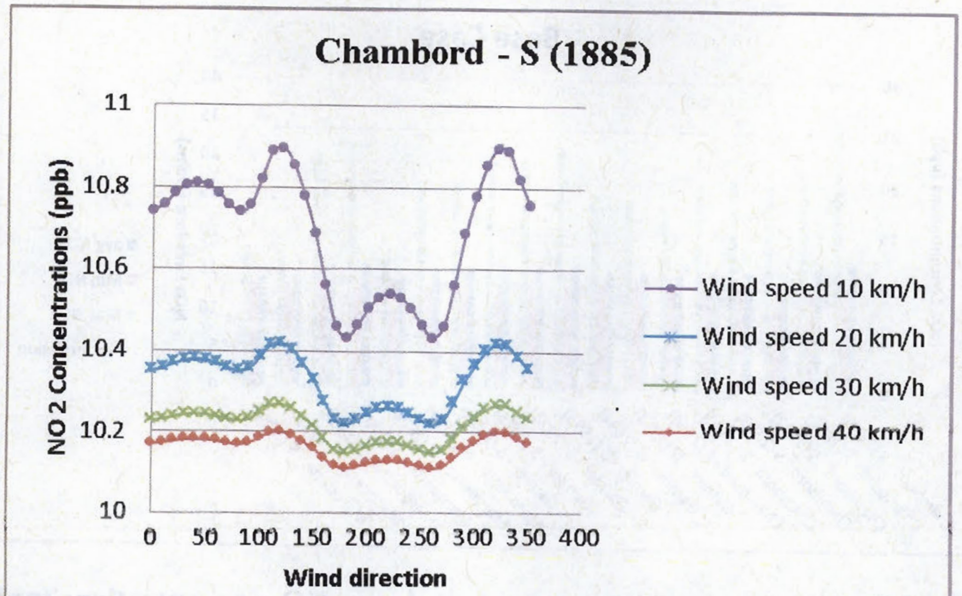

FIGURE 5.4 The effects of wind speed on NO_2 concentrations for a road segment of Chambord corridor (wind direction is expressed as degrees from the true North).

FIGURE 5.5 shows the NO_2 concentrations for both sides of one road segment along the Chambord corridor for the base case with the wind speed of 20 km/h. In FIGURE 5.5, receptors 1 and 2 are placed on both sides of the roadway. The segment orientation is 130 degrees from the true North and receptor 1 is located on the East side of the segment while receptor 2 is located on the West side. In this case, when the wind blows between 0 and 130 degrees and between 310 and 350 degrees from the true North, receptor 1 will be located on the leeward side of the road. We observe the windward side of the road experiences lower levels of NO_2 due to the urban canyon effect. This trend is observed for all other road segments. Berkowitz *et al.* (1996) and Wang and Xie (2009) also have the same findings that the leeward concentrations are higher than the windward levels. When the wind is aligned with the roadway, both sides experience similar levels.

