AN INTEGRATED MULTI-MODEL APPROACH FOR PREDICTING THE IMPACT OF HOUSEHOLD TRAVEL ON URBAN AIR QUALITY AND SIMULATING POPULATION EXPOSURE

by

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A thesis submitted in conformity with the requirements for the degree of Doctor of Philosophy
Department of Civil Engineering
University of Toronto

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Abstract

The population and economic growth experienced by Canadian metropolitan areas in the past twenty years, has been associated with increased levels of car ownership and vehicle kilometres travelled leading to a deterioration of air quality and public health and an increase in greenhouse gas emissions. The need to modify urban growth patterns has motivated planning agencies in Canada to develop a broad range of policies aiming at achieving a more sustainable transportation sector. The challenge however, remains in the ability to test the effectiveness of proposed policy measures. This situation has led to a renewed interest in integrated land-use and transport models to support transport policy appraisal. This research is motivated by the need to improve transport policy appraisal through the use of integrated land-use and transport models linked with a range of sub-models that can reflect transport externalities. This research starts with an exploration of the transport policy environment in Canada through a questionnaire-based survey conducted with planners and policy-makers. The survey results highlight the need for tools reflecting the sustainability impacts of proposed policies. While the second part of this research explores sustainability indicators and recommends a set of social, economic, and environmental measures, linked with integrated land-use and transport models; effort is
dedicated to estimate the environmental indicators as part of this thesis. As such, the third part of this research involves the development of an emission-dispersion-exposure modelling framework. The framework includes a suite of sub-models including an activity-based travel demand model (TASHA), an emission factor model (Mobile6.2C), a meteorological model (CALMET), and a dispersion model (CALPUFF). The framework is used to estimate link-based emissions of light-duty vehicles in the Greater Toronto Area under a base scenario for 2001. Dispersion of emissions is then conducted and linked with population in order to estimate exposure to air pollution.
Acknowledgments

After having written this dissertation and revising it numerous times, the last thing I expected was to experience writer’s block over this final task. I find myself pausing and recollecting the past four years and thinking about all those who affected my life as a PhD student and as an adopted Torontonian. There are so many people I wish to thank and hopefully, with the last bit of sanity left in me, I manage to express my gratitude to all!

First and foremost, I would not be writing this thesis if it wasn’t for the tremendous opportunity given to me by Dr. Eric Miller to join the ILUTE team. Dr. Miller, you have been a true inspiration. Thank you for your insurmountable advice, support, and guidance throughout the entirety of my doctoral research. I also would like to extend special thanks to Dr. Amer Shalaby, Dr. Chris Kennedy, Dr. Greg Evans, and Dr. Lawrence Frank for your valuable time, constructive suggestions and your role on the supervisory committee. Dr. Isam Kaysi and Dr. Mutasem El-Fadel, thank you for encouraging me to pursue a doctorate in Transport Planning.

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<tbody>
<tr>
<td>AFR</td>
<td>Air to Fuel Ratio</td>
</tr>
<tr>
<td>AMT</td>
<td>Agence Métropolitaine de Transport</td>
</tr>
<tr>
<td>CAC</td>
<td>Criteria Air Contaminant</td>
</tr>
<tr>
<td>CMM</td>
<td>Communauté Métropolitaine de Montréal</td>
</tr>
<tr>
<td>CO</td>
<td>Carbon Monoxide</td>
</tr>
<tr>
<td>CST</td>
<td>Center for Sustainable Transport</td>
</tr>
<tr>
<td>EA</td>
<td>Environmental Assessment</td>
</tr>
<tr>
<td>EC</td>
<td>Environment Canada</td>
</tr>
<tr>
<td>EF</td>
<td>Emission Factor</td>
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<tr>
<td>GHG</td>
<td>Greenhouse Gas</td>
</tr>
<tr>
<td>GTA</td>
<td>Greater Toronto Area</td>
</tr>
<tr>
<td>GVRD</td>
<td>Greater Vancouver Regional District</td>
</tr>
<tr>
<td>HC</td>
<td>Hydrocarbon</td>
</tr>
<tr>
<td>HDDV</td>
<td>Heavy Duty Diesel Vehicle</td>
</tr>
<tr>
<td>HOV</td>
<td>High Occupancy Vehicle</td>
</tr>
<tr>
<td>ILUTE</td>
<td>Integrated Land Use Transportation and the Environment</td>
</tr>
<tr>
<td>I/M</td>
<td>Inspection and Maintenance</td>
</tr>
<tr>
<td>IUM</td>
<td>Integrated Urban Models</td>
</tr>
<tr>
<td>LDGT</td>
<td>Light Duty Gasoline Truck</td>
</tr>
<tr>
<td>LDGV</td>
<td>Light Duty Gasoline Vehicle</td>
</tr>
<tr>
<td>LR</td>
<td>Long Range</td>
</tr>
<tr>
<td>NH$_3$</td>
<td>Ammonia</td>
</tr>
<tr>
<td>NO$_x$</td>
<td>Nitrogen Oxides</td>
</tr>
<tr>
<td>PM</td>
<td>Particulate Matter</td>
</tr>
<tr>
<td>PM$_{10}$</td>
<td>Particulate Matter with diameter $\leq$ 10 microns</td>
</tr>
<tr>
<td>PM$_{2.5}$</td>
<td>Particulate Matter with diameter $\leq$ 2.5 microns</td>
</tr>
<tr>
<td>QoL</td>
<td>Quality of Life</td>
</tr>
<tr>
<td>RTC</td>
<td>Réseau de Transport de la Capitale</td>
</tr>
<tr>
<td>RVP</td>
<td>Reid Vapour Pressure</td>
</tr>
<tr>
<td>SEA</td>
<td>Strategic Environmental Assessment</td>
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<tr>
<td>SO$_x$</td>
<td>Sulphur Oxides</td>
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<td>SOV</td>
<td>Single Occupancy Vehicle</td>
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<td>SR</td>
<td>Short Range</td>
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<tr>
<td>TAC</td>
<td>Transportation Association of Canada</td>
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<tr>
<td>TASHA</td>
<td>Travel Activity Scheduler for Household Agents</td>
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<td>TAZ</td>
<td>Traffic Analysis Zone</td>
</tr>
<tr>
<td>TC</td>
<td>Transport Canada</td>
</tr>
<tr>
<td>TDM</td>
<td>Transportation Demand Management</td>
</tr>
<tr>
<td>TPM</td>
<td>Total Particulate Matter</td>
</tr>
<tr>
<td>TTC</td>
<td>Toronto Transit Commission</td>
</tr>
<tr>
<td>USEPA</td>
<td>United States Environmental Protection Agency</td>
</tr>
<tr>
<td>VKT</td>
<td>Vehicle Kilometres Travelled</td>
</tr>
<tr>
<td>VOC</td>
<td>Volatile Organic Compounds</td>
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Chapter 1
Introduction

1.1 Background and motivation

Urban areas in Canada are no exception to a global trend toward increasing car use, both in terms of vehicle ownership and vehicle kilometres travelled (VKT). According to Environment Canada’s (EC) latest National Pollutant Release Inventory, road transportation is a major contributor to emissions of greenhouse gases (GHGs) and Criteria Air Contaminants (CACs). The latter are composed of Total Particulate Matter (TPM), Particulate Matter less than or equal to 10 Microns (PM$_{10}$), Particulate Matter less than or equal to 2.5 Microns (PM$_{2.5}$), Sulphur Oxides (SO$_x$), Nitrogen Oxides (NO$_x$), Volatile Organic Compounds (VOC), Carbon Monoxide (CO) and Ammonia (NH$_3$). In fact, road transportation was found to be responsible for 45 percent of total CO emissions, 25 percent of total NO$_x$ emissions, 11 percent of total VOC emissions, and 18 percent of total GHG emissions (Figure 1.1) (EC, 2008 a; b). Among roadway vehicles, light-duty gasoline vehicles and trucks are responsible for a significant part of emissions (Figure 1.2).

![Figure 1.1 Contribution of different sources to Canadian emissions of selected CACs in 2006 (excluding natural sources) (EC, 2008a)](image-url)
Despite the growing demand for travel; on a national scale, vehicle-induced emissions of CACs in Canada have decreased between 1985 and 2006 according to the latest National Pollutant Release Inventory (Figure 1.3).

This finding goes in hand with results of emission inventories conducted in the US and Europe. Based on a study of the evolution of NO\textsubscript{x} emissions from road transport in Europe, Venstreng et al. (2008) found an increase in vehicle emissions of NO\textsubscript{2} between 1980 and 1990 followed by a
decrease between 1990 and 2005 to levels below 1980 (Figure 1.4). In its “Latest Findings on National Air Quality Report”, the USEPA also found decreasing emissions of CACs between 1980 and 2006: NO\textsubscript{x} were found to decrease by 33 percent, VOC by 52 percent, SO\textsubscript{2} by 47 percent, PM\textsubscript{10} by 28 percent, and PM\textsubscript{2.5} by 31 percent (USEPA, 2008). While an overall decrease in total vehicle emissions is observed, an examination of emissions for different vehicle types shows that while emissions for light-duty gasoline vehicles and trucks have indeed decreased, emissions from heavy-duty diesel vehicles have increased between 1985 and 2006 (Figure 1.5).

![Figure 1.4](image1.png)

Figure 1.4 Evolution of vehicle NO\textsubscript{2} emissions in Europe between 1980 and 2005 (Venstreng et al., 2008)

![Figure 1.5](image2.png)

Figure 1.5 Evolution of light-duty vehicle emissions compared to heavy-duty diesel emissions (EC, 2008a)
Despite the decrease in vehicle emissions observed in Canada and other countries between the 1980’s and 2006; the evolution in GHG emissions has followed an opposite trend. In Canada, GHG emissions associated with road transportation have increased between 1990 and 2006 indicating that the growth in population has indeed been matched by a growth in travel demand (Figure 1.6). The tightening of vehicle emission standards and improvements in vehicle technology could be responsible for the reduction in emissions of CACs.

![Figure 1.6 Evolution of vehicle-induced GHG emissions between 1990 and 2006 in Canada (EC, 2008b)](image)

An examination of air quality trends in Toronto reveals disappointing results. Indeed, while on the national level Canadian vehicle emissions have achieved a significant decrease, this trend does not seem to be reflected in Canada’s largest metropolitan area. The growth in single occupancy vehicle (SOV) travel, auto ownership, and the suburbanization of population and employment into non-transit service areas observed between 1964 and 2001 in the Greater Toronto Area (GTA) seem to have had a stronger effect on air quality than technological improvements (Miller and Shalaby, 2001; Miller and Soberman, 2003). In 2007, the City of Toronto’s Public Health department estimated the contribution of traffic related air pollution to about 440 premature deaths and 1,700 hospitalizations per year in Toronto. The report also estimates that costs associated with traffic pollution in the city are about $2.2 billion annually. In Toronto, vehicles are the largest source of CO and NOx emissions. Toronto Public Health (2007)
examined the evolution of annual average concentrations of common air pollutants in Toronto over a 26 year span (1980 to 2006). While CO and SO₂ showed a slight decline in recent years, particulate matter did not. NO₂ levels showed a decline between 1996 and 2006 but did not go below the 1980 levels, a trend which is quite different from the national trend in NOₓ emissions. Of greatest concern are ozone levels which are showing a steady increase between 1996 and 2006. Indeed, the growth experienced by the GTA has occurred at a much higher rate than growth in Canada as a whole. Pollution trends in Toronto do not show much improvement since 1980. Toronto Public Health (2007) suggests that:

> Despite many important initiatives by all levels of government to improve air quality, progress is slow. It may be that gains in the transportation sector, such as the introduction of less polluting vehicles and improvements in fuel quality, are being offset by the increased volume and frequency of vehicle use.

In the GTA, response to the air pollution and fuel consumption challenges has included the development of several innovative policy options which typically rely on sustainability principles (City of Toronto, 2001; COSGP, 2003; MPIR, 2005; City of Toronto, 2007). Road transportation is a major focus of such policies. The challenge however, remains in the ability to test the effectiveness of proposed policy measures and policy packages. Policy appraisal is a major precursor to decision-making, providing decision-makers with information on the potential impacts of proposed measures, thus ensuring that informed decisions are being made. The growing complexity of travel demand patterns as well as residential and firm location processes, added to the GHG challenge and sustainable development objectives, have put enormous pressure on policy-makers to factor these issues within policy appraisal.

Worldwide, the challenge of transport policy appraisal has motivated the development of integrated land-use and transport models, also known as integrated urban models (IUMs). Since the 1990’s, there has been a renewed interest in the use of activity-based travel demand and integrated urban modelling as instruments for assessing the sustainability impacts of land-use and transportation changes (Southworth, 1995; Wegener and Fürst, 1999; Wegener, 2004; Buliung et al., 2005). In general, the IUM framework internalizes linkages and feedback between urban transport and land-use systems to support investigation of urban policy scenarios and to
forecast future urban conditions. In some instances, the structure has been extended to include environmental modelling and feedback mechanisms (Strauch et al., 2003; Wegener, 2005). In Canada, the ILUTE (Integrated Land Use Transportation Environment) project is an IUM framework currently under development by a consortium of researchers\(^1\). ILUTE uses a microsimulation modelling method in which the behaviour of individual entities is simulated over time. The cumulative effects of these individual behaviours form the overall behaviour of the system. The objects or actors in the system represent real-world entities such as persons and firms. The behaviour of these objects is designed to reflect the behaviour of their real-world counterparts. ILUTE is discussed in more detail in Miller et al. (2004) and Salvini and Miller (2005). The overall structure of ILUTE is presented in Figure 1.7.

While ILUTE is proposed as a tool to support transport policy appraisal and assess urban sustainability in the GTA, it should be recognized that its use by planning organizations involves many challenges, notably related to the overwhelming amount of output and the complexities associated with processing and interpreting this information. In addition, the current version of ILUTE does not explicitly estimate air quality impacts, energy consumption, as well as other measures of urban sustainability.

\(^1\) University of Toronto, University of Calgary, Université Laval, McMaster University, Wilfred Laurier University
This research is motivated by the need to improve transport policy appraisal in the GTA through the use of ILUTE as a tool for assessing the sustainability of proposed policies. This entails providing ILUTE with the capability of “measuring sustainability” as well as making its results comprehensible and useful for decision-makers.

1.2 Scope of work

Based on the motivation for this research which invokes the assessment of urban sustainability impacts of proposed transport policies in the GTA, the aim of this research is to develop a modelling framework for the estimation of vehicle induced emissions, air pollutant concentrations, and population exposure to air pollution. Recognizing that urban sustainability involves environmental, social, and economic objectives, the current research investigates those three dimensions in the context of ILUTE; yet, it focuses on the quantification and in-depth analysis of the environmental dimension. Clearly, the most significant environmental impacts of transport relate to air quality and GHG emissions. The use of the modelling framework will be as a tool that relies on ILUTE outputs to estimate air quality impacts of proposed policy scenarios.

In order to achieve the objectives of quantifying air quality and informing transport policy decisions, the scope of this research involves three core tasks briefly described below.

- **Task 1:** Exploring the current mechanisms for transport policy appraisal and decision-making across Canada with a focus on the challenges of modelling and policy analysis as well as the needs of planners and policy-makers in terms of tools that can assist decision-making. The core of this task is a questionnaire-based survey conducted with planners and policy-makers at the three levels of government in Canada.

- **Task 2:** Examining ways of bridging modelling and decision-making through making model results more accessible and comprehensible to decision-makers. This is achieved through the development of sustainable transport indicators derived from modelling results. The core of this task is the investigation of indicators which encompass the three pillars of sustainability (environmental, social, economic) and could be linked with ILUTE.

- **Task 3:** Modelling and assessing the air quality impacts of transport in the GTA and development of a set of air quality indicators that can be linked with ILUTE. The core of this task is the emission and dispersion modelling for vehicle-induced air pollutants in the GTA thus generating policy-sensitive estimates of GHGs and major air pollutants. Based on the modelling, a set of indicators reflecting the environmental dimension of sustainability is proposed.
1.3 Research significance

The climate change and sustainability agenda have added a new dimension to policy in most metropolitan areas around the world. Despite significant efforts dedicated towards the development of IUMs and activity-based travel demand models as policy-assessment tools, they still lack the capability of “measuring” urban sustainability. Indeed, few examples exist today where the IUM framework has been extended with capabilities for simultaneous evaluation of the environmental, social, and economic performance of land-use and transport policy scenarios (Buliung et al., 2006). This research provides ILUTE with capabilities for quantifying the impacts of land-use and transport scenarios on environmental sustainability. It also provides a blueprint for further linkages between ILUTE and measures of social and economic sustainability. While the aim of this research is the estimation of air quality impacts, the driver is the policy, and this research is characteristic in terms of encompassing a close look on both policy and modelling thus ensuring that the proposed framework responds to policy needs.

1.4 Thesis structure

Based on the three tasks presented in Section 1.2, this dissertation is structured into three parts: Part A, which is formed by Chapters 2, 3, 4, and 5, contains a description of the questionnaire-based survey conducted with planners and policy-makers across Canada and discusses the survey results. It is considered as the background or exploratory work that has helped shape the objectives of ILUTE in general and this research in particular. Part B, which is composed of Chapter 6, investigates the use of sustainable transport indicators to bridge modelling and decision-making. It proposes the overall scope for the integration of ILUTE with sustainability indicators and selects the modelling area that would be the focus of this research. Part C, which is composed of Chapters 7, 8, and 9, includes the modelling and analysis of air quality impacts in the GTA. It describes the methods and results of the emission-dispersion-exposure modelling. Following the eight main thesis Chapters, Chapter 10 links the three parts of the thesis: policy, indicators, and modelling by discussing policy implications of the air quality modelling conducted and proposing a set of environmental indicators. Chapter 11 concludes with a summary and recommendations for future research. Figure 1.8 illustrates the various research components (and Chapters) as well as their interactions.
Chapter 1: INTRODUCTION

Part A: Exploring the policy environment to refine research objectives

Chapter 2: Survey Design

Chapter 3: Survey Results – Theme 1
Role of Modelling in Decision-Making

Chapter 4: Survey Results – Theme 2
Role of Sustainability Objectives in Planning

Chapter 5: Survey Results – Theme 3
Institutional Integration for Sustainable Transport

Findings of Part A:
- Challenges in modeling & policy analysis
- New dimensions to decision-making
- Importance of performance measures to facilitate understanding of model results

Part B: Proposing a Framework for Improving Policy Appraisal and Decision-Making

Chapter 6: Sustainability Indicators and Policy Appraisal

Findings of Part B:
- Need to assess policies on the 3 levels of sustainability: environmental, social, economic
- Usefulness of sustainability indicators
- Focus on environmental indicators in this research

Part C: Modelling and Analysis

Chapter 7: Modelling of Vehicle Emissions in GTA

Chapter 8: Methodology for Modelling Dispersion
Meteorological Modelling in GTA

Chapter 9: Results of Dispersion Modelling and Population Exposure

Findings of Part C:
- Wide range of concentration results
- Hot-spots of air pollution in urban area

Chapter 10
Proposed Air Quality Indicators
Implications of Modelling for Policy

Chapter 11: CONCLUSION

Figure 1.8 Research components and thesis chapters
Chapter 2
Design of a Planners and Policy-Makers Survey Exploring the Context for Transport Planning and Decision-Making in Canada

2.1 Introduction
In light of the recent challenges brought by global warming issues and the need to curb environmental degradation and promote sustainable transportation in urban areas, Canadian planners and policy-makers are faced with a major challenge: the development and implementation of transport policy that can reduce GHGs and air pollutant emissions and at the same time not hinder economic growth and offer people transportation alternatives. The increasing complexity in policy questions makes it impossible for “mental models” or professional judgement alone to provide convincing answers. As a result, the need for modelling in general and IUMs in particular is becoming essential in the context of policy development. In the academic sphere, the need for modelling to assist policy-making is unquestionable. In transport policy, however, this “necessity” for modelling remains a controversial and debatable issue; the main question being: “can models inform policy and are they worth the significant time and resource investments?”

Since the inception phase of the various components of this dissertation, a recurring theme, which became the driver of this research, was to inform the ILUTE model development and make it more “policy-relevant”. Through an exploration of the ways in which the “policy-relevance” of ILUTE and large-scale travel demand models could be addressed, communication with potential users of model results was considered the most valuable. Indeed, an investigation of the ways in which model results currently influence decisions, the effect of the sustainability agenda on planning, and the institutional mechanisms that can favour modelling and sustainable transport were all questions that became highly important in the context of this research thus driving the need for a survey to be conducted across government agencies with transport-related responsibilities.

For this purpose, a survey was conducted by the author of this dissertation on planners and policy-makers pertaining to the three levels of government (municipal, provincial, federal) in
Canada. The aim of the survey was to collect information with respect to the current evaluation process of transport policy and plans and its associated pitfalls as well as the desired state of policy appraisal and the need for more formal evaluation tools. The survey targeted three main components of transport policy namely, 1) modelling capabilities within agencies and attitudes towards models and decision-making; 2) current evaluation of external impacts of plans and assessment of transport sustainability; and 3) institutional framework for modelling and decision-making of transport plans and the extent to which transport decisions are integrated among different agencies. This Chapter describes the questionnaire, survey setup, as well as agencies and personnel that participated. The next three Chapters (3, 4, and 5) are dedicated to a discussion on the results of the different survey components.

2.2 Description of the questionnaire

The questionnaire is divided into three components and seven sections (Table 2.1). Each component explores a specific theme of interest to the research.

Theme 1 is dedicated to the current role of modelling in decision-making within government agencies. In this context, participants are asked to describe the tools currently available for policy analysis; the extent of “in-house” modelling as compared to the reliance on consultants; the problems/challenges they are currently facing in policy evaluation; the types of people (background, skills, etc.) involved in modelling and policy analysis; as well as to provide their opinion on the role of models and model results in decision making. The results of this component are discussed in Chapter 3.

Theme 2 attempts to capture the impact of the sustainability agenda on planning and decision making. Participants are asked about the existing means for assessing environmental, social, and economic impacts of policies. They are also probed to comment on the concept of sustainability planning and whether it has been integrated within their plans. A discussion on the usefulness of sustainable transport indicators for policy analysis is also conducted. Finally, a scenario planning exercise is done whereby participants are asked to envision the future (20 years) of their urban area based on three different scenarios sketched to them. The three scenarios almost replicate the
three pillars of sustainability: environmental, economic, and social. The results of this component are discussed in Chapter 4.

The third survey component, Theme 3, explores the effect of institutional integration on the promotion of sustainable transport plans. In this part of the survey, participants discuss the current situation with respect to integrating decisions within their urban areas and comment on ways to improve the current situation. Stakeholder and public participation in the planning process is also discussed. Finally, participants are asked to highlight the major changes in planning and policy that they have witnessed throughout the course of their career in public policy. The results of this component are discussed in Chapter 5.

Table 2.1 Components of the questionnaire

<table>
<thead>
<tr>
<th>Theme</th>
<th>Sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theme 1</td>
<td>1) Existing modelling tools and role of models in decision-making</td>
</tr>
<tr>
<td></td>
<td>2) Involvement in modelling and decision-making</td>
</tr>
<tr>
<td>Theme 2</td>
<td>3) Assessment of external impacts of plans (environmental, economic, social) and sustainability planning (including a discussion on the potential use of sustainable transport indicators as a link between models and policy-making)</td>
</tr>
<tr>
<td></td>
<td>4) Scenario planning exercise aiming at capturing the expected business as usual future of transportation in the region</td>
</tr>
<tr>
<td>Theme 3</td>
<td>5) Extent of and success in engaging stakeholders and the general public within the planning process</td>
</tr>
<tr>
<td></td>
<td>6) Extent of and success in communicating as well as integrating decisions with other agencies (lower or higher tier, or same tier but in neighbouring jurisdictions) regarding policy appraisal and implementation of plans</td>
</tr>
<tr>
<td></td>
<td>7) Major changes in overall policy environment and decision-making witnessed by participant within her/his agency and region throughout the past 15 years</td>
</tr>
</tbody>
</table>

In addition to the three survey components, background data on agencies (types of plans and policies currently being drafted/implemented and time frames for long-term and short-term plans) and participants (position in agency, years spent in current position, educational background, and main responsibilities) were collected. A complete questionnaire is presented in Appendix A.
2.3 Implementation of the survey

Following development of the questionnaire, a selection of Canadian cities that are possible candidates for the survey was conducted. In fact, Canadian cities that are either major metropolitan areas or medium-sized cities that are expected to grow as a result of an increasing rate of immigration to Canada (Statistics Canada, 2006) were selected as part of this study. These areas are expected to have more pressure in terms of developing and implementing strategic growth plans and integrated transportation policies and therefore more exposure to the process of policy appraisal, implementation, and monitoring. The following cities were selected: Vancouver, British Columbia; Calgary, Alberta; Edmonton, Alberta; Montreal, Quebec; Quebec City, Quebec; Ottawa, Ontario; Waterloo-Kitchener, Ontario; and various regions within the GTA, Ontario as it is the fastest growing area in Canada in terms of population.