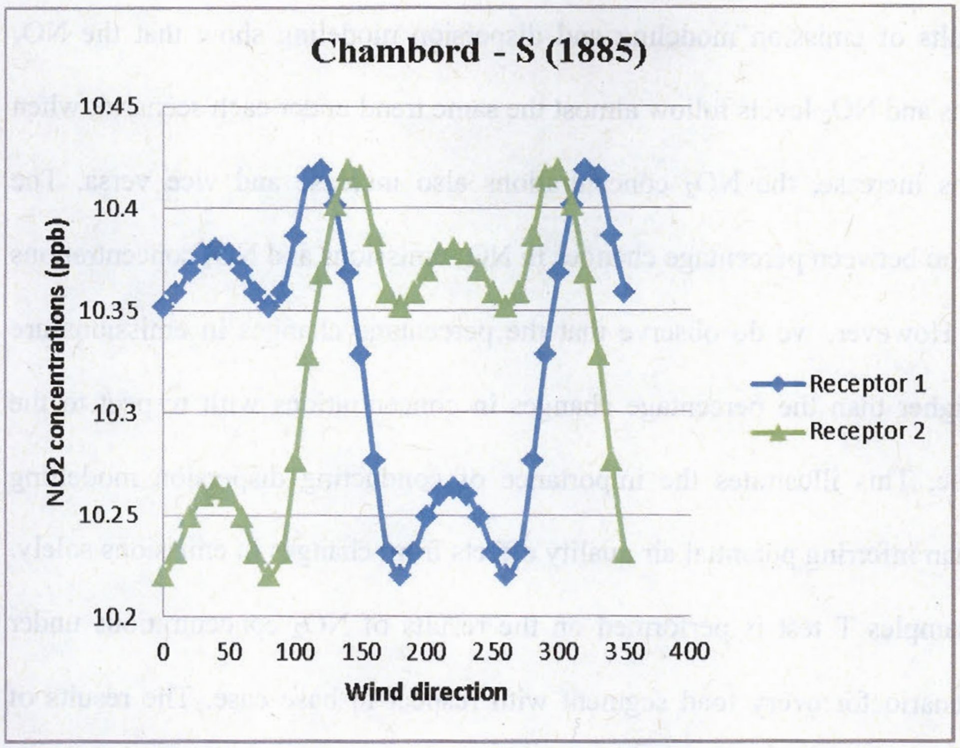

FIGURE 5.5 The NO_2 concentrations for both sides of road segment of Chambord corridor for the base case (wind direction is expressed as degrees from the true North).

5.3.2 Scenario Analysis

As shown in Table 5.7, scenarios with both isolated and area-wide speed bumps, in general lead to higher air pollutant concentrations than speed humps. The maximum percentage change in the NO_2 concentrations with respect to base case is 9% observed along Marquette under a scenario with speed bumps on the road. Even in some cases such as scenario 6 and 7 where area-wide speed humps are simulated some segments experience a decrease in NO_2 levels which is less than 2% with respect to the base case.

The results of emission modeling and dispersion modeling show that the NO_x emissions and NO_2 levels follow almost the same trend under each scenario; when emissions increase, the NO_2 concentrations also increase and vice versa. The correlation between percentage changes in NO_x emissions and NO_2 concentrations is 0.66. However, we do observe that the percentage changes in emissions are much higher than the percentage changes in concentrations with respect to the base case. This illustrates the importance of conducting dispersion modelling rather than inferring potential air quality effects from changes in emissions solely. Paired-samples T test is performed on the results of NO_2 concentrations under each scenario for every road segment with respect to base case. The results of statistical analysis show that the differences between NO_2 levels of each scenario and base case are significant. FIGURE 5.6 presents such trends in more details for four segments of Chambord corridor.

Table 5.7 Percentage Change in NO_x Emissions and NO_2 Concentrations under Each Scenario for Every Study Corridor