Following the selection of urban areas, a review of growth plans, transportation master plans, and other transport-relating planning documents related to the selected cities, was conducted. The review allowed for pinpointing the different agencies that have a role in transport planning and policy-making as well as relevant individuals that are senior enough to provide both a technical and a policy perspective.

Selected individuals were contacted by email and invited to participate in the survey, a brief description of the survey and its goal were provided at the time the email was sent. A total of 35 individuals were contacted, out of whom four did not respond to the invitation and the rest all agreed to be interviewed. The survey consisted of 27 interviews conducted between May and October 2006. Most of the interviews were conducted with one participant while 4 interviews were conducted each with 2 participants at the same time, thus amounting to a total of 31 participants.

Interviews were semi-structured and lasted for 1 to 1.5 hours. Semi-structured interviews enabled the researchers to focus the discussions around the main survey themes and at the same time, not restricting the participants to a fixed structure. All interviews were recorded. Interview scripts were developed in both French and English. All interviews in the province of Quebec and one interview with the federal government in Ottawa were conducted in French.
2.4 Review of plans in selected urban areas

A literature review of various strategic growth plans, transportation master plans, and municipal official plans related to the selected urban areas was conducted (City of Toronto, 2007; City of Toronto, 2001; Region of York, 2007; Ville de Montreal, 2007; GVTA, 2006; Region of Waterloo, 2006; City of Calgary, 2006; City of Vancouver, 2006; GVRD, 2006; GVRD, 1999; City of Edmonton, 2005; City of Edmonton, 1999; CMM, 2005; RTC, 2005; Region of Peel, 2005; MPIR, 2005; AMT, 2003; COSGP, 2003; City of Ottawa, 2003; City of Markham, 2002).

All of the selected cities have an official plan or growth strategy and a transportation master plan which includes a long range transportation vision. In terms of their overarching objectives, the plans reviewed are quite similar and have more or less the same goals of promoting economic growth, improving the environment and safety, reducing social disparities, and alleviating congestion. Parking management in downtown areas, the promotion of alternative modes of transportation (walking and cycling), and Transportation Demand Management (TDM) initiatives are also recurrent themes. Transit investments and an increase in transit share are considered as a priority in all transportation master plans. The City of Toronto official plan makes a bold statement that no new roads will be built in Toronto and the increase in travel demand will be handled by transit (City of Toronto, 2007). The Montreal transportation master plan proposes to treat transit as a cornerstone of the development of the City of Montreal (Ville de Montreal, 2007).

In terms of the evaluation of potential external impacts arising from the proposed transport plans; only a few of them suggest the development and use of evaluation measures. The Montreal transportation master plan recommends the development of indicators for measuring 1) the reduction in automobile use, 2) environmental impacts, 3) safety, 4) public and private investments, 5) positive economic impact on the transport sector in Quebec, 6) direct transport costs, and 7) reduction in public costs (Ville de Montreal, 2007). The plan does not mention how these indicators will be estimated. The Calgary transportation master plan proposes the adoption of a “triple bottom line (TBL)” approach to decision making that considers economic, social and environmental issues. The plan however, falls short of articulating how economic, social, and environmental impacts will be estimated (City of Calgary, 2006). The Edmonton transportation master plan attempts to estimate the potential impacts of the plan on mobility, emissions, community impacts, and traffic noise. However, it is not clear how those impacts are quantified.
(City of Edmonton, 2005). While most plans start with a coherent set of objectives for achieving more sustainable transport patterns, and propose initiatives that are in line with reducing automobile use and promoting transit, walking, and cycling; they overlook the evaluation phase that is crucial for assessing whether proposed initiatives can indeed achieve sustainability.

2.5 Overview of participating agencies

The 27 interviews were distributed among the three levels of government (4 interviews at the federal level, 3 interviews at the provincial level, and 14 interviews at the municipal / regional municipality level) and 6 interviews were within transit agencies. Beside the 4 interviews conducted at the federal level (National Capital), the rest had a cross-country representation with 12 in Ontario (Ottawa, Toronto, York, Peel, Durham, Markham, Waterloo), 6 in Quebec (Quebec City, Montreal), 2 in British Columbia (Vancouver), and 3 in Alberta (Calgary, Edmonton). A total of 20 different agencies were surveyed (Figure 2.1).

AMT = Agence Métropolitaine de Transport, CMM = Communauté Métropolitaine de Montreal, GVRD = Greater Vancouver Regional District, MPIR = Ministry of Public Infrastructure Renewal, MTO = Ministry of Transport Ontario, MTQ = Ministry of Transport Quebec, NRCan = Natural Resources Canada, TTC = Transport Canada, TC = Transport Canada, TTC = Toronto Transit Commission, RTC = Réseau de Transport de la Capitale.

Figure 2.1 Geographic distribution of agencies surveyed
The breadth of agencies surveyed represents the wide range of government departments with transport-related responsibilities in Canada. In fact, the decentralization of the Canadian government structure, involving three levels of government (federal, provincial, and municipal) has led to a spread of the transport-related jurisdiction over a number of government departments. The federal government is responsible for policies and programs targeting the national transportation system. It is also responsible for international issues in transportation, new vehicle standards, aviation, and with some exceptions, marine transportation, as well as national and interprovincial rail, bus, and truck transportation. On the federal level, Transport Canada is the major regulator and policy maker. The provincial government is responsible for intraprovincial transportation, economic regulation of interprovincial trucking, construction and maintenance of major highways, vehicle licensing and inspection, as well as enforcement of traffic rules. Most provinces involve their departments of transportation, public works, economic development, and environment in decision-making related to transportation. Often, provincial responsibilities are passed on to regional and local municipal governments to provide for a more sensitive delivery of services. Municipalities are usually responsible for local planning decisions, such as municipal transportation, development of transportation plans, public transit, and parking fees. Municipal responsibilities mainly depend on the degree of delegation by provincial governments and on their size; larger municipalities generally have more scope for action than smaller municipalities. Regional municipalities mainly work with the lower-tier municipalities in their region since by law, municipal long range plans have to be consistent with those of the region. Also, when municipalities prepare their transportation plans, the region has to approve these plans and can change them. The Federation of Canadian Municipalities (FCM) provides guidance to municipal decision-makers on issues including transportation and environmental protection (TC, 2004).

Beside the three levels of government, agencies have been established in some Canadian cities as a proxy to regional municipalities or as a means to link municipal and provincial visions as well as integrate various actors in transport decisions. The agencies of interest to this study include the Greater Vancouver Regional District (GVRD), TransLink, Communauté Métropolitaine de Montreal (CMM), and Agence Métropolitaine de transport (AMT). The following discussion provides a brief overview of the role and responsibilities of each.
The GVRD is a partnership of 21 municipalities and one electoral area. The Board of Directors comprises mayors and councillors from the member municipalities, on a representation by population basis. It was established in 1967. The GVRD is responsible for the delivery of water, sewerage and drainage, solid waste management but also for developing plans and activities aimed at improving air quality, regional parks, and housing (Alexander et al., 2005). GVRD’s most significant and innovative role was the creation of its regional strategic plan thus allowing it to develop a sustainability agenda (GVRD, 2006).

The Greater Vancouver Transportation Authority (GVTA), more commonly known as TransLink, was created by the British Columbia Greater Vancouver Transportation Authority Act in 1998. TransLink is governed by a 15 member board of directors. The GVRD is responsible for appointing 12 of the board members, and the Province is responsible for appointing the other three members. GVRD approves and ratifies TransLink strategic transportation plans, property taxes, toll charges, parking taxes or vehicle levies. TransLink has the responsibility for the following, within the GVRD: transportation planning and funding, operation of the regional transportation system (bus, rail, custom transit services, ferry service), funding cycling facilities, transportation demand management, the Major Road Network (in conjunction with the municipalities), and administering GVRD’s portion of the AirCare program (vehicle inspection and maintenance program) (TransLink, 2004).

The AMT was established in 1996. It is governed by a council consisting of seven members: four are assigned by the Province of Quebec and three are assigned by the CMM. It is responsible for planning, managing, coordinating and supporting the Montreal metropolitan transit system (bus, metro, taxi-bus, commuter trains and adapted transit), as well as for improving the efficiency of roads of metropolitan significance. AMT has the capability to implement high vehicle occupancy (HOV) lanes, integrate fares and services, and manage and develop the commuter train network. The territory of the AMT includes 82 municipalities, 13 regional county municipalities, and 14 transit authorities (MAMM, 1999).

The CMM is a planning, coordinating and financing agency which regroups 82 municipalities in the Montreal metropolitan area; it was created in 2001. CMM’s mandate spans land-use planning; economic development; cultural development; social housing; metropolitan
infrastructures, services, or activities; public transport and the metropolitan arterial road network; solid waste management; air quality management; and water treatment. It has five commissions: land-use, environment, economic development, social housing, and transport. In terms of its involvement in public transport, CMM approves the strategic plan of AMT and has the authority to reject proposed changes in fares. It reviews and has the power to approve or reject AMT’s budget. CMM also approves the strategic plans of public transit operators in metropolitan Montreal (CMM, 2002).

Réseau de Transport de la Capitale (RTC) and Toronto Transit Commission (TTC) are the transit providers within the City of Quebec and Toronto respectively. RTC has a strategic plan (2005-2014) for the development of their services (RTC, 2005) and the TTC has a new Light Rail plan for the City of Toronto (TTC, 2007).

This decentralization in transport-related authority in Canada is further accentuated by fragmented jurisdiction with respect to the economic, social, and environmental impacts of transport. In fact, Transport Canada; Natural Resources Canada; Environment Canada; provincial ministries of Transportation, Infrastructure, and Environment; and the National Round Table for the Environment and Economy have all addressed -with more or less detail- the issue of sustainable transport in Canada (e.g. TAC, 1999; EC, 2003; TC, 2001; NRTEE, 2003).

2.6 Characteristics of participants

Most surveyed departments were planning departments and most participants were either heads of departments or managers of transportation thus indicating a certain level of seniority within the survey sample. Table 2.2 presents a generic list of agencies and position of interviewed persons within each agency. In addition to the occupied position, the number of years spent at the current position was recorded. Out of the 31 participants, 11 have been in their current position for more than 10 years while 12 have been in the current position for 6-10 years and 8 have been in the position for less than 6 years. Note that if this classification is made based on the years of experience, a significantly higher number of participants would be in the >10 years range since a large portion of “new directors” with less than 5 years in their current position, have had senior positions in other agencies or other departments within the same agency. In terms of participants’
training, the three backgrounds encountered among the survey sample include, economics, engineering, and planning/geography. Federal level, participants are predominantly economists while in municipalities, there is predominance in engineers (Table 2.3).

Table 2.2 List of surveyed agencies and participants

<table>
<thead>
<tr>
<th>Agency</th>
<th>Department / Division</th>
<th>Participants - Interview 1</th>
<th>Participants - Interview 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Municipality</td>
<td>Transportation Planning</td>
<td>Head of modelling</td>
<td></td>
</tr>
<tr>
<td>Municipality</td>
<td>Transportation Planning</td>
<td>Director</td>
<td>Manager – Forecasting</td>
</tr>
<tr>
<td>Municipality</td>
<td>City Planning</td>
<td>Program Manager of Transportation Planning</td>
<td></td>
</tr>
<tr>
<td>Municipality</td>
<td>Engineering</td>
<td>Manager of Transportation</td>
<td></td>
</tr>
<tr>
<td>Municipality</td>
<td>Transportation – Strategic Planning</td>
<td>1) Director</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2) Director of data and modelling group</td>
<td></td>
</tr>
<tr>
<td>Regional municipality</td>
<td>Planning and Development Services</td>
<td>Director of Infrastructure Planning Branch</td>
<td>Manager of Transportation Planning</td>
</tr>
<tr>
<td>Regional municipality</td>
<td>Planning</td>
<td>Director of Transportation Planning</td>
<td></td>
</tr>
<tr>
<td>Regional municipality</td>
<td>Regional Development</td>
<td>Manager</td>
<td></td>
</tr>
<tr>
<td>Regional Municipality</td>
<td>Planning</td>
<td>1) Director</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2) Head of modelling</td>
<td></td>
</tr>
<tr>
<td>Regional Municipality</td>
<td>Directorate of Metropolitan Planning</td>
<td>1) Director of Land-Use Planning</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2) Director of Transport Planning</td>
<td></td>
</tr>
<tr>
<td>Regional municipality</td>
<td>Planning department Works department</td>
<td>1) Manager of Transportation Planning and Research</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2) Manager of Transportation Infrastructure</td>
<td></td>
</tr>
<tr>
<td>Provincial &amp; municipal board</td>
<td>Planning</td>
<td>Vice president</td>
<td></td>
</tr>
<tr>
<td>Transit</td>
<td>Service Planning</td>
<td>Director</td>
<td>Superintendent – Route and System Planning</td>
</tr>
<tr>
<td>Transit</td>
<td>Planning and Development</td>
<td>Project Manager</td>
<td>Coordinator: Systems &amp; IT of Metropolitan Transport</td>
</tr>
<tr>
<td>Transit</td>
<td>Planning and Development</td>
<td>Director</td>
<td>Chief of Surveys and Project Manager</td>
</tr>
<tr>
<td>Provincial ministry</td>
<td>Transportation Planning</td>
<td>Senior Planner</td>
<td></td>
</tr>
<tr>
<td>Provincial ministry</td>
<td>Modelling of Transport Systems Unit</td>
<td>Chief</td>
<td></td>
</tr>
<tr>
<td>Provincial ministry</td>
<td>Ontario Growth Secretariat</td>
<td>Assistant Deputy Minister</td>
<td></td>
</tr>
<tr>
<td>Federal agency</td>
<td>Economic Analysis</td>
<td>Director: Economic &amp; Environmental Analysis &amp; Research</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Economic Analysis</td>
<td>Director General</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Environmental Affairs</td>
<td>Director General</td>
<td></td>
</tr>
<tr>
<td>Federal agency</td>
<td>Transportation Energy Use</td>
<td>Assistant Director</td>
<td></td>
</tr>
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</table>
Table 2.3 Participants’ training/education

<table>
<thead>
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<th>Agency</th>
<th>Economists</th>
<th>Engineers</th>
<th>Planners</th>
</tr>
</thead>
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<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Provincial</td>
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<td>2</td>
<td>-</td>
</tr>
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<td>Municipal</td>
<td>-</td>
<td>14</td>
<td>3</td>
</tr>
<tr>
<td>Transit</td>
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<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>20</td>
<td>6</td>
</tr>
</tbody>
</table>

2.7 Time frame for planning

Before starting the survey, participants were asked to state the time frames of the transportation policies/plans that they are involved in through their agency. Table 2.4 presents a summary of time frames for these plans, based on participants’ responses. The aim for this discussion is to capture 1) whether an agency is more involved in short range (SR), operational planning or long range (LR), strategic planning; 2) differences in decision-making and policy analysis between LR and SR planning; and 3) credibility of LR vs. SR plans. Those three components would provide information on the perspective from which participants are approaching the discussions on policy evaluation and modelling, i.e. whether they are focusing on SR operational planning or have had experience in LR planning that involves scenario building.

Federal level participants mentioned that they are not really engaged in planning but more in setting a framework related to national transportation policy. Short range applications at this level are related to implementation of policies and programs. Long range applications look at transportation markets (in terms of infrastructure, vehicles, fuels, etc.). They also mentioned that new realities are currently forcing the federal government to push forward short range policy rather than longer-run strategic programs. They talked about a need to build model systems that can be fast enough to respond to decisions-makers’ requirements/questions. They also highlighted the growing need for real-time data as a basis for short range forecasts. Provincial ministries surveyed said that they were not engaged in long range modelling or planning. In one of the provinces, it was a political decision not to engage in long range planning due to limited financial means. Needs and means are available only for small projects rather than strategic plans. According to one participant in Quebec, the current challenges facing the province do not warrant the development of new infrastructure but rather maintenance of existing facilities.
Table 2.4 Time frames for plans

<table>
<thead>
<tr>
<th>Agency</th>
<th>Short Range planning</th>
<th>Short Range time frame</th>
<th>Medium Range planning</th>
<th>Medium Range time frame</th>
<th>Long Range planning</th>
<th>Long Range time frame</th>
</tr>
</thead>
<tbody>
<tr>
<td>Federal</td>
<td>x</td>
<td></td>
<td>10-15</td>
<td>√</td>
<td>20-50</td>
<td></td>
</tr>
<tr>
<td>Federal</td>
<td>√</td>
<td>2-5</td>
<td>10</td>
<td>√</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Provincial</td>
<td>x</td>
<td>x</td>
<td></td>
<td>x</td>
<td></td>
<td>25</td>
</tr>
<tr>
<td>Provincial</td>
<td>√</td>
<td>2-5</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Municipal</td>
<td>√</td>
<td>3months-2years</td>
<td>x</td>
<td>√</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Municipal</td>
<td>√</td>
<td>5 year</td>
<td>√</td>
<td>10-15</td>
<td>√</td>
<td>20-30+</td>
</tr>
<tr>
<td>Municipal</td>
<td>x</td>
<td></td>
<td></td>
<td>√</td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>Municipal</td>
<td>x</td>
<td>√</td>
<td>5-10</td>
<td>√</td>
<td></td>
<td>30</td>
</tr>
<tr>
<td>Municipal</td>
<td>√</td>
<td>1-5</td>
<td>x</td>
<td>√</td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>Regional municipality</td>
<td>√</td>
<td>1-3</td>
<td>x</td>
<td>√</td>
<td></td>
<td>25</td>
</tr>
<tr>
<td>Regional municipality</td>
<td>√</td>
<td>1-3</td>
<td>x</td>
<td>√</td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>Regional municipality</td>
<td>x</td>
<td>√</td>
<td>10</td>
<td>√</td>
<td></td>
<td>25</td>
</tr>
<tr>
<td>Regional municipality</td>
<td>x</td>
<td>√</td>
<td>10-15</td>
<td>√</td>
<td></td>
<td>25-30+</td>
</tr>
<tr>
<td>Regional municipality</td>
<td>x</td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td>20-25</td>
</tr>
<tr>
<td>Transit</td>
<td>√</td>
<td>3 months-1 year</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transit</td>
<td>√</td>
<td>3 months-1 year</td>
<td>√</td>
<td>10</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Transit</td>
<td>√</td>
<td>1-3</td>
<td>√</td>
<td>10</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Transit</td>
<td>√</td>
<td>3</td>
<td>√</td>
<td>10</td>
<td>x</td>
<td></td>
</tr>
</tbody>
</table>

At the municipal level, participants in planning departments (except in small municipalities) mentioned being more engaged in long range planning rather than short range planning. The latter is typically under the responsibility of other departments (operations, infrastructure, etc.). All interviewed cities were proud to say that they had a master plan or growth strategy which includes a long range transportation vision. In fact, most municipal participants agreed that long range visioning exercises were essential as precursors to long range plans (“Visioning is an essential part of setting up a road plan; how we are going to move from this point to a future we envision and want to end-up”)\(^2\). All plans have more or less the same goals of promoting

\(^2\) Direct quotes from respondents are consistently shown in italics
economic growth, improving the environment and safety, reducing social disparities, and alleviating congestion. Transit investments and an increase in transit share were considered as a priority in all master plans. Most participants agree that long range plans used to be less credible than short range plans but now they are becoming more sophisticated and there is a higher “appetite” for them especially to establish a direction to a certain government.

In the case of transit agencies, except for one (which only conducts short range operational planning), the surveyed organizations mentioned being involved in short range operational planning, as well as have their own medium-range plans (10-years). They also assist cities in their strategic plans but have limited influence on their decisions.

When asked about the main differences in both analysis and decision-making between LR and SR plans, two main points of view arose. In terms of modelling and analysis; one portion of participants think that SR plans are subject to short analyses and to political pressures while LR plans have a more holistic approach and therefore a more thorough analysis of all impacts/elements can be done. Another portion think that LR plans have a less thorough analysis while SR plans are more apt for thorough analysis. They think that LR planning has a vaguer context and its needs for precision are not very significant. In terms of decision-making, a portion of participants stated that LR plans are more abstract and more about a vision and an end state of what the region will look like while SR plans are more detailed and more focused on implementation. They feel that SR plans are more thorough in terms of details but LR plans are more thorough in terms of comprehensiveness and vision/direction; they allow us to see priorities. Contrary to the latter statement, the other portion of participants stated that LR plans represent some goals or directions but they rarely allow us to see priorities. Most respondents agreed that the current political expediency and immediacy makes SR planning more prevalent; decisions are more imminent and people are more active. One participant stated: “Generally, LR planning is constrained by provincial and regional visions and corporate policies while SR is constrained more by political realities, funding availability, market conditions (where to improve the transportation system, what areas), and more immediate types of inputs that are not transportation-related or engineering related factors.”
Chapter 3
Survey Results - Theme 1
Exploring of the Role of Modelling in Decision-Making

3.1 Introduction
This Chapter describes the results of the first survey component, namely investigating the role of travel demand models in decision-making. This discussion theme was motivated by concerns regarding the use of ILUTE by planning organizations in Canada, which would involve various challenges notably related to the overwhelming amount of output and the complexities associated with processing and interpreting model results. Travel demand forecasting is a crucial element in the overall transport planning process as it enables planners and policy-makers to formally test alternative policy scenarios and provides decision-makers with a basis for comparing costs and benefits of tested alternatives (Meyer and Miller, 2001). Most metropolitan planning agencies recognize travel demand modelling as a major component of transport planning. Yet, despite the growing role of travel demand models, there remain a large number of jurisdictions within Canada, the US, and around the world that adopt outdated models or do not rely on modelling to support decision-making. This can be due to a range of factors such as a lack of resources, expertise, and data for model development or political resistance towards formalizing policy appraisal. In recent years, various research boards and high-level governments expressed concerns over the prevailing state of practice for organization, financing, development, and implementation of travel demand models in transport planning and raised questions regarding the role that “advanced” tour-based or activity-based models of travel demand can play in policy appraisal and the propensity of planning agencies to switch from traditional to advanced modelling practices. In order to address these issues in a systematic way, a number of studies have been conducted that rely on reviews of strategic plans, questionnaire-based surveys, or semi-structured interviews as means for collecting information regarding the state of practice in travel demand modelling within planning agencies.

In 2007, the Transportation Research Board/National Research Council published the findings of a web-based survey conducted with more than 200 Metropolitan Planning Organizations (MPOs) around the US and in-depth interviews conducted with a smaller sample of MPOs (VHB Inc.,
The aim of the study was to capture the state of practice in metropolitan area travel forecasting both on the technical (general modelling methodology) and institutional (funding mechanisms and organizational structures) levels. In terms of the general methodology for travel demand forecasting, it was observed that the large majority of MPOs currently rely on trip-based four-step travel demand modelling, while only a few MPOs are using activity-based or tour-based models, and a small number of MPOs do not use travel demand modelling. In-depth interviews revealed that many MPOs are satisfied with their current model and believe it is adequate for most of their planning needs. Most areas have reported an increase in staff and budget for modelling since 2003 with a 78 percent increase in federal funding to support planning activities between 1992 and 2006. The most cited barriers to improvement of models were staff and budget; agencies that were found to be most active in exploring advanced practices were the ones with the larger staffs and budgets. In addition, a major issue that was brought-up was the level of comfort of agency staff in model results in general and in the advanced models in particular. Many agencies mentioned a reluctance to switch to more complicated and data-intensive tools unless it is proven that the new model structures would produce “better” results.

In the context of a research dissemination initiative, face to face interviews were conducted with participants in higher and lower-tier municipalities in the Greater Toronto Area (GTA) as well as provincial ministries in Ontario, Canada (Roorda et al., 2006). The survey aimed at capturing participants’ reactions towards the potential for applying integrated land-use and transportation models as well as activity-based models of travel demand in policy and planning. Most of the participating organizations expressed limited capabilities to run large-scale integrated land-use and transportation models while stressing the need for such models in assessing the sustainability of transport and land-use plans. Reservations were also expressed regarding model specification and logistics for running advanced models and processing their results. One participant suggested that such models are so far beyond the industry standard that it would be unlikely for practitioners to use them directly. Davidson et al. (2007) discuss the reluctance of many large MPOs to adopt advanced models because they perceive them as yet unproven and hence are unwilling to abandon the techniques they are used to. The authors stress on communication between modellers and practitioners in order for transportation planners to understand how the new approaches can better address their planning needs. Four key issues that need to be
communicated to practitioners are suggested: 1) theoretical advantages of activity-based/tour-based models in terms of their behavioural realism, 2) practical advantages of advanced models, discussed in terms of particular policy issues and project types, 3) addressing misunderstandings and widely shared beliefs that added complexity is an opportunity to introduce errors rather than additional accuracy and that simpler models are more robust, 4) valid concerns with advanced models that are objects of ongoing research.

In 2006, Shephered et al. published a paper summarizing the results of a study conducted in the UK designed to provide input guidance to the second round of Local Transport Plans (LTP) covering the period 2006-2011. The research included a review of available LTPs as well as a series of interviews conducted with five local authorities of different sizes. The authors observed a wide range of levels of model use among authorities in the preparation of the LTPs. In general, authorities whose LTPs were of higher quality were those that used modelling more than those with the less successful LTPs. The interviews highlighted concerns regarding the resources and skills required for modelling. Other issues that arose during the interviews include: the need for support in terms of expertise and models rather than just financing local authorities to develop and implement models; the need for local models to be approved prior to application since their results would be used to allocate funds; the need for research into ways of assessing the impacts of new instruments -such as information provision and telecommuting- as well as ways of representing the impacts of policy combinations within one model.

Through a review of strategic regional transportation plans of selected MPOs in the US, Handy (2008), observed a discrepancy between planning goals and the technical aspects of policy appraisal namely; performance measures and travel demand forecasting tools. The author notes evident change in regional transportation goals which may be attributed to a shift in thinking brought about by recent challenges facing planning organizations in terms of achieving smart-growth and urban sustainability, reducing greenhouse gas emissions, and improving the quality of life of urban populations. Nevertheless, the fit between goals and measures was found to be weak; the most widely used performance measures remain traditional, using the concept of level-of-service. The single MPO that had measures matching its goals, made little use of modelling while the other MPOs that relied more heavily on modelling, did not closely match measures to goals. In addition, the author investigated the use of forecasts to support strategic planning and
provide data for computing performance measures. A potential struggle on the part of MPOs is suggested, in terms of how to use forecasts in the planning process especially with the widening range of transportation goals, most of which cannot be assessed using traditional models. The author suggests potential evolutions of regional planning ranging from becoming “a much less quantified process” as new goals may not all be apt for inclusion within models, to “a more sophisticatedly quantified process” in light of the emergence of activity-based and microsimulation models.

These earlier studies suggest a need to improve travel demand modelling practices currently adopted in metropolitan areas in order to enable planning organizations to appraise policy measures based on the “new planning goals” in a systematic way. While many success stories exist whereby planning agencies have transitioned from the use of traditional 4-stage models to activity-based or integrated land-use and transport models, means adopted to achieve such a transition are highly context-specific and depend on local organizational structures for metropolitan transportation planning.

Planning agencies in Canadian urban areas are no exception to the global pressures for improving policy appraisal tools in order to reflect the growing complexity in travel demand patterns and the wider range of planning goals such as accessibility, environmental protection, and quality of life. The adoption of large-scale models or of IUM results within planning organizations highly depends on available resources for modelling and formal policy evaluation. Besides modelling capabilities, it is hypothesized that the attitudes of senior planners and policy-makers with respect to the usefulness of models in decision-making and political climates within specific agencies -favouring or not the use of models- have an effect on the adoption of IUMs to inform policy decisions. For this purpose, assessing the viability of such hypotheses holds value in bridging the gap between modelling and decision-making and understanding the potential for using IUMs when evaluating strategic policy directions.
3.2 Existing modelling tools and role in decision-making

A series of questions were designed in order to capture the different facets of modelling and its use for informing transport and land-use planning and policy; these questions target 1) the types of models developed and run within surveyed departments, 2) challenges faced in modelling, 3) extent of reliance on consultants for modelling, 4) roles of models in decision-making, 5) level of confidence in existing models, and 6) current questions facing the agencies and for which there is a need for better tools.

3.2.1 In-house modelling capabilities

The first question in this section directly probes participants to describe the types of models and analysis tools developed and run within the department. Three main categories emerge\(^3\) namely; those who have relatively advanced models (Group 1), those who adopt classical modelling approaches (Group 2), and those who do not conduct much modelling but rely more on trends in existing data (Group 3).

Among the 22 departments surveyed\(^4\), 4 have relatively advanced modelling capabilities. These include an enhanced 4-stage model that looks at all day travel and weekly data, might have a feedback loop to trip generation, and includes more choices than the classical 4-stage model. In addition, those agencies run dynamic and microsimulation models in-house. In one of the cases, the agency also has a tour-based commercial vehicle travel model.

Most of the departments (10) are classified under the “classical models” category. In this case, most of the tools used are aggregate static equilibrium models (e.g. the 4-stage modelling approach incorporating static user equilibrium traffic assignment, travel time-based elasticity models, and Cost Benefit Analysis or Cost Recovery Analysis). Little microsimulation is done and when needed, it is often outsourced.

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\(^3\) Even though federal-level agencies are included in this categorization, it should be noted that in the surveyed federal agencies/departments, modelling is not conducted at the urban level but more on a policy level.

\(^4\) 20 different agencies but 3 departments within one Federal Agency
In the last category, 8 departments have significantly lower modelling capabilities whereby most of the tools are either geomatic or spreadsheet-type tools; or else, trends in existing data and professional judgement are relied upon. Among the participants in this group, some seem to be quite satisfied with the tools at hand ("I find that these types of models are more informative than the simulation models. Also simulation takes a lot of time and most often, we do not have that much time") while others recognize some drawbacks ("We use a lot of professional judgement, stakeholder advice and indirect input. Also we use some analytical information and look into the results of academic research. We had long discussions, so professional judgement is fine but we also need better understanding of the interactions between policies").

3.2.2 Challenges in modelling

Participants were probed to cite the main challenges experienced in modelling, as presented in Table 3.1. The main cited challenges include a lack of resources, lack of skills/expertise, low confidence in existing models, high needs for refining and calibration of existing models, and data.

<table>
<thead>
<tr>
<th>Challenge/response</th>
<th>Number of times mentioned</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resources (staff and funding)</td>
<td>14</td>
</tr>
<tr>
<td>Skills/expertise</td>
<td>8</td>
</tr>
<tr>
<td>Level of confidence in the models</td>
<td>7</td>
</tr>
<tr>
<td>Refining, calibration, evolution of models</td>
<td>5</td>
</tr>
<tr>
<td>Data</td>
<td>5</td>
</tr>
<tr>
<td>Understanding of problems to be modelled</td>
<td>2</td>
</tr>
<tr>
<td>Explaining model results</td>
<td>2</td>
</tr>
<tr>
<td>Difficulty to keep up with the demands for analysis</td>
<td>1</td>
</tr>
<tr>
<td>Questions have become increasingly complex</td>
<td>1</td>
</tr>
<tr>
<td>Current impact measures are not enough</td>
<td>1</td>
</tr>
<tr>
<td>Tools are limited and don’t allow them to do the type of calculation and manipulation easily</td>
<td>1</td>
</tr>
<tr>
<td>Cannot take responsibility of developing models</td>
<td>1</td>
</tr>
</tbody>
</table>

* Some participants mentioned more than one response
In terms of the lack of resources for modelling, many participants tied this issue with a certain “agency culture” or prevailing political climate whereby there is a general cut back in in-house modelling resources and a reduction in the number of modelling personnel within government agencies (“The main challenge is usually a resource challenge. We have very few resources with limited budget but overwhelming demand. Before, we used to do everything in house but in the past 5 yrs the government changed its policy and decided that government agencies will become managers not doers”). Beside the lack of resources, a large portion of participants feel that their low level of confidence in existing models is their most important challenge. Some of the responses include the fact that existing models are static, not sensitive to minor modes, can only model peak-period travel, and are not able to predict the effects of various Transportation Demand Management measures. Most participants who complained about data mentioned the fact that existing trip diary data are not sufficient for modelling transit and walk trips, especially in small cities as the number of households that are captured becomes minimal. Participants raised the issue that they are having a hard time finding skilled modellers and that junior modellers generally have a short lifetime in the agency (“You can’t hire experienced modellers since they don’t exist”). One participant raised the issue that academic institutions dedicate more time on the theoretical basis of models rather than making them operational (“In public organizations, maybe we have the ability to evolve models and maintain them alive but refinement of models is done in the academic field and if a model is disconnected from the university environment, it loses its precision and methodology. One problem of the academic field is that academics attach too much importance on the theoretical basis instead of finding a sub-optimum to be able to advance the model more rapidly”).

3.2.3 Extent of reliance on consultants
In terms of outsourcing of modelling exercises and reliance on consultants for the purpose of modelling, five different groups are distinguished based on the type of response provided: Group 1) work with universities rather than consultants (5 agencies), Group 2) use consultants to develop and maintain the tools but run them in-house (7 agencies), Group 3) work with consultants in a partnership (5 agencies), Group 4) employ consultants only for specific studies such as Environmental Assessments (EAs) or microsimulation projects (10 agencies), and Group
5) fully rely on consultants for analysis (2 agencies). Note that Group 4 (specific studies) includes agencies in other categories as well.

Most of those who mention relations with universities have the best modelling capabilities. Their main concerns include refining and evolution of models and the ability to keep up with the increasing complexity of the questions faced. In the most advanced modelling groups, it seems that resources and data are not the most significant issues. They are more concerned with improving their models and advancing their modelling capabilities.

As reliance on consultants starts to increase, participants’ fear of becoming dependent on consultants’ work increases as well. Most of the agencies that use consultants to develop the models, calibrate them, and maintain them, prefer to run the models and interpret them in-house so as not to create a situation where they are dependent on consultants. Often, when an outsider develops a tool, they also get involved. Work done by consultants is viewed as a “black box” and when a consultant provides numbers they are not very confident. Within this group, the main challenges mentioned include resources, data, and expertise. It seems that consultants are relied upon to fill these gaps even though agencies are very cautious with respect to the work conducted by consultants and the “fear of dependency” is quite prevalent. Note that four of the six participants in this group are from the federal level. Also, four of the six participants in this group were categorized in the “lowest modelling capabilities” group.

Opposite to the previous group, where consultants are hired for development of the tools but where most of the modelling is done by the agency itself, this group works with consultants in a partnership relation. Irrespective of whether a consultant was hired to develop the model or not, the consultant would be working with the in-house team on the same project. In most of the cases, the consultant develops the scenarios and prepares the input data while the agency runs the model and provides the consultant with the results for high level interpretation and report writing. This group has less modelling expertise and resources than Group 1 but not necessarily less modelling expertise than Group 2. The relationship with the consultant is established based on a certain “culture” within the institution. Note that among the responses of participants within this group, mistrust and lack of credibility in the work of consultants is rarely mentioned. Participants do not have a problem trusting the work of consultants especially since the work is
conducted in partnership. However, they mention previous bad experiences with consultants that led them to become more proactive when a consultant is hired for a specific task. The main challenges mentioned by this group include resources, data, and expertise. All of the agencies in this group were previously categorized in the “classical models” group.

In most of the cases, consultants are also hired for specific studies such as EAs or work requiring advanced simulation (e.g. traffic microsimulation). In this case, modelling, high level analysis, and report writing are entirely dedicated to the consultant. Two participants mentioned a complete reliance on consultants for any type of modelling/analysis. Those two agencies do not want to invest in a modelling unit.

3.2.4 Role of models in decision-making

Based on the existing conditions within each agency, participants were asked to discuss the role that their own models and model results play in decision-making within their urban area. Participants were urged to talk about the current situation rather than provide their opinion on what they view the model’s role to be. Attitudes with respect to the role of models were classified into 5 main categories ranging from those who treat the model as a cornerstone in the evaluation of strategic directions to those who find their models not useful for decision-making. Table 3.2 summarizes the 5 main categories of responses as well as the number of interviews in each category. Each participant\(^5\) was attributed to only one category based on his/her attitude towards modelling in the context of decision-making. Two participants did not address the question per se and responded by associating the usefulness of the model with understanding its limitations or explainability of results.

\(^5\) In this case, one response per interview is included even if an interview is conducted with more than one person at the same time since participants in the same interview had the same positions/attitudes.
### Table 3.2 Summary of participants’ view of the roles of models in decision-making

<table>
<thead>
<tr>
<th>Category/response</th>
<th>Number of participants/interviews</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model is a cornerstone in the evaluation of strategic directions</td>
<td>4</td>
</tr>
<tr>
<td>Recognize role in decision-making but acknowledge other factors (public and stakeholder opinions, political agendas)</td>
<td>8</td>
</tr>
<tr>
<td>Help refine and optimise projects. Are useful more at the design stage after a decision has been made.</td>
<td>5</td>
</tr>
<tr>
<td>Help remove ideologies/anecdotes in debates. Increase credibility of the planning process</td>
<td>4</td>
</tr>
<tr>
<td>Models are not useful for decision-making</td>
<td>4</td>
</tr>
<tr>
<td>Understand limitations of models and try to compensate for that</td>
<td>1</td>
</tr>
<tr>
<td>Usefulness associated with explainability of results</td>
<td>1</td>
</tr>
</tbody>
</table>

The 4 participants who mentioned the model to be a real driver of decisions belong to Group 1 in the modelling capability classification, i.e. they have the most advanced models. This is not surprising as the more advanced the tools are in a certain agency, the higher the level of trust in those tools, the more modelling is actually conducted, leading to more reliance on model results (“We rely fairly thoroughly and excessively on the results of models to justify some of the decisions and look at some of the policies that shape the transportation system as well as set directions as to where we should be investing our capital and resources”).

The next category in Table 3.2, includes the majority of the responding agencies whereby participants mention that they attribute a certain role to models in decision-making but also acknowledge that other factors(such as public opinion, political agendas, “externalities”) come into play that diminish the weight of the model on the ultimate decision. This is not to say that the previous group states that decisions are made solely based on modelling results but in the case of this group, the model seems to be relied upon but not as heavily thus giving more weight to the other components (“We could make better decisions if a model was available but even without a model we can still make the right decisions”). Most of the participants in this group adopt “classical models”.

Participants in the third category view the usefulness of models mainly for operational planning or optimization of design solutions rather than for informing strategic decisions. Some of the responses categorized in this section include: “Models are useful but secondary to decision-
making. They are mainly useful for technicians for optimization issues”; “We should not start with modelling to make a decision but start with a decision and go down to modelling”.

Participants in the fourth category view models as useful only to add credibility to the planning process by “generating a number” but are not really useful in the ultimate decision (“The model definitely adds credibility to the questions we were trying to answer. But it could also be argued that it didn’t tell us anything that we didn’t know at the onset. It just proved what we always thought. In no case did the results of a simulation really affect the final decision. Information was only used in support of the decision we were leaning towards”).

The 4 participants in the last category, who are very pessimistic with respect to the role of models in decision-making, hardly conduct any modelling. It seems that the weight of model results in the final decision is related to the level of model sophistication whereby as the model is more advanced, it is relied upon more heavily which in-turn puts pressure to keep on improving and refining it. Whereas, in the case where models are not developed or run to start with, there is a resistance to internalize “analytical results” into a decision (“Transport planning decisions are not modelling decisions but societal choices. In the context of decision-making, we think that we will make decisions based on the strength of analysis. In reality, we make decisions where sometimes the strength of analysis has no role in the final decision”).

3.2.5 Confidence in existing models

This question was mainly addressed to agencies with reasonable modelling capabilities (not the ones who mostly rely on data and expert judgement). Most of the responses are in the same range; there is a kind of overall satisfaction with the models available despite the recognition of their main weaknesses. Whether they have advanced modelling capabilities or less advanced ones, participants have more or less the same level confidence in the analysis they conduct. In general, participants are aware of the drawbacks of current models but are fairly satisfied with the way the analysis is conducted and the way model results are handled (“We have a good level of confidence in the model but we recognize the limitations of such models that we are trying to capture a myriad of individual decisions into basic aggregates and averages for the
populations”, “We recognize that the model will give the right indication or analysis but there will always be variations in the numbers”).

Some participants mentioned the desire to improve their models but in only two cases did participants mention a strong need for integrated land-use and transportation models to be developed for the region (“By having only a transport model, we are not taking into account feedbacks that will result in different spatial allocations and give different economic outcomes so we need to have an integrated land-use transport model. The reality now is that everyday we have to support decisions with only the transport part and try to get people a level of confidence that the decisions we are making are good decisions while cautioning them that they do not have the whole picture. You cannot tell them that without an integrated model, you cannot make good decisions because it means that you are leaving them in the vacuum. We need to caution them about what the model does not take into account but also give them something that can support their decisions”). One participant is a strong advocate that the ability to understand is fundamental to making better decisions (“We need more understanding of transportation and land-use effects to be able to plan for transportation and land-use together”). He is adamant that we should have better techniques and look at other options to make better decisions (“The tools are absolutely vital. Usually people who give money want some assurance that it is spent wisely, they want some evaluation”, “Integrated land-use and transportation models will give us a better understanding; maybe not make better decisions because the modellers are not the ones who make decisions so the challenge is to communicate better. Still, the key is to get the models operational so that we can start to demonstrate the value to get credibility”). The highest level of confidence is seen in the agencies that were classified under the “advanced models” category in the previous section (“We have a high confidence in the model; it is a very powerful tool because we have spent much time trying to produce something that is useful and provides sensible results”).
3.2.6 Policy questions that current models do not address

The main drawbacks in existing models were briefly discussed by some participants when they were probed to cite the main challenges they are currently faced with in terms of modelling (Table 3.1). This issue was reiterated when all participants were asked about the most pressing policy concerns that they are currently facing and that current models fail to address or provide an explanation for.

From a land-development or planning perspective, the issues raised by participants relate mainly to the effect of increased population and employment densities as well as live/work opportunities. Most of the issues are tightly linked with projects that are currently on the agenda of municipalities and where the outcomes of such initiatives are still uncertain. For example, in the Greater Golden Horseshoe, in Ontario, the Places to Grow Act, developed by MPIR (2005), has imposed on municipalities specific population and employment densities to be achieved within a time frame. This has put enormous pressures on planning departments in terms of determining how to achieve those densities and where to put their urban boundaries. In one of the cities, the participant mentioned that a density cap had recently been lifted to promote an increase of densities thus allowing them to become anything that a community can sustain. However, planners are faced with the question of what a sustainable density is (“From a transportation perspective would we allow congestion to occur? Do we try to manage it?”) Another participant also raises the issue of intensification and its extent (“Intensification is now on the agenda but it is hard for us to know how much of a walkable community is feasible”). In another city, where expansion of the light rail transit (LRT) network is planned, one question that planners are trying to answer relates to the development close to LRT stations (“...from a market perspective, what does it take for developers to build close to LRT?”) One municipality mentioned difficulties in assessing the success of live/work developments and the types of residences and jobs that must be promoted (“For the master plan, we have developed a live/work area but the houses are expensive therefore, the people living there are not employed in the area and the people who have jobs there cannot afford to live in the residences provided. We wish we had a model that can predict who will locate where and who will work where. The main question is how far do we rely on the market and how far do we become social engineers. Do we have the capability to match residences and jobs? We need to look beyond providing population and employment: What kind of employment? What type of people? What kind of socio-economics?”)
In addition, several questions were raised with respect to the representation of minor modes within existing models and the need for models that have a better representation of transit and walking. One participant also mentioned the need for measures of transit reliability within existing models. In terms of assessing the impacts of TDM measures on actual travel, many participants raised the issue that no tools are capable of analysing TDM and they have to rely on assumptions at this stage. There is also a need to assess expenditure on transportation such as the percentage of household budgets devoted to transportation (as a social issue) in addition to the opportunity cost of dedicating urban space to roads and parking.

Finally, many participants mentioned their concern about the value of time; stating that current estimation procedures are not appropriate (“We are ending up with a flawed estimation with the way we are estimating travel time right now which could lead to biased results in favour of long distance commuting and big projects”).

3.3 Involvement in modelling and decision-making

This section deals with the human involvement in modelling and decision-making; as such, participants were asked to describe 1) the type of personnel responsible for modelling, mainly in terms of background/training, and 2) the relationship between modellers and non-modellers within the same agency.

3.3.1 Personnel in surveyed departments

Survey participants, who are often heads of planning departments or of modelling groups, were asked to list the backgrounds of their staff; three main disciplines were mostly mentioned: engineering, planning/geography, and economics (Table 3.3). At the municipal level, there is a prevalence of engineers (civil and transportation); planners and geographers are also employed but they are less numerous than engineers. In transit agencies, there is a mix of geographers/planners and engineers with more planners than engineers. On the provincial level, there are some engineers and planners, but also the presence of mathematicians, statisticians, and economists starts to be noticeable. On the federal level, the dominance of economists over engineers or planners is clear. Backgrounds of the different heads of departments follow this pattern as well.
### Table 3.3 Type of personnel in surveyed departments

<table>
<thead>
<tr>
<th>Agency type</th>
<th>People in department</th>
<th>Head of department/ person interviewed</th>
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</thead>
<tbody>
<tr>
<td>Municipality</td>
<td>All transportation engineers (legacy)</td>
<td>Engineer</td>
</tr>
<tr>
<td>Municipality</td>
<td>With the exception of 1 planner with 25 years of modelling experience, the rest are all engineers</td>
<td>Engineer</td>
</tr>
<tr>
<td>Municipality</td>
<td>Transportation engineers, transportation planners, transportation technologists</td>
<td>Engineer</td>
</tr>
<tr>
<td>Municipality</td>
<td>Mainly transportation and development engineers except for TDM coordinator (marketing background)</td>
<td>Engineer</td>
</tr>
<tr>
<td>Municipality</td>
<td>Planners or engineers</td>
<td>Engineer</td>
</tr>
<tr>
<td>Regional municipality</td>
<td>Technologists, civil engineers, planners (with background in landuse planning or environmental studies)</td>
<td>Engineer</td>
</tr>
<tr>
<td>Regional municipality</td>
<td>Engineers and planners; the TDM coordinator has a marketing background</td>
<td>Engineer</td>
</tr>
<tr>
<td>Regional municipality</td>
<td>8 planners and 3 research officers with background in geography and math/statistics</td>
<td>Planner</td>
</tr>
<tr>
<td>Regional municipality</td>
<td>Planners and engineers</td>
<td>Planner</td>
</tr>
<tr>
<td>Regional municipality</td>
<td>All are engineers</td>
<td>Engineer</td>
</tr>
<tr>
<td>Regional municipality</td>
<td>Engineers and planners</td>
<td>Engineer</td>
</tr>
<tr>
<td>Transit</td>
<td>Engineers, planners, geomorphers</td>
<td>Planner</td>
</tr>
<tr>
<td>Transit</td>
<td>Mainly geographers and urban planners, less engineers</td>
<td>Planner</td>
</tr>
<tr>
<td>Transit</td>
<td>Engineers, economists, but mostly geographers and urban planners</td>
<td>Engineer</td>
</tr>
<tr>
<td>Transit</td>
<td>25 planners/urban geographers and 15 transportation engineers</td>
<td>Planner</td>
</tr>
<tr>
<td>Provincial ministry</td>
<td>Civil and transportation engineers</td>
<td>Engineer</td>
</tr>
<tr>
<td>Provincial ministry</td>
<td>Engineers, mathematicians, statisticians, geographers, economists, planners, financial analysts</td>
<td>Engineer</td>
</tr>
<tr>
<td>Provincial ministry</td>
<td>Economists, planners, architects, environmental scientists</td>
<td>Economist</td>
</tr>
<tr>
<td>Federal</td>
<td>Economists</td>
<td>Economist</td>
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<tr>
<td></td>
<td>Computer scientists, engineers, economists</td>
<td>Economist</td>
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<tr>
<td></td>
<td>Economists</td>
<td>Economist</td>
</tr>
<tr>
<td>Federal</td>
<td>Engineers and economics</td>
<td>Engineer</td>
</tr>
</tbody>
</table>
3.3.2 Relation between modellers and policy group

Mutual reinforcement between analytical work and policy advice is very important. In most of the agencies, participants noted a good working relation between modellers and non-modellers. In many cases, teams of modellers and analysts are formed on a project or task basis and discuss both modelling and interpretation approaches within the team. In a few cases, incomprehension between modellers and the policy-group were noted especially on the federal or provincial level. This could be mainly attributed to the fact that on the municipal level, there isn’t much segregation between the two groups; they normally comprise common members, are under the same department, and physically in the same space. While on the provincial and especially the federal level, modelling/analysis and policy/program groups are under different departments, physically in different locations, and headed by different people, which could promote different cultures and ways of thinking thus causing more clashes.