	Sc 1, 2, 3: Speed bumps on roads		Sc 5 : Network-wide speed bumps		Sc 6 : Network-wide speed humps		Sc 7 : Network-wide speed humps & speed limit		Sc 8 : Network-wide speed bumps & speed limit	
	%NO_2 Conc.	%NO_x emission	% NO_2 Conc.	% NO_x emission	% NO_2 Conc.	% NO_x emission	% NO_2 Conc.	% NO_x emission	% NO_2 Conc.	% NO_x emission
Chambord - S (1885)	7.0	44.3	7.2	43.0	1.8	7.7	1.8	5.3	7.2	42.5
Chambord - S (1886)	7.9	46.1	8.6	55.0	6.6	9.2	2.0	-5.0	8.2	51.7
Chambord - S (2332)	6.5	50.3	6.8	54.0	2.3	23.0	0.6	-2.7	5.5	35.3
Chambord - S (2333)	7.3	75.9	7.2	68.0	2.2	24.0	1.1	5.8	7.2	68.3
Chambord - S (2640)	4.0	19.4	4.3	22.9	0.8	1.2	-0.9	-23.7	3.5	13.2
Chambord - S (2766)	7.9	135.8	8.5	161.2	2.4	47.0	1.2	17.5	7.9	132.4
Garnier - N (1894)	6.2	104.6	6.4	110.4	2.6	47.5	0.1	-3.6	4.6	60.4
Garnier - N (2634)	6.5	112.1	6.7	116.5	3.5	58.8	2.1	27.9	6.0	95.8
Garnier - S (1893)	3.7	23.2	3.5	18.6	-0.3	-12.7	-1.1	-22.5	3.4	13.5
Garnier - S (2324)	5.5	29.3	6.0	35.8	1.5	6.1	-0.2	-16.8	4.9	20.4
Garnier - S (2325)	4.1	20.5	4.2	21.5	1.4	7.5	-0.5	-16.9	4.2	15.3
Garnier - S (2774)	8.9	92.4	8.6	82.8	2.6	27.9	1.5	5.6	8.1	81.1
Marquette - N (1902)	6.2	66.4	7.1	78.9	2.4	22.6	-0.5	-16.3	5.7	50.8
Marquette - N (2624)	1.4	104.9	1.3	98.2	0.7	58.8	0.1	11.9	1.0	72.2
Marquette - S (1901)	6.8	48.3	6.6	51.9	0.4	-2.9	0.2	-6.9	6.9	53.6
Marquette - S (2316)	6.4	41.8	6.7	45.6	2.4	19.0	-0.9	-15.7	5.4	28.4
Marquette - S (2317)	1.9	55.2	2.0	58.9	1.0	29.3	-0.2	-7.3	2.0	62.5
Marquette - S (2780)	2.5	81.8	2.3	77.6	0.9	30.1	0.1	1.3	2.0	65.0