In many cases, modelling groups act also as service groups for outside clients. In that case, they not only conduct modelling related to the SR and LR plans of the department but address the needs of other departments within the agency (environmental or energy groups, etc.) as well as external clients such as some community leagues, environmental groups, etc.

Another issue that was mentioned during several interviews at the municipal level are the clashes between planning groups and operations groups within cities. As interviewed city personnel are all from transportation planning departments that mainly deal with LR planning and public transportation, many of them expressed differences in thinking due to the differing mandates of planning and operations groups. While the operations department’s main motive is mobility; for the planning group, it is accessibility and alternative transportation (“We are not quite working to the same end. Operations side are doing the day to day work, but the planning department is not yet at a stage where they can communicate and convince them to divert some road funding into transit. We still need more integration and dialogue between operation and planning functions to make sure that the capital planning is met with the strategic planning because this is the biggest difficulty for the moment. The main challenge is coming to a compromise where planning will maintain the existing operations but not expand… this is a fundamental shift”). Other clashes within municipalities are noted between planners and engineers whereby one participant mentioned the need to overcome a “cultural divide” between engineers and planners
who see models differently ("The main issue is not running the models but dealing with the planners and the land use department. A change process is needed within the municipality but also a significant cultural change from the part of land use planners. This is a significant challenge. The stumbling block is not in maintaining or developing models since expertise and knowledge is fairly available. The main problem is in overcoming the fear of planners that the model is going to take away their decision capabilities. Engineers see the model as a decision-support tool but planners see it as a threat. They are afraid that the model will tell them what to do and they won’t be planners anymore. A human change process is therefore required").

3.4 Conclusion

This Chapter has presented the outcome of the first survey component targeted towards assessing the status of existing long range urban transport models and their role in decision-making. This survey component substantiates the ever-existing debate on the usefulness of models for decision-making, the need for improved models, and the obstacles to improving current modelling structures or switching to more advanced models. This situation is more accentuated Canada due to the following factors: 1) There is a lack of sustainable funding for modelling and policy appraisal, which translates into reduced capabilities for staffing and model improvement; 2) Responsibility for strategic transportation planning and travel demand forecasting is primarily attributed to local municipalities, each municipality has its own travel demand model, and has responsibility over funding and maintaining it; 3) Where local municipalities and regional municipalities coexist, it is not always the case that local municipalities would rely on the travel demand forecasting capabilities of the region; often, they would have their own travel demand model for assessment of their own strategic plan which eventually have to be in-line with the region’s plan.

At this stage, the most pressing need is not to move selected planning agencies in Canada to more advanced activity-based or tour-based models but rather to provide the wide majority of agencies with support to fully maintain and improve their traditional models in order to achieve “good” state-of-practice travel demand models. In order to achieve this, changes need to occur on various fronts: funding and staffing, expertise, standardization of models, and organizational structures. Funding, staffing, and expertise go more or less hand in hand; with a lack of
sustainable sources of funding for travel demand modelling, it is a tremendous challenge for municipalities to improve their models and build modelling expertise. This situation is particularly relevant to the Canadian context since most municipalities fund their modelling activities from general levy and development charges, which inevitably disadvantages smaller municipalities. There is no standard and sustainable mechanism for funding of models. Federal and provincial funding may be offered on occasions but the situation differs from one urban area to another and among provinces. Funding mechanisms for travel demand modelling need to be improved and “standardized” within Canadian provinces and urban areas to ensure a level playing field for all municipal agencies. In addition to funding, local municipalities within large metropolitan areas should “share” the same model structure to ensure that local municipal plans within large regions are in-line with regional plans. At this stage, since different models are used by different municipalities within regions or by neighbouring regions, a multitude of forecasts can be obtained by the jurisdictions involved in a specific project; this is particularly important in the treatment of cross-boundary projects. Finally, organizational structures for travel demand modelling need to be improved in the Canadian context whereby centralization of modelling should occur at the level of specific metropolitan agencies which in-turn can devote funds for building modelling expertise. This responsibility is overwhelming to small municipalities which can benefit from the use of a central model refined to their local area and updated/maintained by a central agency. Lessons can be learned from the organizational structures in the US, in particular, the relations between MPOs, state transportation agencies, and local counties.
Chapter 4
Survey Results - Theme 2
Role of Sustainability Objectives in the Planning Process

4.1 Introduction

Sustainable transport planning, in its broadest sense, involves planning for the three main elements of sustainability namely, environmental preservation, social equity, and economic growth (Himanen et al., 2005; Steg and Gifford, 2005; Shiftan et al., 2003; Feitelson, 2002; Black, 2000; Black, 1996). The environmental, economic, and social pressures exerted by population and economic growth in major urban areas worldwide have driven policy-makers to promote sustainable transportation and urban form as a means to achieve greenhouse gas reductions, reduce land consumption, improve air quality and public health, as well as enhance the overall welfare and quality of life of urban populations. In most metropolitan areas of the developed world, various policies following sustainable transport principles have been developed to accommodate growing urban populations. In Canada, metropolitan areas are no exception to the worldwide trend of developing master plans aimed at promoting sustainable transport and urban form as a response to the challenges brought by growth in population and travel demand. This Chapter attempts to assess the extent to which sustainability objectives drive the planning and policy agenda in Canada and to investigate whether policy appraisal and funding mechanisms actually reflect these objectives. Our general hypothesis is that Canadian metropolitan areas have indeed developed sustainable transport policies with diverse external impacts and a multi-sectoral nature; however, to date, an adequate framework for appraisal and funding of sustainable transport policies is still lacking.

Results of the second survey component are used in order to test this hypothesis. First, the prevalence of the sustainable development terminology within existing plans and policies are examined and opinions of survey participants on sustainability as a concept are captured. The results of this first exercise are then contrasted with the existing status of funding and implementation of sustainable transport plans as portrayed by the respondents in order to test whether sustainable transportation is only a vision or has been translated into plans that have received funding. Then, existing policy appraisal in terms of sustainability impacts is examined;
again as a means to assess whether sustainability objectives have changed the appraisal process. Finally, the results of a brief visioning exercise conducted with participants on the long-term future of transportation are discussed and used as a means of gauging the level of satisfaction of planners and policy-makers with the current situation and its potential evolution.

4.2 Prevalence of sustainable development terminology

In this section, opinions of participants regarding the concept of sustainability and its importance within their respective agencies are captured. In addition, the development of sustainable transport visions and definitions within long-range master plans or other planning documents are investigated. The aim of this section is to examine the extent to which planners and policy-makers are aware of the new challenges facing urban areas and their inclination to set long-term goals that would serve the objectives of urban sustainability.

4.2.1 Sustainability planning concept

Participants were probed as to their personal opinion with respect to the concept of sustainability, the specific question says: “How do you understand the concept of sustainability planning? What aspects does it engulf?” Diverse responses were obtained ranging from those who recognize the 3 pillars of sustainability to those who simply state that it is an “important concept” (Table 4.1).

<table>
<thead>
<tr>
<th>Environment/Resource preservation</th>
<th>Social equity</th>
<th>Economic growth</th>
<th>Transit/transportation options</th>
<th>Limit sprawl/Increase density</th>
<th>Plan responsibly/Manage growth</th>
<th>Important concept</th>
<th>Number of participants</th>
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</table>
Beyond the three main pillars of sustainability that 6 out of 26 participants who addressed this question recognize to be the main elements, transit and the provision of alternative transportation is considered by many as a significant component of sustainability. In fact, two participants identify sustainability as being achieved solely by promoting alternative transportation ("Sustainability is all about options, giving people different transportation options not just the car"). Another concept that was associated with sustainability is limiting sprawl; in fact, two participants believe that sustainability planning is all about limiting sprawl. Four participants mention that it is a “buzz word” and is nothing but another way of saying “planning responsibly and managing growth” ("Sustainability is really a buzz word but the direction is very clear and there is no problem explaining its components"). Finally, three participants failed to provide their own definition of sustainability and only mentioned that it is an “important concept”.

Among all responses, environmental and resource preservation is the mostly cited, followed by economic growth. Most participants recognize the environmental side to be very important but also many of them stress economic vitality as a major precursor for improved environmental quality through technological innovation and updating of environmental standards. While most of the respondents did not recognize the three facets of sustainability together, overall there is a good understanding of the concept and its ramifications on planning and policy.

Many participants mention difficulties associated with trying to assess the effects of a policy on the three levels of sustainability ("It is not always possible to assess a policy based on all the effects. There is nothing called a sustainable program, there is a program that is social, environmental, or economic. There is always more of an emphasis on a certain aspect. Sustainability is too multidimensional. Sustainability is not an end, it is one good characteristic of a program; if we have a good understanding of those three elements, we are on the right path. We don’t need to look for the interactions between the three elements to materialize, it is too difficult"). Responses were not found to differ among levels of government, urban regions, or educational background and were randomly distributed among the survey sample.
4.2.2 Definitions and visions of sustainability / sustainable transport

Participants were asked whether they had a vision or definition of sustainability incorporated within their long-range plans. Among the 20 surveyed agencies, 3 have a formal definition of sustainable transportation, sustainability, or a sustainable development strategy; 6 have long-range visions that incorporate some or all elements of sustainable transportation; 2 have a smart-growth strategy (with more or less the same direction and components of a sustainable transportation strategy); and 9 have neither a vision nor a definition of sustainability. All transit agencies are included within this last category. This can be explained by the fact that transit agencies are more involved in short-range operational planning rather than long-range strategic planning, as discussed in Chapter 2. Federal agencies have had formal sustainable development strategies for at least the past 10 years. Most municipalities have broad visions with elements of smart growth or sustainable development within their long-range transportation master plans. Most agencies, including the ones that do not have formal definitions or visions, affirm looking at the different components of sustainability even if it is not used as a keyword. They claim that sustainability objectives drive most of their plans.

4.3 Implementation of sustainable transport plans

The prevalence of sustainability visions, definitions, or objectives within long-range plans has only real significance if those plans are approved by decision-makers, funded, and fully or partially implemented. As such, it is important to compare “planning philosophies” with funding and implementation to be able to detect any real change. The questionnaire does not directly target funding and implementation. However, one of the sections (which was originally designed to capture major changes in the policy environment over the past 10-15 years) provides a good indication of planning vs. implementation in light of the discussion it set off.

In response to the question “Have you witnessed any major changes in policy evaluation and decision-making in your agency for as long as you have held the current position? If yes, which?”, the first most frequently mentioned major change is the fact that decision-makers and the public are more sensitized and have a better understanding of sustainability, environmental issues, and the importance of transit and alternative modes. It seems that planners are sensing an emerging awareness within communities and decision-makers of transportation in general and
road congestion in particular as pressing issues. Some participants even mentioned a change from the perspective of engineers and planners whose approach has moved from building roads to planning for sustainable transportation and building communities. In spite of the growing awareness of the need to shift growth patterns and promote more sustainable communities, very few participants mention an actual increase in funding. Indeed, most participants recognize a failure to induce change in current development trends despite a change in thinking and crafting plans. A more detailed discussion of participants’ responses to this question per se and of planning vs. implementation is conducted in Section 5.4.

4.4 Performance assessment of sustainability objectives

Starting with the premise that emerging plans have noble sustainability objectives addressing issues such as the promotion of transit and walking, reducing vehicle kilometres travelled, and building denser urban areas; this section assesses the extent to which potential impacts of the proposed plans are evaluated in a formal way prior to implementation. The development and use of indicators or performance measures of urban sustainability within planning agencies are also investigated.

4.4.1 External impacts of plans and performance measures

Most participants mentioned that at this stage of policy analysis, the most widespread measures being estimated are the ones that are direct outputs of transportation models, e.g. time, delay, speed, mode split, transit ridership, vehicle kilometres travelled, and trips; in addition to direct costs and benefits. Currently, estimation of environmental, social, and economic impacts of strategic plans is still in its infancy. While most participants recognize the importance of estimating the impacts of different long-range scenarios, few agencies have impact measures that are derived from model results. Even in these few cases, most are environmental (especially air pollution, greenhouse gas emissions, and land consumption) and economic. The latter are not clearly defined by the agencies and could be mistaken for direct costs and benefits. Federal and provincial institutions seem to be in a better position than municipalities with respect to impact estimation. Still, most participants in these agencies recognize that there is a lot of work to be done on this level, especially concerning social impacts (“On the social impacts side, we are not doing as well, but this is understandable”). Even though they are still at their infancy in terms of
strategic impact assessment, higher-level institutions seem to be more aware of such impacts and their importance in policy analysis.

At the municipal level and within transit agencies, hardly any impacts are estimated (except some environmental impacts in a few cases). This is firstly due to the lack of sufficient resources and expertise to develop and estimate such measures but also because up till now, even though long-range modelling is conducted in many municipalities, scenario analysis is not yet well established. Only a few municipalities run long-range scenarios. In the City of Calgary, long-range plans are assessed based on model results as well as what is called “the triple bottom line approach” whereby environmental, economic, and social impacts are factored into the decision. However, most of those impacts are assessed qualitatively without thorough estimation. It seems that there is still much confusion about how sustainability impacts should be internalized within the decision-making process on strategic plans and what they really mean. Many agencies think that by merely promoting transit and improving accessibility they are already factoring in sustainability in their decisions: “We tried at many times to come up with social criteria and measures and we finally decided that the benefit out of a transit trip is transit ridership. So we have decided that the single most important measure for transit as a social benefit is ridership. A rider gets benefit out of a trip. Now, we treat all riders the same. There isn’t more social benefit for a senior taking transit to a doctor’s appointment than a low-income person accessing a job. It was a whole discussion evolution that got us into this decision”; “Equity and accessibility are part of our policies and fare systems. We do look at these things not exactly in terms of evaluation but our bus system and rail system are targeted towards these things”; “We promote public transit hence we are promoting sustainable development”.

In a way, sustainability impacts are a subject of discussion around the table when it comes to making strategic decisions in all agencies; still, there is no formalized way of internalizing these impacts within policy analysis. The only place where the three types of impacts are indeed used for comparing scenarios is within the EA process. However, EAs are conducted at the project level whereby different scenarios express different alignments, geometries, operational parameters, etc. rather than strategic directions. In addition, impact analysis in the EA process is mostly based on comparative analyses, weighted decision matrices, and professional judgement rather than formal estimation. While some municipalities feel that they are assessing impacts on
the three pillars because of the EA process, most municipalities admit that impact assessment should not only occur on a project basis but also on the strategic level. Indeed, according to the Canadian Environmental Assessment Act (CEAA, 1992), the project EA focuses on site-specific design and construction, operation or decommissioning issues. By contrast, the Strategic Environmental Assessment (SEA) applies at the level where decisions are initially made regarding a particular strategic direction. It addresses broad policy issues, long term planning and regional environmental concerns. The Canadian Environmental Assessment Agency requires a SEA if the proposal for a policy, plan or program is submitted to an individual Minister or to Cabinet for approval and implementation of the proposal may produce a significant environmental impact, whether positive or negative (CEAA, 2004). Among all of the surveyed agencies, none of them has conducted a SEA for their transportation master plans.

Despite recognizing the importance of measuring the impacts on sustainability, some participants feel that the principles of sustainable development are too demanding and force planners to focus more on negative impacts rather than benefits, thereby often compromising transportation projects. Many participants mention that financial stakes are often more important than environmental preservation and social equity and that financial sustainability (through continuity of funding) is at this stage their most important concern.

4.4.2 Usefulness of sustainable transport indicators for policy
Participants were asked about the effectiveness and practicality of using indicators of sustainable transportation derived from model results as a means of internalizing impact assessment within strategic decision-making. As a response, most participants stated that such measures are indeed important for informing decision-making. Still, many participants mentioned reservations towards internalizing sustainable development objectives within the decision-making process. Their main objection was that sustainable development principles are too demanding and overwhelming to the planning process (both in terms of resource needs and analytical tools) and the results may not be very satisfying (“Questions will become much more complex and the answers will not say much”). Municipalities are still struggling with their own modelling tools in terms of updating them and finding modelling/analytical personnel and are not yet at a stage where they can estimate -or process information related to- sustainability impacts of policies.
Among the participants who agree with the use of sustainability indicators for decision-making more than half stress that it should be tightly linked with the planning process ("Indicator work is more academic and not very connected to planning and implementation of plans. We cannot divorce the indicators from the plans, we need to think about how to measure them and what are they measuring in the context of our plan. Performance measures should be tied to objectives and actions of plans"). There is also a general awareness of the usefulness of indicators for communicating results to the public on a local level and informing decision-makers ("Ultimately, decision-making is done by people who do not know all the details that experts and modellers do. Decision-makers need indicators because they do not have a full understanding of all impacts and it will help them have a fuller understanding of all the details in the picture. Indicators will therefore be a surrogate for decision-making").

When asked about what the most useful indicators would be for decision-making, participants dwelled on enumerating transportation-related measures (some of which are direct model outputs) (e.g. speed, convenience, efficiency, usage, modal split, average trip length, total vehicle kilometres travelled) and to some extent, certain measures that they think would reflect sustainability (e.g. share of sustainable modes, car pooling or drive sharing, greenhouse gas emissions and costs, public satisfaction, truck share or energy per tonne of goods transported, land-use related measures, impacts on potential environmental areas). This also ties in with the previous discussion about the general lack of knowledge with respect to impact analysis at the strategic level. Only in one case did a participant recognize the importance of a broad range of indicators that is not affected by the model structure ("Performance measures are tricky and we need to be careful that they are not biased by the structure of the model").

### 4.5 Future of land-use and transportation

As a means of assessing the opinion of participants on how the current status of land-use and transportation will potentially evolve in the next 20-25 years, a crude visioning exercise was conducted with each participant. Participants were faced with three different scenarios of the
long-range future of transportation in their region. They were asked to choose which scenario or combination of scenarios best describe the most probable future in their region taking into account current trends in travel, car ownership, urban sprawl, and socio-economics, as well as emerging policies and plans. In 1992, a scenario project was undertaken in several European countries. A questionnaire was developed to solicit the opinions of experts involved in transport and communications planning and research with respect to seed scenarios targeting population and lifestyles, regional development and urban form, transport and communications, as well as other fields. The results indicated a widely-shared concern that the existing growth-driven patterns of the time were not sustainable (Masser et al., 1992).

The scenarios adopted in this describe respectively 1) an economic growth scenario, 2) a social equity scenario, and 3) an environmental preservation scenario. These scenarios represent more a set of possible political directions or philosophies rather than potential futures given that they were constructed without the reliance on data or expert judgment. The scenarios were developed to express the three pillars of sustainable transport and represent three extremes which have often been debated by politicians knowing well that the reality would be somewhere in between. The economic growth scenario is characterized by an economically stronger region with increased energy consumption, auto ownership, and vehicle emissions. The social scenario emphasizes a growth in collective rather than individualistic lifestyles; accessibility to basic services and to the downtown core is improved and transit improvements are highly favoured over road investments. The environmental scenario emphasizes limited population and economic growth to reduce pressure on environmental resources; a radical decrease in environmental pollution is witnessed as a result of tighter environmental standards and higher fuel taxes thus creating financial burdens on industries. A summary of the selection of the 26 participants who responded to this question is presented in Table 4.2.

Federal-level participants were asked about the future of Canada as a whole whereas the rest were urged to focus on their own urban area.
Table 4.2 Summary of business as usual scenarios selected by participants

<table>
<thead>
<tr>
<th>Scenario</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic growth</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Social equity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>√</td>
<td></td>
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<tr>
<td>Environmental preservation</td>
<td>√</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of participants</td>
<td>2</td>
<td>2</td>
<td>9</td>
<td>2</td>
<td>6</td>
<td>2</td>
</tr>
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<td>3</td>
</tr>
</tbody>
</table>

√ → main scenario  
√ → additional scenario moderating the main one

Out of the 26 participants who responded, 18 pointed towards one scenario while the rest chose one main scenario moderated by one or two others. The economic growth scenario was selected by 15 participants as the main scenario; 6 of them chose to moderate it with the environmental, social, or both scenarios, indicating that despite high individualistic tendencies and a continued dominance of the private car, there is hope that the future will look slightly better. They claim to be adopting a balanced approach between transit and road investments. Accessibility to transit services within the downtown areas is looked at in addition to parking restrictions and better management of truck travel. High densities, active transportation, as well as live/work opportunities are also elements that they are striving to achieve. This group does not have a particular characteristic in common and it is not clear whether they are genuinely more optimistic of the future than those who selected only the growth scenario or just assuming that the future will look better because they are aware of sustainability issues and would hope to achieve them.

The 9 participants who selected the economic growth scenario seem to be very pessimistic with respect to any improvements on the social or environmental level, mentioning that highly individualistic tendencies are prevalent and here to stay. This group acknowledge the recent trends towards smart-growth and sustainability planning but they also recognize the lack of funding for such plans and the unwillingness altogether of decision-makers to choose a different direction. Participants in this group are at the federal level, in Calgary/Edmonton and in the GTA. Many of the GTA participants mentioned that the development of the GTA is tightly linked to that of the US and that the GTA is moving in the same direction. The dissatisfaction with the current situation among this group is quite noticeable.

Participants who identify with the social scenario are mainly in Ottawa, Montreal and Quebec. They indicate that their cities have been aggressively pushing towards promoting social values,
improving mobility for the disabled, and looking at health issues. Note that these cities are suffering from an aging of the population which normally puts social issues as a priority. The two participants in Vancouver chose the environmental scenario indicating that environmental preservation is the main priority in Vancouver and most of their policies are headed towards aggressively curbing road emissions through parking policies, taxation, and promoting public transit. Participants mention that residents in Vancouver highly value being able to have a view to the mountains and clean air, thus rendering them quite accepting of policies targeting car use.

The trend observed in the responses to potential futures is clearly geographic. It was observed that responses were not affected by resources, skills, modelling capabilities, institutional integration, or funding available at the different agencies; but rather, they reflect the “culture and politics” of different urban areas. Among the three scenarios, the economic growth scenario is by far the most selected. Nevertheless, some less extreme components have been incorporated to it. These relate especially to an increase in transit services within downtown areas and a densification of development in urban areas. This outcome is very similar to the one observed in Europe, 15 years ago (Masset et al., 1992). The authors observed that despite some less radical notes added to the growth scenario, a rather gloomy outlook on Europe’s future remained:

“The most likely scenario of transport and communications in Europe is a veritable horror scenario. It presents a continent with an unprecedented level of material wealth and technological perfection yet with unparalleled spatial disparities between its regions and cities, congested roads and a collapsed public transport system”

An even gloomier picture was painted by one Toronto participant about the fate of the GTA:

“We have become a highly consumer-driven society: no regard for environmental issues, high energy consumption. We need a crisis, a calamity to bring those issues into people’s attention. But whenever this happens (energy runs out or an environmental catastrophe), people will start saying why didn’t you see this sooner? In Europe, governments have the guts to tax gasoline or impose environmental and resource preservation policies but in the GTA, things are too comfortable. In addition, we are unable to achieve economic growth anyway
because we cannot create a highly attractive business environment. We are also unable to establish a strong investment environment in the GTA. In addition, there is not much social will or acceptance of more social welfare; we are not moving in this direction. On the contrary, we are going right wing: reduce taxes and provide fewer services. In the absence of crisis, there will not be a strong commitment; the industry will not be punished. We are on the road to a major disaster!”

While European governments may have come a long way since that last study was conducted, it remains to be seen whether Canadian cities will eventually take the leap into more sustainable development patterns.

### 4.6 Conclusion

Recently, sustainable development objectives have been at the forefront of planning initiatives in most Canadian urban areas. Many political debates have focused on the need to curb environmental degradation, energy consumption and greenhouse gas emissions, and promote health and social equity. Public environmental and social awareness has also increased which has put pressure on decision-makers to factor in the “sustainability terminology” in public discourses and political campaigns. In light of the new challenges facing urban areas, planners have also followed this trend through incorporating sustainability visions and objectives within strategic plans. Sustainability and smart-growth terminology have become widespread and most long-range plans have incorporated transit expansions, promotion of live/work areas, and intensification of development. In addition, visioning exercises and scenario planning that engage the public in “imagining” how their urban areas will look like in the future; have taken a significant role in long-range planning. All of this surely constitutes a step in the right direction; unfortunately, the progress in thinking and crafting plans at the urban level has not been matched by increased funding. As a result, frustration among current planners has become common. This frustration has translated into a rather gloomy vision of the future of Canadian cities in the next 20-25 years. Many view their cities as moving towards increased energy consumption, dominance of the private car, social disparity, and environmental damage.
Chapter 5
Survey Results - Theme 3
Institutional Integration for Sustainable Transport Policy

5.1 Introduction

Based on the overview of existing plans in Canadian urban areas, presented in Section 2.4, and on the discussion of the second component of the survey, presented in the previous Chapter (4), it is clear that there is a trend in Canada towards the development of policies that follow sustainable transport and “smart growth” principles. A common denominator among the proposed policies within the different urban areas is their multi-sectoral nature whereby their impacts extend beyond the transport sector itself to other sectors such as environment, health, and education. This situation puts enormous pressure on decision-makers in order to achieve coordinated action among the range of actors involved in transport policy appraisal, funding, implementation, and monitoring. In the context of the “Civilizing Cities” initiative in the UK, Jones et al. (2003) propose a broad policy monitoring framework that highlights the inter-sectoral nature of transport measures. One main feature of the project includes the development of a set of quality of life indicators that span various areas of quality of life; thus stressing the need for cross-sector evaluation of transport policies. Such a framework certainly highlights the need for coordinated action between the range of public and private bodies typically involved in transport provision thus raising the question of the extent to which institutional structures can affect the decision-making environment.

Various studies have addressed the issue of institutional integration in the context of transport decisions. This is especially the case in European Union countries where there is a strong drive and regional responsibility for transport integration. When discussing different barriers to implementation of sustainable transport policy measures, Banister (2002) recognizes the institutional/political structure as one such barrier. He attributes it to “differences in cultures between departments” and “distribution of legal powers”. Sometimes decision-makers themselves may not be committed enough to introduce policy measures in a comprehensive way. Banister (2002) also links resource barriers to institutional ones. He argues that lack of funds for implementation is partly an institutional issue, as government agencies would only provide
resources for schemes that are in line with their own policies. Marsden and May (2006) describe local government decision-making within three areas of the UK and investigate the effect of major institutional changes on transport policy development and implementation. Among the various conclusions attained, their study suggests that integrated strategies, among other transport policies, are more susceptible to institutional barriers. Ways of overcoming institutional barriers have also been proposed. In 2006, the UK Commission for Integrated Transport conducted a review of the state of integrated transport delivery across government departments. Among its recommendations, the commission suggested a “city region wide” approach to the development of strategic transport authorities for large conurbations whereby such authorities would have powers over strategic transport planning (CfIT, 2006). In the study conducted by WS Atkins (2001) on “European best practices in the delivery of integrated transport”, the presence of regional authorities bridging between national policy formulation and implementation of local transport is viewed as a crucial element for success provided these authorities have their own budgets (from national government allocations as well as a portion of local revenues). Within the case studies examined, WS Atkins (2001) found that regional authorities have helped increase the accountability of decision-making and to focus investment on achieving integrated planning across the region rather than merely on local priorities. Regions were also found to improve coordination of transport and land-use planning and to reduce competition between neighboring authorities. Haynes et al. (2005) also discuss the benefits of regionality in terms of economies of scale in purchasing and pooling of resources and expertise, thus minimizing conflicts and allowing for more effective operations. The authors also discuss the need and opportunity to operate transportation facilities at a regional scale if they are to be sustainable. Marsden and May (2006) talk about an “overarching tier of government” responsible for organizing travel over a spatial area compatible with that of major commuter patterns. Jones and Lucas (2000), propose to develop a “common shell” for policy appraisal that identifies key impact areas and responsibilities adapted for different departmental needs. Where several departments have a shared interest in an area, cross-departmental working groups may be set up. The authors propose, in the extreme, to take this approach as part of a wider process of making strategic policy formulation a cross-departmental responsibility.

The issue of institutional integration in the context of transport has not been explored sufficiently in the Canadian context. It is still unclear whether any progress is being made towards
overcoming the complexities of the decision-making environment and whether true attempts at integrating decisions among the various actors have occurred. Based on the third component of the survey, this Chapter explores the extent of institutional integration in the appraisal, funding, and implementation of transport policy and plans in Canada. Our general hypothesis is that there is a lack of integrated policy making across government departments in Canadian urban areas thus leading to ineffective development and implementation of policies that span over different municipalities, disciplines, or government levels. In particular, we are interested in investigating whether 1) institutional change is more likely to disrupt effective policy implementation than to facilitate it (Marsden and May, 2006); 2) regions help focus on integrated rather than local plans (WS Atkins, 2001); and 3) new agencies that oversee strategic transport plans should be created (CfT, 2006). This survey component attempts to capture planners’ and policy-makers’ opinions on the existing integration and their own assessment of the success or failure of institutional integration. Different levels of integration are explored as outlined by Geerlings and Stead (2003): 1) vertical integration, which occurs between different levels of government; 2) horizontal or inter-sectoral integration; 3) inter-territorial integration which occurs between neighbouring authorities with shared interests; and 4) intra-sectoral integration, which occurs between different sections within one department (e.g. transport operations and planning).

5.2 Public and stakeholder involvement in planning

Participants mentioned that the recent challenges posed by internalizing sustainability objectives within the planning process and the complexity of the questions that they are faced with, have pushed them to put greater emphasis on soliciting public participation, conducting stakeholder meetings, and addressing the concerns of increasingly vocal non-governmental organizations (NGOs). This section summarizes their comments regarding public and stakeholder consultation.

While federal, provincial, and transit agencies consult with stakeholders or the general public occasionally and depending on the policy/program under development (it is not part of their mandates); public consultation is a standard course on the municipal level especially as part of long range plans. In this case, municipalities have to conduct public meetings during plan development and every time there is an amendment to the plan. Public meetings are normally
held at a council chamber with displays and open house. When a transportation plan is approved, there is also a mandated public hearing.

Most municipalities explained that they were facing difficulties in engaging the general public in long range plans. Public hearings organized for strategic plans often attract only a few members of the community. The public feels that such plans will not materialize and as such people become more involved when specific projects are in effect, both at the planning but mostly implementation stages, and especially through project-specific EAs (“People are more interested in what will happen within the next 2 or 3 years. There are basic principles that people value (associated with the general concepts of their quality of life) but people cannot tie their daily actions with overall long range goals. But when we talk about a new rail route or bus route or a new subway system, it is very much in their face and they do want to talk about it: cost, impacts on the community”).

Apart from public consultation, stakeholder consultation seems to be heavily conducted at the municipal level whereby technical advisory committees (including: environmental groups, affected communities, adjacent land owners, community leaders, political leaders, transit agencies, boards of trade, school boards, etc.) are formed and meet with the municipalities for purposes of consultation, information and advice. According to the participants, stakeholder consultation is more successful than consultation of the general public (“…public consultation takes time and often dominates the agenda and the other difficulty is what the role of people in the decision-making is? Difficult to get consensus and if we aim at getting consensus, it will never work”). The stakeholder groups that were the most cited as having influence on decision-making include environmental groups (Table 5.1). While some participants feel that environmental groups are very vocal but not necessarily influential (“Some environmental groups are very vocal and professional but cannot say that influence decisions”, “Environmental groups are more vocal than they are influential, still not very strategic in their ways of changing things”), most of the participants acknowledge the growing influence of environmental activism and its improved structure and lobbying power (“Environmental groups are catching up too as they have become much more important and have been able to improve some of the region’s projects”). The second mostly cited influential stakeholders include the business community/development industry followed by the public at large. Some participants
recognize the growing influence of community leagues (groups of neighbours that get together through organized meetings and advocate on issues that affect communities such as recreation, sports and social activities; they have no legal status). In fact, if the results for community leagues and public at large are added together, they would lead to a significant stakeholder group indicating the growing importance of local citizens/affected populations. Again, this is mostly the case when specific projects are being discussed rather than general policy directions.

Table 5.1 Summary of most influential stakeholders

<table>
<thead>
<tr>
<th>Stakeholder group</th>
<th>Number of times cited</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental groups</td>
<td>10</td>
</tr>
<tr>
<td>Business community/developers</td>
<td>9</td>
</tr>
<tr>
<td>Public at large</td>
<td>6</td>
</tr>
<tr>
<td>Community leagues</td>
<td>3</td>
</tr>
<tr>
<td>Pedestrian and cycling committees</td>
<td>3</td>
</tr>
<tr>
<td>Student committees</td>
<td>2</td>
</tr>
</tbody>
</table>

Some geographic differences were also noted in terms of the most cited stakeholder groups. In fact, while environmental groups were found to be most influential in Quebec, Montreal, and the Greater Toronto Area; in Calgary, Vancouver, and Edmonton, the community was found to have the most influence on the decision-making process. In the latter case, participants felt that the EA process and environmental standards were well established and adopted in the region thus decreasing the need for the involvement of environmental groups. In fact, in the cities of Calgary and Vancouver, municipal participants mentioned an active and highly engaged community, while in Toronto, most participants noted that there is a general feeling that apathy is more widespread (“Citizens themselves have been the most influential in Calgary. Community is very engaged in Calgary; very interested in transportation and community has influence also”. “Vancouver city is quite active, not so much the suburbs. Many city residents are quite interested in how the city is developing, very pro-environment”. “Not a highly engaged community in Toronto”).
5.3 Views on institutional integration
This section of the interview dealt with the existing level of institutional integration for planning and decision-making in each surveyed urban area at the three levels of government. Both horizontal and vertical integration was discussed. Participants were also probed on their personal opinions about agency mandates and how to achieve better integration.

5.3.1 Federal, provincial, and municipal integration in urban areas

5.3.1.1 Greater Toronto Area (GTA) and rest of Ontario
In the GTA, because of their mandate, regional municipalities should have a direct role in helping the local municipalities in shaping their strategic plans. According to participants in regional municipalities, they occasionally sit on the technical advisory committees of other regional municipalities particularly when cross-boundary road projects are in effect (“It seems that the only thing that links the regional municipalities together is the road network; whenever we meet on an inter-regional issue, it’s something to do with a road extension and boundary effects”) or in the development of transportation master plans but only for information purposes rather than real participation. Both lower-tier and regional municipalities complain about the lack of involvement of the provincial level (“We have good coordination with other area municipalities but with the province, there is a huge gap. We can’t get any kind of long range transportation vision or even a 10 year capital program to know what they are planning to do within the next 10 years. So how do we plan our own transportation network if we don’t know what they are planning to do? Or they will start on a project and not give any deadline for that and they won’t say when they are going to finish it so how are we going to plan around this and in conformity?”). Most municipalities surveyed in Ontario (five out of seven) mention the aggressive road building plan of the Ministry of Transportation Ontario (MTO) and how it conflicts with their land-use development plans which promote a higher transit share and more walkable communities (“MTO wants to spend a lot of money in roads in our region and we don’t know what to say to them because we cannot turn down the money but we are thinking about transit. We understand that all these highway programs are meant to reduce congestion but we feel that there should be more money into transit”). In addition, municipal participants state that cooperation between the federal level and municipalities in the GTA is minimal; in fact, most surveyed municipalities complain about the lack of interest of federal agencies in the challenges
currently facing most municipalities such as the need for additional funding for public transit and alternative modes of transportation.

Participants in the GTA were asked to comment on the proposed Greater Toronto Transportation Authority (GTTA), a public authority that had recently been created at the time of the survey by the Government of Ontario to manage transportation and public transit planning within the GTA (GTTA Act, 2006). It seems that there is a prevailing pessimism with respect to what the GTTA will be able to achieve in terms of integrating decisions. Most participants feel that the proposed GTTA does not seem to have what it takes to provide leadership, and does not have any sources of funding (“They are not powerful enough to get the job done. They need independent and sustainable sources of funding and to make decisions and make them stick”). While respondents think that there is a need in the GTA for a central agency that coordinates and prioritizes the critical improvements, they realize that such an agency needs to have resources and authority. Other reservations towards the GTTA are political in nature whereby participants in the City of Toronto feel that the GTTA, as it is laid out in the provincial legislation, and considering the structure that is proposed, will not really achieve good integration because it does not recognize the Toronto Transit Commission (TTC) as being a significant component of the transit system and wants to treat all transit systems the same (“Toronto is different from all surrounding municipalities and until they get over that, the GTTA won’t work”). Most participants believe that the GTTA will end up as “a forum where people will get together and talk about what they would like to happen without being able to make it happen”.

In the Regional Municipality of Waterloo, a slightly different picture is drawn than the one painted by the GTA lower-tier and regional municipalities. While most of the GTA municipalities complain about the way the Places to Grow Act was imposed on them by the province rather than developed in partnership and how that exercise failed them in terms of

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7 Now known as Metrolinx
8 Places to Grow is the official growth plan for the Greater Golden Horseshoe (GGH) area in Ontario. It was developed by the Ministry of Public Infrastructure Renewal (MPIR). MPIR has categorized the GGH area as one of the fastest growing regions in North America and developed the plan as a reflection of Ontario’s vision of managing growth and developing stronger communities (MPIR, 2005).
institutional integration, the Regional Municipality of Waterloo sees it as a first success at integrating decisions. Unlike other municipalities in the GTA, in Waterloo, the municipality views the tailoring of their own master plan to provincial policy as a good exercise in integrated decision-making. According to participants from Waterloo, currently, the municipality views the region’s Growth Management Strategy as going hand in hand with the Places to Grow Act.

In Ottawa, although modelling is run in-house, participants mentioned a close collaboration with different governmental organizations in the region of Ottawa-Gatineau. Collaboration occurs under the umbrella of a committee, made up by the City of Ottawa, City of Gatineau, Ministry of Transportation Ontario (MTO), and Ministry of Transportation Québec (MTQ). The committee is not a legal entity but it is driven by the above agencies’ need to discuss modelling issues and policy appraisal in general; this has been in effect for the past 27 years. They meet on a monthly basis and the Ottawa participants believe that there is a lot of coordination across the Ottawa River. The federal level is not very involved in modelling or planning but more in terms of funding (“They just get involved to make sure the project is being developed with a good benefit to cost ratio”). Provincial involvement is also very minimal, mainly in terms of planning the highways and the linkages between the highways and the Ottawa arterial road system. The provincial level does not get involved in transit (“In terms of the province, our relation will always be Ottawa’s road network vs. the provincial highway network. Now there is a better integration with neighbouring municipalities”).

5.3.1.2 Calgary
In Calgary, the City works with municipal districts surrounding the city, (they have their own transportation and development plans) and through the province. Currently, the province is the major partner. One participant talked about a good working relationship between the City and the province but not with the municipal districts (“The work that municipal districts do on their development, they do it on their own and the city does not even have a framework by which it can make sure whether their plans are in conformity with the plans of the city”). Calgary used to have intergovernmental regional committees that would discuss issues associated with the region not just the city itself. The municipality is advocating in the new transportation master plan the need to look at the region rather than just the City of Calgary. Even though the master plan
advocates transit investments, Calgary Transit (a division of the City of Calgary Transportation Department) is not involved in its development. One participant from Calgary mentioned that the City would eventually want to look at a regional public transit authority. In Alberta, the province took over the major road network and ring road development in Edmonton and Calgary as well as the major road investments. There is a lot of provincial involvement because many of the road projects are developed by the province.

5.3.1.3 Vancouver

It is a common belief in Toronto and the East coast cities in general, that the GVRD seems to be the best example of a success story in integrating land-use and transport planning over the three levels of government in a single urban area. This belief is not grounded on solid evidence but mostly because the City of Vancouver has long been viewed as an environmentally and ecologically friendly city. The GVRD participant mentioned that, while according to its mandate the GVRD should work with municipalities, ports, airports, TransLink, and the development industry in Vancouver; the reality is that the GVRD is facing many challenges and such integration is not happening. The most important of these include the lack of a regional vision (“In Vancouver, it is a challenge because sometimes the municipal, regional, and provincial interests do not align. 21 municipalities; it’s a big challenge! There is no overall economic development strategy for the region so each municipality is on its own trying to compete for jobs and set a residential property development tax base to attract people”) and lack of coordination with the Province (“We would like the provincial government to take a more proactive role in discussing with the municipalities and transit agencies. The provincial government tends to take mega-projects and tends to announce rather than consult”). The GVRD participant talked about a good working relation with TransLink and an increasingly good relation with the federal level but this is mainly because of federal funding for the Canada Line project

9 (“In 1999, the federal government had put nothing in public transport, nothing in roadways or public infrastructure. No interest in cities. It has been a huge change ever since. The federal government is becoming a new player in cities mainly through strategic investment funds, public transit capital fund, and

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9 The Canada Line will be an automated rail-based rapid transit service connecting Vancouver with central Richmond and the Vancouver International Airport. The Canada Line will connect with existing rapid transit lines, creating an enhanced transit network to serve the region.
the urban showcase program. So in Vancouver we have recently been able to tap into federal funds. However, the provincial level became disengaged. And we would have been in dire shape if it wasn’t for the fact that the federal government stepped in and gave funds. Relations with federal agencies got much better but with the province, it got much worse since 1999”). The view of the GVRD participant with respect to the existing level of integration is also shared with the TransLink participant in Vancouver (“Contrary to Toronto, Vancouver does not have a 2-tier system. There are many municipalities but no regional municipalities. So there are weak planning powers at the regional level and a lot of what people say is great about this system is not true. We do not have good relations with the Province either. The province has always decided that what they are going to do, they are going to do it and they have the money for it anyway even if it is opposite to regional planning objectives. This situation changes with government. The previous provincial government was more interested in municipal interests while the current one is less interested”).

5.3.1.4 Montreal
The recently established (since 2001) CMM has a mandate similar to that of the GVRD whereby it has to integrate metropolitan transport and land-use planning within the 82 municipalities in the region. CMM has no implementation or taxation power. So far, it has also been a big challenge for CMM to establish a regional vision and match the interests of the different municipalities (“In Montreal, we are not on the right track with respect to integrating decisions. CMM has a mandate to do this but they were not able to conduct planning on the regional level especially that there are many municipalities and actors. It will take a long time to establish a functional entity”). In addition, according to the AMT participants, the creation of the CMM has diffused some of the powers of the AMT. Indeed, CMM was given a similar mandate to that of AMT on some axes, which has weakened the structure of AMT. Unlike the successful relationship of the GVRD with TransLink in Vancouver, the Montreal example shows significant clashes between the regional land-use and transport planning agency and the regional transit agency.
5.3.2 Transit agencies and municipalities
Transit agencies mention working closely with municipal planning departments. They mostly have an advisory role in terms of the cities’ official plans which all have distinctively pro-transit orientations. According to transit agency participants, they provide cities with only an opinion but it is not necessary that their visions be adopted. Most transit agencies surveyed are distinct and autonomous entities from the cities. They accompany cities in their strategic plans but the final decision-maker is the city (“We will present different scenarios to the city but the city will make the choices”, “We collaborate with the city but have no influence over decisions”). In reality, most transit agencies feel that they are not very influential in terms of city decisions and they feel that their recommendations are often highly ignored (“We are fairly powerful advocates of transit, we are knowledgeable and technically capable and quite outspoken. In contrast with city planning people who are more conciliatory with Council, we are more straight and blunt about things. We see that as a weakness of city planning that they do not tell people how they think things should evolve; they only tell them what they want to hear. Still, we do not have final control over how land-use is developed, how road space is allocated, how traffic signal systems will operate. We see the City as trying to implement more what the communities want as opposed to what their own plan says. They are undergoing more of a conciliatory, mediating type planning rather than being leaders and leading people and helping them understand the vision for the city”). Some transit agencies admit having some influence over municipal decisions (“We do have influence but not really in terms of power over the municipality. Especially in terms of development decisions, we have no power but we can choose not to serve them either. We comment on municipal decisions or community plans but in the end the municipalities do their own thing”).

5.3.3 Views on improving institutional integration
As part of the discussion on the existing level of institutional integration, the issue of agency mandates, in general, was discussed with participants. In most Canadian urban areas, it is often the case that each department is responsible for part of the problem but no department has a holistic outlook on an entire issue. As a result, integrating decisions becomes a matter of overcoming defined responsibilities, while respecting departmental portfolios. Indeed, when asked whether they thought agency mandates were an obstacle to integrated policy appraisal and
decision-making, most participants found mandates to be a hindrance to integrated policy appraisal but cannot be avoided since agencies need to have a defined set of functions. These functions have to be different for different agencies. Some participants disagree that mandates constitute an obstacle and mention that it is possible to achieve better integration with the existing mechanisms ("Integrated policy appraisal is not a matter of setting aside mandates, we need mandates to define responsibilities but we also have to work closely together").

All participants agree that there is still a need for improving the integration of policy appraisal ("Integrated policy appraisal is highly needed. So far, we haven’t been able to bring all the perspectives together (energy, industry, transport policy, health, and research), we need to bring them in a cohesive way"). Some participants mentioned the need to integrate policy making not only with other governmental bodies but also with developers and environmentalists.

The previous section clearly highlights a current weakening of “regional visions” in most metropolitan areas. The GTTA, GVRD, and CMM are all examples of sub-optimal attempts at integrating decisions. Still most participants stress the need for making decisions and implementing plans on a regional level. Benefits of regionality and authors’ views on improving institutional integration were discussed in the Introduction to this Chapter. Many of the issues discussed by the European literature were brought up by participants during the interviews. These include: establishment of new strategic institutions, importance of regional municipalities, and establishment of cross-departmental working groups. Some participants think that there is a need in Canada for bodies like MPOs in the US to achieve better integration (Haynes et al., 2005); while other participants think that there is no need for new institutions and that provincial governments are in a good position to play that role provided there is enough interest and leadership ("The province should provide leadership on coordination but also with funding, they have to become more assertive to promote inter-regional issues"). Most participants agree that the federal level should not play this role due to its general detachment from urban/local issues ("The federal level is out of touch; it is only good at collecting and redistributing funds. Most transportation is local so the federal level is not really needed. Provincial and municipal governments are best at coming up with the blueprints"; "I have a good feeling about the provincial government playing this role but not for the federal. A federal judge would be horrible!"). This point goes in parallel with the observation of Haynes et al. (2005) regarding the
evolution of US transportation institutions which suggests that universal and far-reaching federal mandates may undermine long-term institutional sustainability.