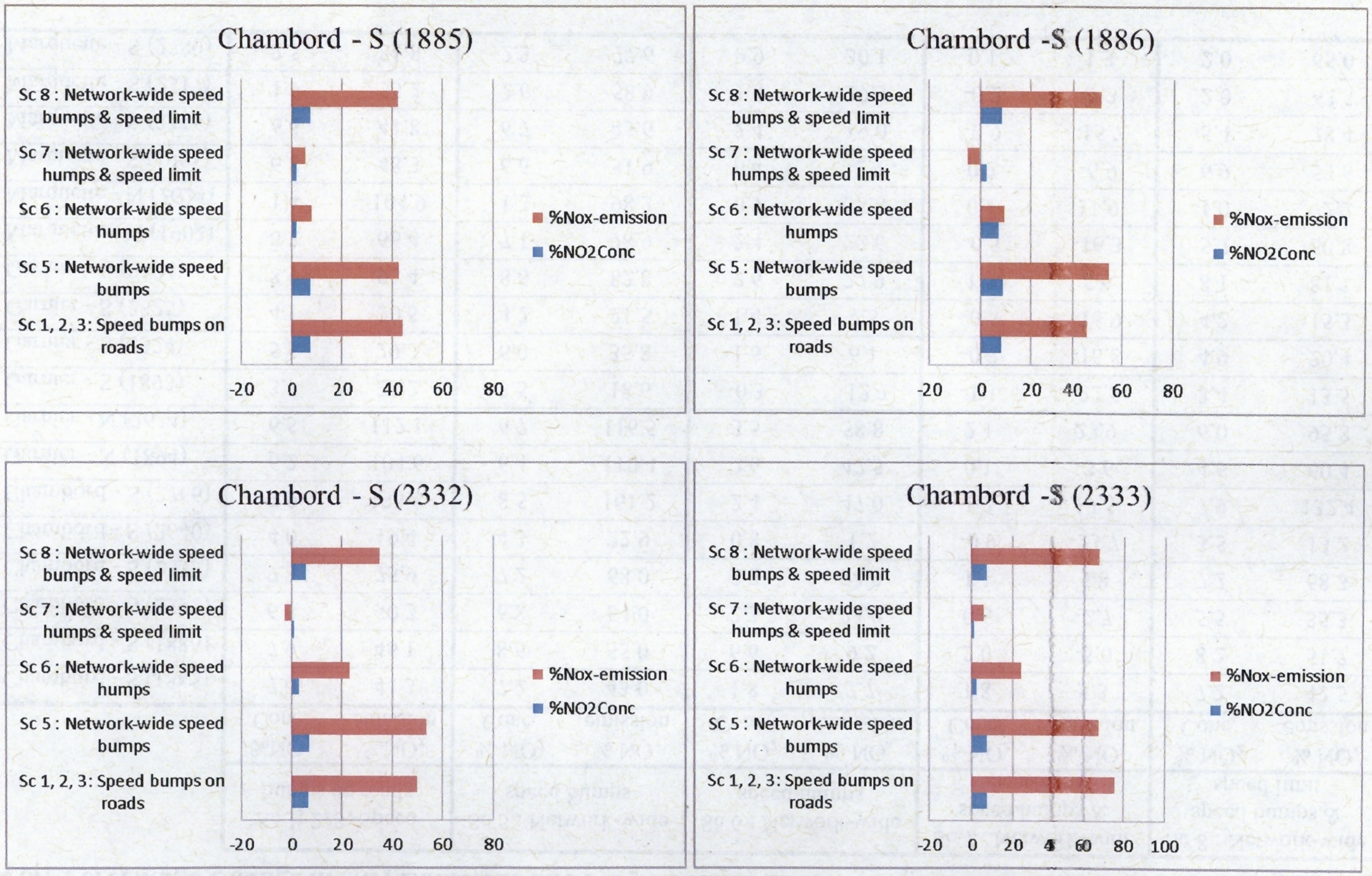

FIGURE 5.6 Percentage changes in NO_x emissions and NO_2 concentrations for foursegments of Chambord.

5.4 Conclusion

In this chapter, results for the effects of traffic calming measures on air quality are presented. The results for air quality modeling suggest that traffic calming measures do not have as large an effect on concentrations of NO_2 as the effect observed on NO_x emissions. We observe that on average NO_2 levels increase between 0.1% and 9% with respect to the base case; however, increases of up to 40% are observed under specific meteorological conditions. Clearly, we observe a high positive correlation between segment emissions of NO_x and concentrations of NO_2. Also, the effects of wind speed and direction are investigated in this thesis. The results show that higher wind speeds decrease NO_2 concentrations on both sides of the roadway while winds orthogonal to the road increase the difference between concentrations on the leeward and windward sides with the leeward side experiencing higher levels. Similar to their effect on emissions, speed bumps produce the highest increases in NO_2 levels.

CHAPTER 6
CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Traffic calming refers to a combination of physical changes in road design and speed management aiming at improving road safety especially for users of non-motorized transportation sharing the road with drivers (Lockwood 1997). Traffic calming strategies are based on either one of two approaches: 1) black-spot approach or 2) area-wide approach. In the black-spot approach, isolated measures are installed on a specific segment of a road network, while area-wide approach measures are planned systematically and installed on the entire network (Elvik and Vaa 2004).

Various traffic calming measures with the means of improving road safety have been implemented all over the world for decades. While the safety impact of traffic calming has been studied in depth, relatively few studies have been conducted to capture the environmental impact of traffic calming. Most of the literature presented many advantages such as the use of real drive-cycles, traffic volumes, and air pollution measurements to quantify the effects of traffic calming on air quality. However, they lack the capability of evaluating the effects of instantaneous speed changes and traffic volumes simultaneously and in isolation.

In this thesis, the effects of isolated traffic calming measures at a corridor level and area-wide calming schemes are estimated with respect to traffic volumes, vehicle speeds, and emissions using a combination of microscopic traffic simulation, emission and dispersion modeling. The study area is set in Montréal, Canada, where a traffic simulation model for a dense urban neighborhood is extended with capabilities for microscopic emission estimation and dispersion modeling both at a link-level and at a network-level. Within this neighborhood, this research mostly focuses on a small sub-area that is facing increasing traffic volumes and speeds along several residential streets. Instantaneous link speeds and traffic volumes are extracted from the traffic simulation and are input into the emissions simulator. Hourly CO_2, CO, and NO_x emissions for the 352 links of the study area are quantified under a range of traffic calming scenarios. These include simulating speed bumps and speed humps at a corridor level and network-wide level, simulating speed limits, and simulating combinations of speed limits, speed bumps and speed humps. Later, the estimated NO_x emission factors as well as extracted traffic volumes and vehicle speeds are input within a dispersion model to quantify concentrations of NO_2 along several residential corridors under almost the same traffic calming scenarios employed for emission modeling.