In spite of the impetus for better integration, participants expressed some reservations mainly due to the time and resources it entails ("Integrated appraisal means more time to the decision process and if different agencies are looking at different things, we need to have a way to bridge these perspectives whereby we don’t end up having endless discussions until a consensus is built").

5.4 Significant changes in policy and planning

In response to the question “Have you witnessed any major changes in policy evaluation and decision-making in your agency for as long as you have held the current position? If yes, which?” participants provided a range of answers summarized in Table 5.2. Each participant provided one or more than one answer.

The first most frequently mentioned major change is the fact that decision-makers and the public are more sensitized and have a better understanding of sustainability, environmental issues, the importance of transit and alternative travel modes. It seems that planners are sensing an emerging awareness within communities and decision-makers of transportation in general and road congestion in particular as pressing issues. Some participants even mentioned a change from the perspective of engineers and planners whose approach has moved from building roads to planning for sustainable transportation and building communities. In spite of the growing awareness of the need to shift growth patterns and promote more sustainable communities, very few participants mention an actual increase in transit funding which presupposes a kind of “gap” between planning and implementation/funding: “The main question is: what did our master plans bring to the area? In fact, through these plans, we have managed to sensitize decision-makers to the pressing issues. However, we cannot really say that our master plans have succeeded in modifying growth patterns in the metropolitan area.”
Table 5.2 Major changes witnessed in past 10-15 years

<table>
<thead>
<tr>
<th>Response</th>
<th>Number of times cited</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decision-makers and public are more sensitized (better understanding of sustainability, environmental issues, importance of transit and alternative modes)</td>
<td>12</td>
</tr>
<tr>
<td>Decrease in community interest in transit</td>
<td>1</td>
</tr>
<tr>
<td>Decision-making has not really changed</td>
<td>1</td>
</tr>
<tr>
<td>Facing new problems (climate change, global driving forces, growth, sustainable development ) and more complex questions</td>
<td>8</td>
</tr>
<tr>
<td>Arrival of federal and provincial funding</td>
<td>4</td>
</tr>
<tr>
<td>Lots of planning but not much implementation</td>
<td>3</td>
</tr>
<tr>
<td>Doing less modelling in-house (culture change + more reliance on consultants)</td>
<td>3</td>
</tr>
<tr>
<td>More modelling is conducted</td>
<td>2</td>
</tr>
<tr>
<td>Decrease in funding/subsidy for transit</td>
<td>3</td>
</tr>
<tr>
<td>Increase in transit investments</td>
<td>2</td>
</tr>
<tr>
<td>Better regional vision and long range planning/analysis</td>
<td>3</td>
</tr>
<tr>
<td>Regional vision weakened</td>
<td>1</td>
</tr>
<tr>
<td>Availability of more information/data</td>
<td>1</td>
</tr>
<tr>
<td>No progress in terms of usability of data</td>
<td>1</td>
</tr>
<tr>
<td>Models are more advanced/complex</td>
<td>1</td>
</tr>
<tr>
<td>Not much progress in models</td>
<td>1</td>
</tr>
<tr>
<td>Expanding mandate</td>
<td>1</td>
</tr>
<tr>
<td>More cooperation/integration of policy appraisal</td>
<td>1</td>
</tr>
<tr>
<td>Preoccupations in goods movement</td>
<td>1</td>
</tr>
</tbody>
</table>

The second most cited major change is that currently planners and decision-makers are facing new problems and more complex questions. Indeed, planners feel confronted by issues like climate change, smart-growth, and sustainable development, all of which they believe entail more complex solutions to be developed and surely more sophisticated models and tools to answer those questions. Participants recognize that in the future, they will be faced with tough questions and decisions and they will have to provide good information to make good decisions. Indeed most transportation institutions in Canada have been recently faced with complex questions and needs that force them to look beyond the traditional objectives of policies and into health, social, and environmental goals.

The two response types mentioned constitute almost 40 percent of all responses; yet they only indicate an increased awareness rather than a real change in how plans are evaluated and implemented. If the “optimistic” responses in Table 5.2 are counted (funding, better planning,
more information, better models, more integration), they would only amount to less than a quarter of the total. No geographic differences were noted among the range of responses; it seems that the attitudes of participants towards the evolution of planning and decision-making in their urban areas are similar, whereby there is an overall sense that positive changes are occurring on the level of awareness and that transport issues are increasingly being recognized as a priority. People understand the importance of public transit and alternative transport modes. However, whether or not this situation will lead to any significant changes in the allocation of funds or in the level of detail in policy evaluation tools is still uncertain.

5.5 Conclusion

The pressures of population and economic growth in most Canadian urban areas have faced planners and policy-makers with new challenges for managing this growth “responsibly”. As a result, the past 10 years have seen the emergence of strategic transportation and land-use plans aiming at promoting growth patterns that respect the general goals of economic, social, and environmental sustainability. The complexity and interdependency of sustainable development objectives call for greater policy integration across government departments. Yet, institutional structures in Canadian cities seem to be struggling between attempts to centralize decision-making under the umbrella of regional organizations and trends towards fragmentation and decentralization of decisions. In most urban areas, long range master plans draw the attention of many different stakeholders, the most notable of which being environmental groups and the business community. Despite an emerging sensitisation of both the public and decision-makers in terms of the negative impacts of urban sprawl and a wider acceptance of public transit, the proper institutional mechanisms for funding, implementation, and integration of the concerned agencies are still lacking. While the surveyed planners and policy-makers are highly critical of many aspects of the process, they also admit an inability to implement or even initiate change. There seems to be low institutional integration among the three levels of government and weakened regional visions within most urban areas. Most municipalities complain about the lack of involvement of the federal government in urban issues. They also suffer from clashes between municipal and provincial visions. Because of their mandate, provincial governments are mostly interested in provincial highways while municipalities are currently at a turning point whereby
the provision of alternative transportation is crucial. Such a vertical government structure has indeed hindered coordinated and focused action.

With the increasing drive towards looking at the broader impacts of transport; such as issues of equity, quality of life, and social inclusion; institutional integration will even need to go beyond merely transportation or land-use planning and reach to education, health, housing, etc. depending on the potential spillovers of different plans. As a result, institutional integration will not only have to occur on the vertical and regional levels but also on an inter-sectoral level whereby various government departments (e.g. environment, health, housing, municipal affairs, etc.) are invited to participate in the policy-appraisal process. In order to achieve such integration, the literature has discussed the importance of regional municipalities, the establishment of cross-departmental working groups or strategic transport authorities. New independent organizations or task forces may be established with the responsibility of appraising land-use and transport plans, providing funding for municipalities in the implementation of their master plans, and integrating decisions across government departments. Lessons could be learned from the experiences of MPOs in the US at achieving institutional integration. Alternatively, as many participants commented, provincial agencies are in a good position to take that responsibility provided they assume more leadership as well as contribute to providing sustainable sources of funding for the implementation of strategic transportation master plans.

Indeed, while it is easy to subscribe to the general concept of sustainability, it is difficult to express it within the planning process and even more difficult to operationalize it with the existing institutional structure. Sustainability objectives and the increasing range of actors involved in decision-making are putting ever more pressure on Canadian institutions to transcend mandates and individual portfolios and coordinate policy appraisal, funding, and implementation. Faced with these challenges, sporadic and localized attempts at integrating decisions have been made in some urban areas. Such attempts have not been very successful thus stressing the need for more aggressive Canada-wide initiatives. It remains to be seen whether the views expressed by Canadian planners and policy-makers are shared by their American or European counterparts. Comparable surveys that would be conducted within major US and European metropolitan areas would surely reveal similarities or differences in the perceptions and views of personnel in agencies with transport-related responsibilities.
Chapter 6  
Sustainability Indicators and Policy Appraisal

6.1 Introduction

The discussion on modelling, policy appraisal, transport sustainability, and institutional integration conducted with planners and policy-makers and described in the previous Chapters (3, 4, and 5) has helped highlight the needs of policy and hence shaped the scope of this research. The increasing recognition of the interactions between land-use and transport has created a need for models that can capture these interactions and hence be used especially for assisting long-range plans by assessing the impacts of land-use changes on travel demand. In addition, beyond the land-use and transport interactions, the sustainability agenda pressing for the reduction in resource consumption and GHG emissions in an equitable way, has added much complexity to the problem of urban transport. There is therefore a need to assess the external impacts of transport and land-use policies and use the output to support decision-making. This leads to the question on model output; whether it is related to land-use and transport models or to impact models, the range of output that can be extracted from these models is vast. However, as discussed with survey participants, planning agencies do not have the resources to process large amounts of output. It is also anticipated that the breadth of model output, if presented to planners and decision-makers, will make models less intuitive and decision-making more difficult.

In light of the policy-related exploratory work conducted in the context of this research, four broad conclusions can be drawn: 1) there is a gap between modelling and decision-making; 2) there is a need to bridge this gap since models are becoming more necessary for decision-making in light of the increasing complexity of travel behaviour and land-use transport interactions; 3) the challenges brought by climate change and sustainable growth have added yet another dimension to transport decisions which have to rely on a range of disciplines; and 4) the need for multidisciplinary assessment of transport decisions is putting pressure on agencies in terms of transcending individual mandates and connecting policy appraisal.

In order to address these policy concerns and achieve common grounds on decisions concerning the implementation of sustainable transport and land-use plans, this research proposes an
integrated framework for policy appraisal. This entails the development of a set of sustainable transport indicators derived from ILUTE outputs and sustainability impact model outputs thus reflecting a range of transport externalities that would become part of decision-making. This framework is motivated by the need to shift transport appraisals from the traditional cost-benefit frameworks involving measurement of time savings, vehicle operating costs and accidents as well as qualitatively assessing environmental impacts, to a broader approach based on an integrated assessment of transportation impacts on three main levels namely, economic, social, and environmental. Recognizing that a single-discipline approach cannot deliver the understanding needed to develop indicators of sustainability of a system, a multidisciplinary approach is advanced to evaluate sustainable transport plans. Indeed, indicators as the product of the transformation of complex interactions into intuitive constructs, provide a mechanism to enhance policy design and debate. Distilling IUM results into readily understandable indicators of urban sustainability may hold value for stimulating greater interchange between modellers and policy makers.

This Chapter reviews some of the existing work on sustainability indicators with special emphasis on the Canadian context. In fact, this Chapter is not intended to conduct a thorough review of indicator research (refer to MiHyeon Jeon and Amekudzi, 2005) but merely to present the reader with background information on the types of indicators that are typically used to measure transport and how they can be used in the context of policy appraisal. In addition, examples of higher-level environmental, social, and economic indicators that can be linked with ILUTE are presented. Clearly this thesis focuses on linking environmental modelling with ILUTE and using modelling results to propose environmental indicators. Social and economic indicators are not discussed in the context of ILUTE. As such, this Chapter serves both as a “scoping” stage for the research conducted in the context of this dissertation and as a road map featuring the work needed to achieve a link between ILUTE and a full set of sustainability indicators.
6.2 Sustainable transport definitions

While the most widely quoted definition of sustainable development is the one developed by the World Commission on Environment and Development in the Brundtland Report (1987): “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”, an equivalent widely accepted definition of sustainable transportation is not available. Alternatively, numerous definitions of sustainable transport and how to achieve it have been forwarded by national and international organizations (e.g. Environment Directorate of the Organization for Economic Cooperation and Development, United States Environmental Protection Agency, European Environment Agency, European Union Council of Ministers of Transport), and researchers (e.g. Steg and Gifford, 2005; Himanen et al., 2005; Shiftan et al., 2003; Feitelson, 2002; Black, 2000). Most definitions emphasize the importance of the three elements of sustainability namely, economic, environmental, and social thus making this three-dimensional framework a crucial element in sustainable transport definitions adopted both in research and practice.

In Canada, visions and definitions of sustainable transportation have been developed by agencies and government authorities including Transport Canada (TC), the Transportation Association of Canada (TAC), and the Center for Sustainable Transportation (CST) (Table 6.1). Clearly, the different visions are based on a need to address a broad range of problems involving almost all of society’s goals for human and natural well-being and spanning over a range of sectors thus entailing the involvement of different experts and policy-makers. Litman (2005a; b) contrasts sustainability planning, which he refers to as comprehensive planning, with reductionist planning, which typically looks at sustainability from a single perspective thereby targeting individual aspects of sustainability while neglecting others. The emergence of comprehensive visions of sustainable transportation in Canada clearly indicates an awareness of the multiple facets of sustainability and the need for integrated plans to achieve a sustainable transport system.
### Table 6.1 Visions of sustainable transportation developed by selected Canadian agencies

<table>
<thead>
<tr>
<th>Agency</th>
<th>Vision/Definition</th>
</tr>
</thead>
</table>
| Transport Canada TC, 2004               | Vision for sustainable transport is guided by the following principles:  
1- highest practicable safety and security of life and property  
2- efficient movement of people and goods to support economic prosperity and a sustainable quality of life  
3- respect for the environmental legacy of future generations of Canadians  
4- user pricing that better reflects the full costs of transportation activity and transportation  
5- infrastructure decisions that meet user needs  
6- reasonable access to the national transportation system by Canada’s remote regions.” |
| Transportation Association of Canada (TAC) TAC, 1999 | Defines sustainable transportation as follows:  
1- In the natural environment: a) limit emissions and waste that pollute air, soil and water within the urban area’s ability to absorb/recycle/cleanse; b) provide power to vehicles from renewable or inexhaustible energy sources such as solar power in the long run; c) recycle natural resources used in vehicles and infrastructure such as steel, plastic, etc.  
2- In society: a) provide equity of access for people and their goods, in this generation and in all future generations; b) enhance human health; c) help support the highest quality of life compatible with available wealth; c) facilitate urban development at the human scale; d) limit noise intrusion below levels accepted by communities; e) be safe for people and their property.  
3- In the economy: a) be financially affordable in each generation; b) be designed and operated to maximize economic efficiency and minimize economic costs; c) help support a strong, vibrant and diverse economy.” |
| Center for Sustainable Transportation CST, 2002 | Vision of sustainable transportation is that of a system which:  
1- Allows the basic access needs of individuals to be met safely and in a manner consistent with human and ecosystem health, and with equity within and between generations  
2- Is affordable, operates efficiently, offers choice of transport mode, and supports a vibrant economy  
3- Limits emissions and waste within the planet’s ability to absorb them, minimizes consumption of non-renewable resources, limits consumption of renewable resources to the sustainable yield level, reuses and recycles its components, and minimizes the use of land and the production of noise.” |

### 6.3 Review of existing sustainable transport indicator sets

While significant research has been undertaken (both internationally and in Canada) in the field of sustainable transport indicators, most studies have aimed at developing “descriptive” indicators of progress towards -or away from- predefined sustainability goals. While such indicators are important for the construction of trends from collected data, they are not always useful for policy-appraisal since they often rely on variables that are hard to forecast. In fact, there is a general lack in “performance” indicators that can be estimated from modelled/forecasted data. In this case, the outcomes of IUMs are post-processed into performance measures that reflect the sustainability of the modelled scenarios thus conveying complex information to policy-makers.
6.3.1 Indicator sets developed by Canadian agencies

The increasing awareness in Canada of the different facets of sustainable transportation has led to the provision of investments for the development of sustainable transport indicators primarily aiming at measuring the progress of different sectors and services towards sustainable transportation, as defined or envisioned by the different organizations. As a result, various Canadian organizations have developed sustainable development indicators; some of them directly targeting the transportation sector (sustainable transport indicators) while in other cases, environmental indicators are developed including some indicators for the transport sector.

A major effort towards the development of Canada-wide Sustainable Transportation Performance Indicators (STPI) is attributed to the Canadian CST, which received start up funds, by the government of Canada. The CST undertook the STPI project to provide a means of determining whether progress is being made towards sustainable transportation. The project was conducted in three phases and culminated in the development of a set of 14 indicators while short- and longer-term additions were proposed to refine the analysis (CST, 2000; 2001; 2002). The outcome of the initial set of 14 indicators developed by CST showed that while on some levels, Canada is making progress towards sustainable transportation, overall, the transport sector in Canada is becoming less sustainable (Table 6.2). The indicators developed by CST include a broad range of factors but lack some major components. For example, air pollutant emissions are included but not human exposure to air pollution; in fact, among long-term additions, an indicator entitled “effects on human health” is included, which may be considered as a proxy for exposure to air pollution. In terms of alternative modes of transport, they are not part of the current set of indicators but a “journey-to-work mode share” indicator in short-term additions could eventually capture walking and biking. The “percent walking to work” indicator is included as part of a short-term addition to land-use and urban form indicators, but it is considered to be an indicator of mixed-use and density of different urban forms. Different measures of accessibility are proposed as long-term additions but they do not explicitly try to link levels of accessibility with socio-economic differences. Similarly, household transportation costs are included but not in terms of socio-economic groups. An indicator for the “percent of alternative fuelled vehicles in the fleet” is proposed as a short-term addition which is considered to be a good indicator that can track the market penetration of such vehicles.
Table 6.2 The initial set of STPI with proposed shorter-term and longer-term additions (CST, 2002)

<table>
<thead>
<tr>
<th>Framework topic and question</th>
<th>Initial set of STPI</th>
<th>Shorter-term additions</th>
<th>Longer-term additions</th>
</tr>
</thead>
</table>
| 1. Environmental and health consequences of transport | Use of fossil fuel energy for all transport  
Greenhouse gas emissions from all transport  
Index of emissions of air pollutants from road transport  
Index of incidence of road injuries and fatalities | Air quality  
Waste from road transport  
Discharges into water  
Land-use for transport  
Proximity of infrastructure to sensitive and ecosystem fragmentation | Noise  
Effects on human health  
Effects on ecosystem health |
| 2. Transport activity | Total motorized movement of people  
Total motorized movement of freight  
Share of passenger travel not by land-based public transport  
Movement of light-duty passenger vehicles | Utilization of passenger vehicles  
Urban automobile vehicle-kilometers  
Travel by non-motorized modes in urban areas  
Journey-to-work mode shares | Urban and intercity person-kilometers  
Freight modal participation  
Utilization of freight vehicles |
| 3. Land-use, urban form and accessibility | Urban land-use per capita | Urban land-use by size class and zone  
Employment density by CMA*, and urban class and zone  
Mixed use (per cent walking to work; jobs to employed labor force) | Share of urban population and jobs served transit  
Share of population and employment growth on already-urbanized lands  
Travel and modal split by urban zone |
| 4. Supply of transport infrastructure and services | Length of paved roads | Length of sustainable infrastructure  
Transit seat-kilometers per capita | Congestion index |
| 5. Transportation expenditures and pricing | Index of relative household transport costs  
Index of the relative cost of urban transit | Percent of net government transport expenditures spent on ground-based public transportation | Transport-related user charges  
Expenditures by businesses on transportation |
| 6. Technology adoption | Index of energy intensity of cars and trucks  
Index of emissions intensity of the road vehicle fleet | Percent of alternative fuel vehicles in the fleet | Per cent of passenger-km and tonne-km fuelled from renewable energy  
Percent of labor force regularly telecommuting |
| 7. Implementation and monitoring | Number of sustainable transport indicators regularly updated and widely reported  
Public support for initiatives to achieve sustainable transportation | Number of CMAs* where planning and delivery of transport and related land-use matters have a single authority |

The Victoria Transport Policy Institute (VTPI) provided guidance on the selection of sustainable transport indicators by pinpointing issues to consider when developing indicators and discussing
problems that may be encountered in the development of sustainable transport indicators (Litman, 2005a) (Table 6.3). In the context of its second sustainable development strategy (2001-2003), TC defined seven challenges for sustainable transportation in addition to commitments, targets, and performance measures relating to each of the challenges (TC, 2001). The TAC developed 13 principles pointing to sustainable transportation systems and urban land-use in Canada (TAC, 1999).

Table 6.3 Recommended indicator sets by the VTPI (Litman, 2005a)

<table>
<thead>
<tr>
<th>Economic</th>
<th>Social</th>
<th>Environmental</th>
</tr>
</thead>
<tbody>
<tr>
<td>Most Important (Should usually be used)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Per capita mobility (person-miles or trips)</td>
<td>Quality of accessibility for disadvantaged people</td>
<td>Per capita energy consumption</td>
</tr>
<tr>
<td>Mode split</td>
<td>Per capita traffic crashes and fatalities</td>
<td>Per capita air pollution emissions (various types)</td>
</tr>
<tr>
<td>Average commute travel time</td>
<td>Community impacts</td>
<td>Per capita land devoted to transportation facilities</td>
</tr>
<tr>
<td>Per capita congestion costs</td>
<td>Portion of low-income household budgets devoted to transport</td>
<td>Air and noise pollution exposure and health damages</td>
</tr>
<tr>
<td>Portion of household budgets devoted to transport</td>
<td>Inclusiveness of planning process</td>
<td>Quality of environmental analysis and planning</td>
</tr>
<tr>
<td>Public/external costs of transport per capita</td>
<td></td>
<td>Community livability ratings</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Water pollution emissions</td>
</tr>
<tr>
<td>Helpful (Should be used if possible)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Degree to which transport planning decision reflect market principles</td>
<td>Portion of residents who regularly walk or bicycle</td>
<td>Impacts on special habitats and environmental resources</td>
</tr>
<tr>
<td>Relative quality of non-automobile modes (walking, cycling, ridesharing, public transit)</td>
<td>Portion of children walking or cycling to school</td>
<td></td>
</tr>
<tr>
<td>Job opportunities and public services within 30-minute commute distance of residents</td>
<td>Consideration of cultural resources in transport planning</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Residents’ overall satisfaction rating of transport system</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Universal design (consideration of disabled people’s needs in transport planning)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specialized (For particular objectives)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Portion of households with internet access</td>
<td>Transit affordability</td>
<td></td>
</tr>
<tr>
<td>Change in property values</td>
<td>Housing affordability in accessible locations</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Planning Process</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Comprehensive (takes into account all significant impacts, using best current evaluation practices)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unbiased (applies objective, least-cost planning and investment practices)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inclusive (substantial involvement of affected people, with special efforts to insure that disadvantaged and vulnerable groups are involved)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Application of smart growth land-use policies</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Market Efficiency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Portion of total roadway and parking costs borne directly by road users</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Implementation of pricing reforms such as congestion pricing, distance-based vehicle insurance and registration fees, Parking Cash Out, unbundled parking, tax reforms, etc</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The set of indicators proposed by the VTPI is considered to be more comprehensive than the indicators proposed by CST; although it should be noted that while the CST has estimated the initial 14 indicators, the VTPI did not estimate the proposed indicators. The indicators proposed by the VTPI are divided into three categories; environmental, economic, and social. Besides estimating transport costs per capita, the proposed indicators include “per capita congestion costs” and a measure for the “relative quality of non-automobile modes”. An indicator for the “quality of accessibility for disadvantaged people” is proposed in addition to the “portion of low-income household budgets devoted to transport” thereby explicitly attempting to measure social equity. In addition, an explicit measure for alternative transport modes is included through the “portion of residents who regularly walk or bicycle”. The set of indicators also includes air pollutant emissions as well as exposure and “impacts on special habitats and environmental resources”. Since the VTPI has not estimated the proposed indicators, the easiness of estimating the proposed set is yet to be determined. Most likely, various models in travel demand, social accounting, economics, and emission/dispersion need to be relied upon to generate the set of indicators; still, they are thought to be highly valuable for decision-making and should be further refined and researched.

Both Environment Canada (EC) and the National Round Table on the Environment and the Economy (NRTEE) developed sustainable development indicators including some indicators related to transportation under the human activities or human capital objective (EC, 1991; 2003; NRTEE, 2003) (Table 6.4, Table 6.5). The set of indicators developed both by EC and NRTEE emphasize the environmental quality at the expense of economic and social factors. Both indicator sets include urban air quality but it is not clear whether it is by sector or not. These indicators follow more or less reductionist approaches to sustainability and in general, they are not suitable for assessing sustainable transport plans as they do not address all aspects of sustainability. Similarly, the set of indicators proposed by the CST, does not address very clearly environmental and resource use impacts at this stage (initial set). In fact, the set of indicators developed by the VTPI is considered to be the most suitable for assessing sustainable transport objectives as they cover the three facets of sustainability.
Table 6.4 EC Environmental Signals (EC, 2003)

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ecological life-support systems</td>
<td>Biodiversity and protected areas</td>
</tr>
<tr>
<td></td>
<td>Toxic substances</td>
</tr>
<tr>
<td></td>
<td>Acid rain</td>
</tr>
<tr>
<td></td>
<td>Climate change</td>
</tr>
<tr>
<td></td>
<td>Stratospheric ozone</td>
</tr>
<tr>
<td>Human health and well-being</td>
<td>Municipal water use</td>
</tr>
<tr>
<td></td>
<td>Municipal wastewater treatment</td>
</tr>
<tr>
<td></td>
<td>Urban air quality</td>
</tr>
<tr>
<td>Natural resources sustainability</td>
<td>Forestry</td>
</tr>
<tr>
<td></td>
<td>Agricultural soils</td>
</tr>
<tr>
<td>Human activities</td>
<td>Energy consumption</td>
</tr>
<tr>
<td></td>
<td>Passenger transportation</td>
</tr>
<tr>
<td></td>
<td>Municipal solid waste</td>
</tr>
</tbody>
</table>

Table 6.5 NRTEE’s Environment and Sustainable Development Indicators (NRTEE, 2003)

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Natural capital</strong></td>
<td></td>
</tr>
<tr>
<td>Air quality trend</td>
<td>Weights exposure to ground-level ozone (O\textsubscript{3}) by population: Factors in the number of people who are exposed to low-level ozone and the ambient ozone concentrations in different parts of the country</td>
</tr>
<tr>
<td>Freshwater quality</td>
<td>Shows the proportion of water bodies in the existing monitoring networks that are classified as “marginal” or “poor” based on the water quality indices calculated using the Canadian Council of Ministers of the Environment (CCME)'s methodology</td>
</tr>
<tr>
<td>Greenhouse gas emissions</td>
<td>Based on the existing national greenhouse gas inventory developed by Environment Canada, the indicator measures aggregate emissions of Greenhouse gases in megatonnes of CO\textsubscript{2} equivalent</td>
</tr>
<tr>
<td>Forest cover</td>
<td>Tracks changes in the extent of Canada's forests</td>
</tr>
<tr>
<td>Extent of wetlands</td>
<td>Tracks changes in the total area of wetlands in Canada</td>
</tr>
<tr>
<td><strong>Human capital</strong></td>
<td></td>
</tr>
<tr>
<td>Educational attainment of the</td>
<td>Measures the percentage of the Canadian population aged 25 to 64 years who have upper-secondary and tertiary-level educational qualifications</td>
</tr>
<tr>
<td>working-age population</td>
<td></td>
</tr>
</tbody>
</table>

As an illustration of potential discrepancies arising in policy appraisal, Jones and Lucas (2000) noted significant disparities and omissions between indicator sets adopted by the transportation
and environment departments in the UK. While transport agencies are responsible primarily for reducing traffic congestion and improving mobility, environmental agencies are responsible for reducing pollution. Each organization evaluates solutions based on its objectives, often giving little consideration to other objectives outside the scope of their responsibility. Munda (2006) also attributes the notion of ecological reductionism to the concepts of urban environmental carrying capacity and ecological footprint\(^{10}\) whereby both measures try to convert a broad range of impacts to land or resource consumption, not taking into account socio-economic and cultural aspects.

### 6.3.2 Indicators used for policy appraisal

Policy appraisal indicators should enable testing the impacts of projected future transportation and land-use policy options. In this respect, they should first include a broad range of impacts related to the three facets of sustainable transport. In addition, only outcomes of the planning process should be used to estimate the indicators whereby they should be policy-sensitive enough to reflect changes in the forecasted strategies. As a result, indicators targeted towards analysis of plans and policies should highly reflect the impacts of the tested policies and their agreement with sustainability objectives. Research into sustainability indicators that are meant to be used for policy appraisal, includes two general types of studies: 1) studies that aim at linking a broad range of indicators with integrated land-use and transport models, and 2) studies that focus on improving the estimation of specific types of indicators.

The SPARTACUS (System for Planning and Research in Towns and Cities for Urban Sustainability) European initiative, which has evolved into the PROPOLIS (Planning and Research of Policies for Land Use and Transport for Increasing Urban Sustainability) program is the best example of the development of a set of social, economic, and environmental indicators that can be linked with integrated land-use and transport models and used for comparing policy scenarios. The PROPOLIS indicators have been linked with the MEPLAN, TRANUS, and

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\(^{10}\) The carrying capacity defines the maximum population of a given species that can be supported indefinitely in a given territory without spoiling its resource base. Rather than measuring population per unit area, the ecological footprint, expresses the resources consumed and wastes produced by a population in terms of an equivalent area of biologically productive land and water (Wackernagel and Rees, 1996).
IRPUD IUMs and implemented in a set of case cities: Helsinki (MEPLAN), Dortmund (IRPUD), Inverness (TRANUS), Naples (MEPLAN), Vicenza (MEPLAN), Bilbao (MEPLAN), and Brussels (TRANUS). The basis for the PROPOLIS framework is the land-use and transport model which simulates the effects of policies and essentially generates population and employment distributions, traffic link loads, and modal splits. Different modules receive the output of the IUM and calculate indicator values. A raster module disaggregates zonal population to a high resolution raster (100x100 meters) and in turn, calculates the environmental and social indicators based on an emission submodel, air pollution and exposure submodel, noise submodel, environmental quality of open spaces submodel, and accessibility to open space submodel. The output of the raster module includes 11 sustainability indicators (Table 6.6). The economic indicator module produces a set of economic indicators in addition to performing a cost benefit analysis (CBA) and outputs CBA standard outputs; the set of economic indicators is listed in Table 6.6. The justice module takes output from the raster module and economic module and links them to population socio-economic groups to assess distributional impacts of economic benefits as well as air pollution and noise (Table 6.6) (Lautso et al., 2004).

Many studies have focused on specific indicators, which are not commonly found within broader studies encompassing a wide range of “descriptive” indicators. Such indicators include, but not limited to, environmental equity, quality of life (QoL), and accessibility. A brief overview of selected studies is presented in this section.

Feitelson (2002) explored the different aspects of environmental equity in the case of the transport sector. The author argued that the conventional environmental equity analyses which typically compare affected to unaffected areas are unlikely to render robust or meaningful results, suggesting that the focus of research should be to analyze systemic differences between users of the transport system with respect to affected populations. The author argues that if users differ from those affected in terms of race, ethnicity, age, or income; there is a distinct case of investigating whether the relationship between use and exposure patterns increase or decrease the overall equity. According to him, the key to meaningful environmental equity analysis lies in the proper overlay (mainly through GIS) of the exposure emanating from the urban transport system over population attributes, in order to identify the percent of those exposed according to socio-economic groups. A difficulty of particular importance from an environmental equity
perspective, in the case of local level transport policies, is the lack of data on the attributes of
transient populations exposed to street-level pollution. These include pedestrians, employees,
and users of the transport system. As these groups can be substantive in parts of the cities (such
as central business districts), estimates of the distribution and magnitude of the benefits of
policies geared to reduce pollution in such areas are likely to be highly inaccurate, if they take
into account only residents in these areas.

Table 6.6 PROPOLIS indicators (Lautso et al., 2004)

<table>
<thead>
<tr>
<th>Module</th>
<th>Indicator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raster Module</td>
<td>Greenhouse gases from transport (tons per 1000 inhabitants per year)</td>
</tr>
<tr>
<td></td>
<td>Acidiﬁng gases from transport (Acid equivalents per 1000 inhabitants per year)</td>
</tr>
<tr>
<td></td>
<td>Volatile Organic Compounds (tons per 1000 inhabitants per year)</td>
</tr>
<tr>
<td></td>
<td>Consumption of mineral oil products from transport (tons per 1000 inhabitants per year)</td>
</tr>
<tr>
<td></td>
<td>Land coverage (percent of study area)</td>
</tr>
<tr>
<td></td>
<td>Fragmentation of open-space (index related to base year)</td>
</tr>
<tr>
<td></td>
<td>Quality of open space (index related to base year)</td>
</tr>
<tr>
<td></td>
<td>Exposure to PM in the living environment (% of population above limit values)</td>
</tr>
<tr>
<td></td>
<td>Exposure to NO2 in the living environment (% of population above limit values)</td>
</tr>
<tr>
<td></td>
<td>Exposure to traffic noise (% of population annoyed)</td>
</tr>
<tr>
<td></td>
<td>Accessibility of open space (index related to base year)</td>
</tr>
<tr>
<td>Economic Module</td>
<td>Transport Investment Costs</td>
</tr>
<tr>
<td></td>
<td>Transport user beneﬁts</td>
</tr>
<tr>
<td></td>
<td>Transport operator beneﬁts (by mode of transport)</td>
</tr>
<tr>
<td></td>
<td>Government beneﬁts from transport (by mode of transport)</td>
</tr>
<tr>
<td></td>
<td>Transport external accident costs (by mode of transport)</td>
</tr>
<tr>
<td></td>
<td>Transport external emissions costs (by zone type)</td>
</tr>
<tr>
<td></td>
<td>Transport external greenhouse gases costs</td>
</tr>
<tr>
<td></td>
<td>Transport external noise costs (by zone type)</td>
</tr>
<tr>
<td></td>
<td>Transport generalized costs variation (by socio-economic group)</td>
</tr>
<tr>
<td></td>
<td>Productivity gain from land-use</td>
</tr>
<tr>
<td>Justice Module</td>
<td>Justice of distribution of economic beneﬁts</td>
</tr>
<tr>
<td></td>
<td>Justice of exposure to particulates</td>
</tr>
<tr>
<td></td>
<td>Justice of exposure to nitrogen dioxides</td>
</tr>
<tr>
<td></td>
<td>Justice of exposure to noise</td>
</tr>
</tbody>
</table>

Steg and Gifford (2005) argue that sustainable transport plans will be strongly opposed when
users believe the plans will signiﬁcantly reduce their wellbeing. In fact, one can hardly speak of
sustainable transport when most citizens believe it will signiﬁcantly reduce their QoL. Thus,
sustainable transport should also be concerned with human needs and values. The effects of
strategies aimed at stimulating sustainable transport should also be assessed in terms of human needs and values. The authors refer to the QoL as a “subjective wellbeing, which refers to individuals’ cognitive and affective evaluations of their lives”. Using the same QoL definition, Poortinga et al. (2004) provide a set of indicators including an importance rating of each QoL indicator as obtained from a questionnaire study of 455 Dutch respondents in 1999. It was observed that impacts on health, partner and family, social justice, freedom and safety were valued more highly than impacts on material beauty, spirituality and religion, status and recognition, challenge and excitement. Steg and Gifford (2005) stress that policymakers should especially consider possible impacts on the most important QoL indicators when designing and implementing sustainable transport policies, because the public will especially oppose measures that negatively affect these QoL indicators.

Bertolini et al. (2005) recognize the integration of transport and land use planning as essential to the achievement of sustainable development; they propose the concept of accessibility to provide a useful conceptual framework for such integration. As such, the authors have used the concept of accessibility as a framework for the interactive design of integrated transport and land use plans in two areas of the Netherlands. The objective of this effort was to identify solutions where economic, social, and environmental goals could be combined, thus leading to the achievement of what they refer to as “sustainable accessibility”. The authors define accessibility as the amount and the “diversity of places of activity that can be reached within a given travel time and/or cost” and recognize that maximizing the synergy between sustainability and accessibility would entail the development of transport and land use conditions for as large as possible a share of environment-friendly transportation methods than the conventional car, while at the same time maintaining and possibly increasing the amount and the diversity of activity places that people can reach within a given travel time and/or cost. As such, they relate accessibility to both the qualities of the transport system (e.g. travel speed) and the qualities of the land use system (e.g. functional densities and mixes). At the same time, they relate it to economic goals (access to workers, customers, suppliers), social goals (access to employment, goods and services, social contacts) and environmental goals (resource-efficiency of the associated activity and mobility patterns).
6.4 Integration of ILUTE with sustainability indicators

While the studies conducted in the Canadian context provide comprehensive sets of indicators for sustainable transport, they are primarily geared towards analyzing a current situation and assessing progress toward goals through trends. As a result, most of the indicators cannot be used to assess policies and plans based on forecasted scenarios, rather than collected data. Litman (2005a) states that sustainable transport indicators should be useful to “identify trends, predict problems, assess options, set performance targets, and evaluate a particular jurisdiction or organization”; this includes the use of indicators in planning decisions to evaluate different policy options. As a result, there is still a need in Canada for sustainable transport indicators that can be commonly used by all government departments in order to appraise different policies rather than just measure trends towards sustainability.

The long-term aim of this research is to link ILUTE with a set of indicators or performance measures which, similarly to the PROPOLIS case, can be used to compare policy scenarios. Figure 6.1 illustrates the framework of ILUTE in addition to proposed high-level indicators. While the current study will focus on developing environmental and exposure indicators, Figure 6.1 presents examples of social and economic indicators thus illustrating the broad framework of the research. Note that work has not been conducted with respect to social or economic indicators in the context of this dissertation; the focus was only on the environmental and exposure parts highlighted in grey in Figure 6.1.

Note that the approach adopted in this research for the development of environmental indicators is somehow different from approaches conducted in other studies. While most studies, especially in Canada, start with defining a set of indicators and then move on to develop methodologies to estimate them; this study starts with a set of high-level indicators (excluding their units, level of disaggregation, etc), generates a broad range of outputs from environmental modelling, and then extracts indicators based on the most illustrative, most intuitive, and most policy sensitive outputs. This approach does not constrain the environmental modelling to estimate a predefined indicator but rather ensures that the set of indicators that are reached at in the end can be realistically extracted from the models. As such, the next three Chapters describing the environmental modelling do not mention the indicators whereby a discussion on possible indicators is provided after the modelling, in Chapter 10.
Figure 6.1 ILUTE framework with proposed high level environmental indicators and examples of social and economic indicators
6.5 Conclusion

Indicators, when used as a means of assessing policies, can bridge the gap between modeling and decision-making since they provide planners and decision-makers with a more or less straightforward way of interpreting the results of integrated transportation and land-use models which would require a higher level of expertise for running and producing forecasts than is usually available in government departments. In addition, they provide a common platform for assessment of the different facets of sustainability. While most sustainable transport indicators are used as a means to establish past and future trends, a comprehensive set of policy-sensitive indicators may well be adopted for policy appraisal. Such a proposition stems from the recognition of policy-making as a network of interconnected actions involving a wide range of stakeholders, and a lack of tools for supporting the design of policies, as opposed to the relative abundance of tools for analyzing trends and problems at hand.

The plan for linking ILUTE with sustainability indicators could in turn serve as a critical piece to overcoming institutional barriers to the development and implementation of IUMs. Note however that efforts to overcome conceptual and technical hurdles should be met with complementary efforts to tackle institutional skepticism concerning the utility of the IUM framework as an approach to adding value to the decision making process.
Chapter 7
Modelling Transport Emissions in the Greater Toronto Area

7.1 Introduction
The past decade has witnessed a dramatic growth in the urbanization and motorization of populations worldwide. As a result, urban travel patterns have become more complex; involving both individual and household decisions with respect to trip scheduling and chaining, mode and route choices, as well as car sharing. The added intricacy in travel behaviour has motivated the development of activity-based models of travel demand for use by planning agencies as decision-making tools (Miller and Roorda, 2002; Kitamura et al., 1998; MBRC, 1998; RDC Inc., 1995). Consequently, there is a growing need to link the results of travel behaviour research with the development and evaluation of transport policies. In terms of policy evaluation, the assessment of environmental performance, in particular, has grown in importance namely due to increasing concern over environmental preservation, resource consumption, limiting GHG emissions, and human exposure to air pollution. As such, there is a need to quantify transport-related environmental impacts by developing models that can be integrated with the emerging activity-based models of travel demand.

This chapter describes the development of link-based and zone-based vehicle emissions in the GTA by exploiting travel information provided by an activity-based travel demand model and supplementing this information with other data obtained from Canadian sources. For this purpose, the Canadian version of the Mobile6.2 model (Mobile6.2C), developed by the United States Environmental Protection Agency (USEPA) for estimation of vehicle emission factors (EFs) (USEPA, 2003a), is fitted with travel activity input data derived from the Travel Activity Scheduler for Household Agents (TASHA), a “next-generation”, activity-based model of travel demand for the GTA, developed at the University of Toronto (UofT) (Miller and Roorda, 2003). In addition, local vehicle fleet characteristics are input into Mobile6.2C to refine the EF estimates.

This Chapter starts with a discussion of the formation of vehicle exhaust emissions, namely CO, HC, NOx, and CO2. A discussion of the environmental and health impacts of each of these
pollutants can be found in De Nevers (1995). The general overview of vehicle emissions is followed by a literature review of emission modelling. The chosen model for estimation of EFs (Mobile6.2C) is then described. The remaining sections describe the methodology adopted for the estimation of vehicle emissions in the GTA and discuss the results obtained.

7.2 Generation of vehicle exhaust emissions

The formation of vehicle exhaust emissions mostly depends on the Air to Fuel Ratio (AFR), a parameter critical for the operation of gasoline internal combustion engines. In theory, complete combustion occurs at an AFR of 14.7 or the stoichiometric ratio whereby there is just enough oxygen to oxidize the fuel thus resulting in the formation of CO₂, water, and nitrogen. Most modern gasoline-fuelled vehicles have fuel injection systems that attempt to optimize combustion. In practice, this perfect combustion never occurs; as a result, 1) some atmospheric and fuel nitrogen is oxidized to form NOₓ, 2) some fuel is imperfectly combusted to form new HC and CO, and 3) some fuel is not combusted at all and emitted as HC. In diesel-fuelled engines, emissions behave differently because of compression-ignition rather than spark-ignition. Lower AFRs characterize the combustion in diesel engines thereby mainly releasing NOₓ, SO₂, and PM. In light of the interest in emissions of gasoline-fuelled vehicles in the context of this research, no further discussion of diesel emissions is made.

7.2.1 Emissions vs. air to fuel ratio

In gasoline spark-ignition engines, for operation at less than the stoichiometric ratio (AFR<14.7), the air-fuel mixture is rich and, as such, there is not enough oxygen for the complete combustion of the fuel, thus causing CO and HC emissions to be high. As the AFR increases toward 14.7, CO and HC emissions decrease rapidly. With leaner mixtures, the engine operates “rougher”; there is excess oxygen so that CO and HC emissions stay low. At even greater values of the AFR, the combustion becomes unstable. In such very lean air-fuel mixtures, fuel particles may be so far apart that the flame may not advance over the intervening space; it may become extinguished (misfiring) and unburned HC are exhausted (Godish, 1991; Colls, 2002). High HC levels indicate unburned or partially burned fuel in the exhaust stream. Spark plug misfire, rich or lean fuel mixture, ignition fault or a mechanical problem may cause excess HC. In contrast, NOₓ levels are at their highest at stoichiometric combustion (AFR = 14.7). Typically, the
temperature of the combustion gases is maximized at stoichiometric burning. However, NOx generation is maximized at high temperatures in the presence of extra oxygen. These conditions are met at AFR’s of 15 to 16. Under lean conditions, excess air is being imported into the combustion chamber, warmed up, and exhausted. This reduces the temperature and again lowers NOx production (Godish, 1991; Colls, 2002).

7.2.2 Control of emissions
Based on the previous discussion of the formation of the main gasoline vehicle pollutants; HC, CO, and NOx; clearly, the control of NOx poses a dilemma since most control measures aiming at decreasing emissions of CO and HC increase the efficiency of combustion. As combustion efficiency increases, higher combustion chamber temperatures result, which enhances the formation of NOx. In fact, lean-burn engines have been designed to give the best compromise of low CO, HC, and NOx emissions. These conditions however may lead to instability of combustion (e.g. stalling during idling or during a cold start) and need advanced fuel and air management. Typically, control measures for NOx have employed techniques which reduce combustion chamber temperatures without significantly increasing emissions of CO and HC. These include retardation of spark plug timing, decreased compression ratios, and exhaust gas recirculation (EGR). The latter aims at recirculating part of the exhaust in the combustion chamber to dilute the air-fuel mixture thus reducing the combustion temperature and contributing to the control of NOx.

Currently, the use of catalytic converters, mounted in the tailpipe, for the oxidation of CO and HC as well as reduction of NOx has become one of the most widespread emission control technology achieving conversion efficiencies of up to 90 percent for the three pollutants. The catalytic converter oxidizes CO and HC to form CO2 and water, and reduces NOx to form Nitrogen (N2) (Godish, 1991; De Nevers, 1995; Colls, 2002; Cooper and Alley, 2002). De Vlieger (1997) estimated that in real traffic conditions, emissions for cars with three-way catalysts were 70 percent lower than for non-catalyst cars. Catalytic converters however are only effective once their surface reaches an optimum temperature (around 350°C); as such, they do not control cold start emissions. Normally, start emissions last until the catalytic converter has warmed up to an optimum temperature. In non-catalyst cars, the high emissions are due to the
high fuel enrichment for a cold start since combustion will only occur when gasoline has evaporated. The most important variable in cold starts is the ratio between the air and the gasoline in gas phase. The AFR is not very important since any gasoline in liquid form will not combust. De Vlieger, (1997) found that absolute CO and HC cold-start emission levels for cars without a catalytic converter are much higher than those equipped with a catalytic converter although the non-catalyst cars had a “cold phase” of 130-180 seconds while catalyst-equipped cars had a “cold-phase” of 130-280 seconds.

7.2.3 Vehicle operation and emissions
Clearly vehicle technology, fuel composition, and emission control technology have a significant effect on emissions. However, real-world emissions are not only affected by vehicle technology but also by the way vehicles are operated and maintained. The most notable “vehicle operation” variables are speed, engine maintenance, and driving behaviour. Also road design (such as intersections, ramps, etc.) is a major determinant of emissions due to its effect on speed and driving behaviour (need for frequent accelerations and decelerations, low average speeds, etc.).

Using on-board vehicle testing, El Shawarby et al. (2005) found that the optimum fuel-consumption rate occurs at a cruise speed of approximately 72 km/hour. Instantaneous emission rates of HC, CO, and NOx, were found to increase as the cruise speed increased from 72 km/hour to 104 km/hour as well as when the cruise speed decreased from 72 km/hour to 56 km/hour. As an illustration of the effect of engine maintenance, Lawson (1993) observed that 55 percent of CO emissions were emitted by only 10 percent of the fleet; composed of the oldest and most poorly maintained vehicles. These are typically referred to as the “gross emitters”. Kazopoulo et al. (2005) found a high variability in emissions measured for different light-duty cars of the same model year thus supporting the fact that engine maintenance or state of repair is a significant variable affecting emissions.

De Vlieger (1997) measured emissions of CO, HC, and NOx for six gasoline-fuelled cars in real traffic situations. The author found that aggressive driving resulted in CO EFs up to three times higher than those for normal driving. In the case of HC and NOx, EFs were up to two times higher. Fuel consumption rates were found to be lower in city traffic compared to highway traffic
for all types of driving behaviour. Driving behaviour alone was observed to increase fuel consumption by 20-40 percent compared to normal driving. In city driving, the average speed throughout the trip was almost the same in normal and aggressive driving. Using a logging device on a selected vehicle, Ericsson (2000) collected data for twelve different subjects who drove the vehicle under various driving conditions for the same street loop. The author observed that street type had a higher influence on driving patterns than driver influence. The driving patterns of female and male drivers differed mainly in terms of acceleration patterns: men had higher average acceleration levels and greater proportion of time in the highest acceleration classes while women had a higher proportion of time in the lower acceleration class. Evidence from on-road vehicle testing, especially under different driving conditions and with different drivers, has shown that laboratory chassis dynamometer testing is not reflective of real world driving and emissions which are better captured using on-board emission instruments.