The results provide important insights into the effects of traffic calming on vehicle-induced air pollutant emissions and air quality. In general, it is observed that total VKT on the network are lower due to the implementation of traffic calming. In spite of this decrease, network emissions are higher. While both isolated and area-wide measures lead to modest increases in network-wide emissions (on average, 1.50% in CO_2, 0.33% in CO, and 1.45% in NO_x under isolated measure and 3.84% in CO_2, 1.22% in CO, and 2.18% in NO_x under area-wide measures) compared to the base case, link-level emissions along roads that have experienced traffic calming and proximate alternative routes increase by up to 83% in CO_2 indicating that localized air quality impacts are inevitable especially in the Plateau which is characterized by dense urban canyons. Under both isolated and area-wide calming measures, speed bumps result in higher increases in emissions than speed humps.

The results for air quality modeling suggest that traffic calming measures do not have as large an effect on concentrations of NO_2 as the effect observed on NO_x emissions. We observe that on average NO_2 levels increase between 0.1% and 9% with respect to the base case; however, increases of up to 40% are observed under specific meteorological conditions. Clearly, we observe a high positive correlation between segment emissions of NO_x and concentrations of NO_2. Also, the effects of wind speed and direction are investigated in this thesis. The results show that higher wind speeds decrease NO_2 concentrations on both sides of the roadway while winds orthogonal to the road increase the difference between concentrations on the leeward and windward sides with the leeward side experiencing higher levels. Similar to their effect on emissions, speed bumps produce the highest increases in NO_2 levels.

6.2 Limitations

This dissertation is associated with a number of new findings pertaining to the effects of traffic calming on emissions and air quality under a range of scenarios. Nonetheless, it is associated with limitations mostly related to data availability and computational burden. In particular, the lack of real drive-cycle information is a limiting factor especially in order to validate the traffic simulation in terms of replicating real drive-cycles in the study area. In addition, since our traffic simulation is limited in terms of simulating traffic calming measures, studying other calming measures such as curb extensions, road closure, raised intersections, and etc. was not feasible. In fact, bumps and humps were not modelled as such but expressed in the traffic simulation as "zones with lower speed limits". Moreover, another limitation of this research is that even with today's impressive computing power, the time it took to run the models is a substantial burden, making multiple scenarios and iterative runs prohibitively burdensome. On average, VISSIM takes approximately 9 hours to converge and 1 hour to generate instantaneous link speeds and traffic volumes under each scenario, and MOVES took approximately 8 hours to generate emission results. There are also limitations with respect to fleet composition and emissions; the assumption that every car represents the distribution of the fleet takes away some of the details in the emission modeling, i.e. in reality a 2008 Chevy Malibu might generate different emissions than a 2005 Kia Rio. Finally, this thesis also has some limitations regarding data including: more repetitions and longer sampling periods for traffic counts is ideal, air quality data does not exactly correspond with the simulation period, weather data is extracted from Montréal-Trudeau station, which is very far from the study area, so it does not express local temperature and wind conditions.

6.3 Recommendations for Future Research

This research is carried out to develop a microscopic traffic, emission and dispersion modeling system which aims to capture the effects of traffic calming schemes on emissions and air quality. In this research, drive-cycles generated from the traffic simulation model were employed for emission modeling. However it is crucial that real drive-cycles are captured using GPS data in order to validate the traffic simulation model.

Traffic calming has recently become at the spotlight throughout Canada. In fact, there is an ongoing study in National Collaborating Centre for Healthy Public Policy (NCCHPP) regarding the effects of traffic calming on road safety, air quality and noise levels. There were several implementations of different traffic calming measures throughout Montreal, especially within The Plateau neighborhood. Therefore, a "before and after study" should also be carried out in the future, where the models can be validated with actual data. Assessment of a range of dispersion models such as Gaussian, or computational fluid dynamics is also recommended in order to investigate the effect of modelling methodology on the resulting air pollution levels.

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