A unique study of the effect of driving behaviour, especially acceleration on vehicle emissions, was conducted by El Shawarby et al. (2005) using on-board emissions testing. The authors found that mild accelerations generate the highest accumulated fuel consumption and CO and HC emissions per acceleration event. Aggressive accelerations were not found to be associated with higher emission rates during the acceleration event. To illustrate this fact, the authors measured second by second HC emissions during an aggressive acceleration. HC emissions were found to exhibit three different regimes: 1) gradual rise, 2) abrupt rise and slow drop, and 3) constant rate. The tested vehicle was found to emit HC at an extremely high rate for 10 seconds following the acceleration event even though the vehicle would be operating at constant speed or decelerating. This happens because the vehicle continues to operate in rich mode (low AFR) to prevent knocking; this enrichment results in a bypass of the catalytic converter. In the case of normal and mild accelerations, instantaneous HC emissions were found to increase while the vehicle accelerates and then return to normal operating conditions after the end of the acceleration event. Based on the comparison of instantaneous emissions during acceleration, the authors concluded that if emissions are gathered over a sufficiently long distance then the conclusion regarding emissions being lower during a hard acceleration is reversed. This is due to the phase that follows an aggressive event which causes emissions to remain high. In contrast to HC and CO emissions, NOx emission rates were observed to decrease with aggressive accelerations.
indicating that NO\textsubscript{x} emissions are affected more by stoichiometric engine conditions as opposed to engine loads.

### 7.3 Review of vehicle-emissions modelling

Although this Chapter does not address actual measurement of emissions; it should be noted that emission measurement constitutes the basis for emission models and is almost always guaranteed to provide emission levels that are closer to reality than model outputs. Emission techniques include Inspection and Maintenance (I/M) tests, on-road remote sensing, chassis dynamometer testing, and on-board emission monitoring. This section reviews methods and applications of emission modelling by focusing on two main approaches: average-speed and microscopic modelling. At a very aggregate level, average-speed models are used for large-scale emission inventories; whereas at a more disaggregate level they can be used to compute link-based emissions for urban areas. Microscopic models are used for assessing the effect of different vehicle operating parameters on emissions as well as to investigate traffic management policies and small-scale network changes.

#### 7.3.1 Average-speed emission modelling

Research on vehicle emissions has traditionally focused on EFs and travel data based on average link speeds. Such models entail significant simplifications of the mechanical processes that cause vehicle emissions. Although the average speed of a link or of the overall trip has a significant effect on emissions, the instantaneous speed fluctuations have an even greater effect. Indeed, for the same average speed, different profiles for acceleration, cruising, idling, and deceleration, may be observed and may result in significantly different emissions. Although they tend to overlook the impacts of local emissions along busy streets or intersections, average speed models are acceptable for regional models that are designed for assessing impacts of a broad range of policies and programs while ignoring the microscopic effects. The use of average-speed models is most promising within the context of integrated land-use and transport models whereby emission impacts of policy tests conducted by such large-scale IUMs can be assessed thus providing an additional dimension for decision-making.
7.3.1.1 Average speed models

There is a large number of operational average-speed models worldwide; the most widespread and used for regulatory purposes include the USEPA Mobile series (USEPA, 2003a); the California Air Resources Board EMFAC series (CARB, 2006); and the European COPERT model (Ntziachristos and Samaras, 2000). Most average-speed models have similar structures: basic emission rates are derived from instrumented vehicle surveys, chassis dynamometer tests, or on-board measurements and used to construct speed-based emission functions as well as databases of emissions for different vehicle types, fuel types, vehicle technologies, etc. Average-speed models require inputs for external conditions, fuels, vehicle types, fleet characteristics, and vehicle activity. The outputs are EFs for different vehicle types, ages, time of day, speed, roadway classification, as well as other variables. A description of the selected average-speed model, Mobile6.2C is presented in Section 7.4.

7.3.1.2 Implementations of average-speed models for regional emissions

Considerable research into integrating emissions models with travel demand models as well as integrated land-use and transport models have been recently conducted and implemented in various cities. Most efforts focus on light-duty vehicles and are integrated with average speed models, which generate average hourly or daily emissions from the area of interest, aggregated over different vehicle types, ages, and other characteristics. Despite their mesoscopic (or sometimes macroscopic and highly aggregated) nature with respect to the treatment of emissions, these modelling frameworks are useful as decision support tools that can assess impacts of urban transport interventions on emissions. Beyond IUMs and their linkages with emission models, some studies have focused on improving traffic emission estimates in urban areas without resorting to instantaneous or microsimulation emission models. The methods developed by these studies may hold value for future IUMs expansion.

Emissions linked with Integrated Urban Models

Scott et al. (1997) used an IUM, IMULATE (Integrated Model of Urban Land Use, Transportation, energy and Emissions) to assess the impact of commuting efficiency on congestion and emissions in the Hamilton area. Mobile5 was used to derive link-based EFs. Under an optimal scenario whereby the mean commuting time for all workers is minimized, the authors have observed a reduction in HC, CO, and NOx of approximately 66, 62, and 56 percent.
compared to a base scenario for 1991. Kanaroglou and Buliung (2008) also used IMULATE to estimate pollutant emissions resulting from commercial vehicle movement (CVM) in the Hamilton area. The authors used Mobile5C to generate truck and other heavy-duty vehicle EFs. It was observed that the increase in overall HC and CO emissions was twice as high as the increase in the number of trips due to the presence of trucks. The presence of trucks was also responsible for a significant increase in PM emissions.

Shiftan and Suhrbier (2002) have used activity-based models developed for Portland (MBRC and Bowman, 1998) to investigate the impacts of Transportation Demand Management measures on mobile emissions, tours, trips, and vehicle kilometres travelled. Tested policies included pricing strategies, telecommuting incentives, transit improvement, and a combination of proposed measures. Emissions were estimated at the link level using the USEPA Mobile model while adjusting for “cold/hot” start operating conditions. Emission reductions were reported to be marginal (~3%) under the various scenarios.

AMOS (Activity Mobility Simulator) and PCATS (Prism-Constrained Activity-Travel Simulator) are examples of activity-based microsimulation models that have been used for emission estimation. PCATS has been coupled with a dynamic network simulator (DEBNetS) and used to forecast CO₂ emissions in Kyoto, Japan (Kitamura et al., 1998). AMOS has been embedded, as a central component with the Sequenced Activity Mobility Simulator (SAMS) conceptual framework that includes a module for generating air quality emissions (Kitamura et al., 1996). While the integrated land-use and transport modelling system, TRANUS, does not directly include a vehicle emissions procedure; modelling of this sort has been achieved by linking TRANUS with external procedures for translating vehicular activities into emission estimates. This approach has been used to look at GHG emissions and other emissions from transport for Mexico City and Sacramento, California (Johnston and de la Barra, 2000).

**Improvement on traditional average-speed emission modelling**

Bachman et al. (2000) developed a GIS-based modelling approach called the Mobile Emission Assessment System for Urban and Regional Evaluation (MEASURE). MEASURE starts with the assignment of a trip matrix; trip origins are disaggregated by census land-use data and by US census block group household data. The spatial accuracy of the road network is improved by
conflating the travel demand forecasting links using a GIS-based conflation procedure. Vehicle technology characteristics and operating conditions are assigned for each ZIP code rather than for the area as a whole. Intrazonal trips are also accounted for using a GIS-based method. Moreover, in order to improve on the average speed assumption without compromising the use of MEASURE for large urban areas, the authors have developed “estimates of congestion” for different roadway classes. Modal emission profiles were developed for interstates, ramps (suspected as high power demand areas), arterials, and signalized intersections. Finally, an emissions inventory module converts the facility-based emission estimates into gridded estimates for use in a photochemical model.

Armstrong and Khan (2004) developed a methodology for modelling urban transportation emissions in the National Capital Region in Canada. A four-stage travel demand model coupled with EMME/2 was used in addition to a GIS-based method for estimating trip lengths for intrazonal trips that are typically overlooked in EMME2. VOC, CO, NO\textsubscript{x}, and GHGs were calculated under two policy scenarios. In the first scenario all road modifications outlined in the Region of Ottawa-Carleton’s Official Plan are assumed to be constructed by the year 2021. In the second scenario, it was assumed that all future road modifications were abandoned thus leading to a 2012 scenario with a network that looks exactly like the base case. Results show that without additional infrastructure to support regional growth VOC emissions would increase by 17 percent, CO emissions would increase by 21 percent, NO\textsubscript{x} emissions would increase by 3 percent, and GHGs would increase by 11 percent. The increase in emissions was attributed to a 16.8 percent drop in overall network average travel speed.

7.3.2 Microscopic emission modelling

In microenvironments, such as busy streets or intersections, vehicle idling, acceleration, and deceleration may have a significant impacts on drive cycle emissions that cannot be adequately represented by average speed models. Air quality in the immediate vicinity of roadways can have significant effects on pedestrians and vehicle drivers. As such, for the purpose of assessing the emissions in urban microenvironments, models that transcend the average speed assumption have been developed.
7.3.2.1 Operational microscopic emission models

Recently, significant efforts have been devoted to the development of dynamic emission models with capabilities for second by second emission estimation of various pollutants. The capability for instantaneous emissions estimation makes these models adequate for integration with traffic microsimulation in order to assess network and traffic management policies. Indeed, traffic microsimulation models explicitly simulate the movements of vehicles within a road network, moving vehicles in real-time and thus providing information for each individual vehicle on instantaneous speeds and accelerations through the entire trip. They account for interaction of drivers with other drivers and with traffic signals. Examples of operational microscopic emission models include the University of California, Riverside Comprehensive Modal Emissions Model (CMEM) (Barth et al., 2000), the Virginia Tech microscopic (VT-Micro) model (Rakha and Ahn, 2004; Rakha et al., 2004), and the Finnish VERSIT+LD model developed by TNO Science and Technology (Smit et al., 2007).

The objective of CMEM is to predict vehicle tailpipe emissions for the different modes of vehicle operation: idle, cruise, acceleration, and deceleration. CMEM is a physical power-demand model which estimates emissions based on physical vehicle operation phenomena and other factors such as vehicle technology, fuel delivery system, emission control technology, and age, etc. The main input into the model is the individual operation on a second by second basis. CMEM does not focus on modelling specific makes and models of vehicles but predicts emissions for average or “composite” vehicles within each of 26 vehicle/technology categories. A separate sub-model is developed for each vehicle/technology category; the 26 sub-models are similar in structure (using three operating variables as input: second by second speed, grade, and accessory use such as air conditioning) but have different parameters. A total of 55 parameters are used to characterize the vehicle tailpipe emissions for the appropriate vehicle/technology category. CMEM provides emissions for HC, CO, NOx, CO2, and fuel use. CMEM is a model for light duty vehicles only and does not include PM emissions (Barth et al., 2000).

VT-Micro is a multiple regression model which uses statistical techniques to estimate emission rates of CO, HC and NOx. The emission rate is estimated as a regression of combined speed and acceleration terms; it relates dependent variables including instantaneous fuel consumption and emission estimates to a set of independent variables: namely, instantaneous speed and
acceleration levels. VT-Micro has been used to estimate emissions in the INTEGRATION traffic simulation framework (Rakha and Ahn, 2004; Rakha et al., 2004). El Shawarby et al. (2005) conducted a comparison between on-road fuel-consumption and emission measurements and the VT-Micro model estimates in an attempt to estimate the validity of the VT-Micro model for the analysis of vehicle cruising and acceleration. The authors found consistency between field measurements and model predictions for the emissions-cruise speed curves for the different pollutants. In addition, in-field fuel consumption and emissions were compared against the VT-Micro estimates for aggressive, normal, and mild accelerations. A high level of consistency was also found between measurements and model predictions. The VT-Micro model however, was found to underestimate emissions following a hard acceleration event during the enrichment phase.

The VERSIT+LD microscopic model for light-duty vehicles is based on data obtained from chassis dynamometer tests using speed-time profiles that reflect real-world conditions. Currently, the model is based on approximately 12,000 emission tests (as opposed to COPERT III which is based on approximately 2,800 tests). VERSIT+LD is a statistical model that calculates emissions based on a number of characteristics of the drive cycle (number of stops, acceleration, acceleration power, change in acceleration, etc.). Input data needed include speed-time profiles, traffic activity data, proportion of vehicles in a cold start, and air conditioning use. VERSIT+ was found to generate comparable EFs as the average-speed model, COPERT III during average conditions (Smit et al., 2007).

Linking the average speed output from traditional traffic assignment models with microscopic emission modelling was one of the objectives behind the development of the Edmonton’s emission model, CALMOB6, developed at the University of Alberta. CALMOB6 includes a fleet model for Edmonton, classified in the same manner as the USEPA’s MOBILE6 fleet. Using information from EMME/2, which includes link description (type, length, volume delay function, maximum speed) and description of traffic on that link (volume, average speed), CALMOB6 internally develops a traffic motion model for each vehicle type based on four main classes of traffic motion. These include; 1) “no delay”: vehicles drive at maximum link speed; 2) “some stops”: some vehicles cruise and others make one stop and possibly idle; 3) “all stop once”: all vehicles make a complete stop with an idle time of less that 30 seconds; and 4)
“congested”: vehicles make more than one stop. CALMOB6 simulates the traffic motion such that the speed trace matches the average speed for every link. Based on the simulated speed traces, emissions are estimated by calculating vehicle tractive power traces first (the tractive force being a function of rolling resistance, slope resistance, aerodynamic resistance, and acceleration); then, by looking-up emissions corresponding to tractive power values using emission functions. Some of the latter were constructed using laboratory dynamometer testing at the University of Alberta (Busawon and Checkel, 2006).

The USEPA forthcoming Multiscale Motor Vehicle and Equipment Emission System (MOVES) model, is intended to replace macro-, meso-, and micro- level emission models with a single comprehensive modelling system that can accommodate the three levels of analysis. At the macroscale total activity inputs will be needed for the entire country (the default domain) and will be allocated to the county level. The mesoscale level requires that the user supply information at the link-level. The microscale level would require detailed data at the link and intersection level. MOVES uses the Vehicle Specific Power (VSP) which combines numerous physical factors influential to vehicle fuel consumption and emissions: vehicle speed, acceleration, road grade, and road load parameters such as aerodynamic drag and rolling resistance. The core of the model will be a database of instantaneous vehicle emission measurements used to derive EFs at all levels of analysis. Driving cycles (expressed as second by second vehicle speed) can be converted to VSP in each second, along with input factors such as road grade, rolling resistance, and wind speed thus allowing for the estimations of emissions. An important element of MOVES will be the quantification, where possible, of uncertainty and variability by developing a utility which would apply Monte Carlo analysis to generate uncertainty estimates of model results (Koupal et al., 2003).

7.3.2.2 Implementations of traffic microsimulation and instantaneous emissions

Ishaque and Noland (2007) analyze pedestrian exposure to vehicle emissions with emphasis on signalized intersections. The authors conducted a microsimulation of vehicle and pedestrian movements (both coded in VISSIM) by dividing the network into 42 links. Vehicle emissions were then estimated based on instantaneous speeds, accelerations, and decelerations using the CMEM vehicle emission model supplemented with a database of average speed EFs. Following
the generation of emissions, the California Line Source Model 3 with Queuing and Hot Spot Calculation (CAL3QHC) was selected to conduct pollutant dispersion. The resulting pollutant concentrations were then used to assess pedestrian exposure. Results showed that the longer signal lengths that would smooth traffic flow decrease total emissions but cause increased pedestrian delay at crossings and hence longer exposure times to pollutant concentrations. Pedestrian exposure on sidewalks was found to be lower than that at crossings on main roads. The authors concluded that long signal cycles resulting in lower overall emissions are beneficial to pedestrians walking on sidewalks but not for those waiting at crossings. Clearly policies looking at traffic management and signal timings should reduce the overall exposure of pedestrians throughout their journey composed both of walking and waiting at crossings. Authors also discussed exposure of vehicle occupants which is likely to be higher inside the vehicle.

Panis et al. (2006) assessed the effect of speed management on emissions caused by acceleration and deceleration of vehicles. For this purpose, an instantaneous emission model was integrated with a microscopic traffic simulation model. The DRACULA (Dynamic Route Assignment Combining User Learning and microsimulAtion) traffic microsimulation model was used which updates speeds and positions of individual vehicles at a fixed time increment of one second. In DRACULA, vehicles are moved through the network based on a car-following model, a gap-acceptance model, lane-changing rules, and traffic regulations at intersections. The car-following model represents the interaction among vehicles in a single traffic stream whereby the behaviour or “response” of a vehicle is based on the behaviour or “stimulus” from the vehicle(s) in front. Following traffic simulation, emissions of VOC, NOx, CO2, and PM were modelled based on second-by-second emission functions developed through actual measurements of several instrumented vehicles driving in real urban traffic conditions (excluding highway traffic). A total of 25 vehicles were measured in order to develop the database. The integrated model (traffic and emissions) was used to test the effect of a new traffic management technology aiming at reducing traffic speeds in an overall urban network. Results showed that the reduction in overall speed (which is expected to decrease emissions) led to an increase in the frequency of acceleration and deceleration in the network thus resulting in an insignificant effect on overall emissions. Similar results were found by Coelho et al. (2005) who assessed the effect of traffic signals, installed on highways and serving as speed reduction devices, on vehicle emissions.
They used a modal emissions approach that categorizes vehicle operation into four modes: idle, acceleration, deceleration, and cruise. Average emission rates for each mode were based on on-board measurements in one gasoline-powered vehicle. The amount of time spent in each one of the four modes was multiplied by the corresponding emission rate to obtain total emissions. The authors found that the effectiveness of such signals at reducing high-speed crashes was associated with an increase in vehicle emissions due to the resulting speed change cycles for approaching vehicles, queue formations, and increase in the frequency of delays. By using a different approach (measurement and modelling) to assess the effect of speed restriction zones on air quality, Owen (2005) supports the results obtained by Panis et al. (2006) and Coelho et al. (2005) that the air quality changes after the implementation of the speed restriction zones are insignificant.

7.4 Description of Mobile6.2

The selected model for derivation of EFs for the GTA fleet was Mobile6.2. Mobile is a software program designed by the USEPA to estimate emission rates for the motor vehicle fleet under a range of conditions. Mobile6.0 was released in January, 2002 and was the latest in a series of Mobile models dating back to 1978 and was the first update in Mobile since the release of Mobile5b in 1996. The revision of Mobile5b was based both on new data and a new understanding of vehicle emission processes thus leading to improved estimates of vehicle emissions by Mobile6.0, which in some cases, are significantly different from the emissions estimated with Mobile5b. The major improvement in Mobile6.2 with respect to its predecessor, Mobile5b, is the ability of the model to estimate and report emissions on an hourly basis, in addition to the standard daily emission estimates. This allows the model to provide more precise output that accounts for the time of day that vehicle emissions occur. As will be seen later in this document, such an improvement requires considerable vehicle activity information, mainly on an hourly basis. Mobile6.2 is the first and latest update to Mobile6.0/6.1 adding the capability to estimate PM and mobile source air toxics emissions.
7.4.1 Pollutants
Mobile6.2 calculates EFs for HC, CO, NOx, CO2, SO2, NH3, brake and tire wear PM, as well as hazardous air pollutants (HAP) (Table 7.1). Depending on the user specification, Mobile6.2 can express HC as total hydrocarbons (THC), non methane hydrocarbons (NMHC), volatile organic compounds (VOC), total organic gases (TOG), or non methane organic gases (NMOG) (Table 7.2). Note that CO2 emissions are estimated simplistically by Mobile6.2, based on fuel economy performance estimates; as such, they are not adjusted for speed, temperature, fuel content, or the effects of inspection and maintenance (I/M) programs (USEPA, 2003a).

Table 7.1 Mobile6.2 pollutant categories (USEPA, 2003a)

<table>
<thead>
<tr>
<th>Number</th>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>HC</td>
<td>Hydrocarbons (gaseous)</td>
</tr>
<tr>
<td>2</td>
<td>CO</td>
<td>Carbon monoxide (gaseous)</td>
</tr>
<tr>
<td>3</td>
<td>NOx</td>
<td>Oxides of nitrogen (gaseous)</td>
</tr>
<tr>
<td>4</td>
<td>CO2</td>
<td>Carbon dioxide (gaseous)</td>
</tr>
<tr>
<td>5 thru 6</td>
<td>(reserved)</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>SO4</td>
<td>Sulfate portion of exhaust particulate</td>
</tr>
<tr>
<td>8</td>
<td>OCARBON</td>
<td>Organic carbon portion of diesel exhaust particulate</td>
</tr>
<tr>
<td>9</td>
<td>ECARBON</td>
<td>Elemental carbon portion of diesel exhaust particulate</td>
</tr>
<tr>
<td>10</td>
<td>GASPM</td>
<td>Total carbon portion of gasoline exhaust particulate</td>
</tr>
<tr>
<td>11</td>
<td>Lead</td>
<td>Lead portion of exhaust particulate</td>
</tr>
<tr>
<td>12</td>
<td>SO2</td>
<td>Sulfur dioxide (gaseous)</td>
</tr>
<tr>
<td>13</td>
<td>NH3</td>
<td>Ammonia (gaseous)</td>
</tr>
<tr>
<td>14</td>
<td>Brake</td>
<td>Brake wear particulate</td>
</tr>
<tr>
<td>15</td>
<td>Tire</td>
<td>Tire wear particulate</td>
</tr>
<tr>
<td>16</td>
<td>BENZ</td>
<td>Benzene</td>
</tr>
<tr>
<td>17</td>
<td>MTBE</td>
<td>Methyl tertiary butyl ether</td>
</tr>
<tr>
<td>18</td>
<td>BUTA</td>
<td>1,3-butadiene</td>
</tr>
<tr>
<td>19</td>
<td>FORM</td>
<td>Formaldehyde</td>
</tr>
<tr>
<td>20</td>
<td>ACET</td>
<td>Acetaldehyde</td>
</tr>
<tr>
<td>21</td>
<td>ACRO</td>
<td>Acrolein</td>
</tr>
</tbody>
</table>
Table 7.2 Mobile6.2 hydrocarbon categories (USEPA, 2003a)

<table>
<thead>
<tr>
<th>Number</th>
<th>Abbreviation</th>
<th>Description</th>
<th>Includes FID HC</th>
<th>Includes methane</th>
<th>Includes ethane</th>
<th>Includes aldehydes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>THC</td>
<td>Total Hydrocarbons</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>2</td>
<td>NMHC</td>
<td>Non-Methane Hydrocarbons</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>VOC</td>
<td>Volatile Organic Compounds</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>4</td>
<td>TOG</td>
<td>Total Organic Gases</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>5</td>
<td>NMOG</td>
<td>Non-Methane Organic Gases</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

FID HC = Flame Ionization Detectable hydrocarbon

7.4.2 Emission types

Beside exhaust running emissions, which constitute the major part of motor vehicle emissions, Mobile6.2 calculates emissions for start, hot soak, diurnal, resting losses, running losses, crankcase, and refuelling conditions (USEPA, 2003a). A description of each emission type is presented in Table 7.3 in addition to a listing of the major USEPA publications addressing the specific emission type.

7.4.3 Vehicle fleet

Mobile6.2 covers a 25-year range of vehicle ages and calculates EFs for 28 vehicle types (Table 7.4) corresponding to 16 composite classes (Figure 7.5). Vehicle classes include light-duty gasoline vehicles (LDGV), light-duty gasoline trucks (LDGT), heavy-duty gasoline vehicles (HDGV), light-duty diesel vehicles (LDDV), light-duty diesel trucks (LDDT), heavy-duty diesel vehicles (HDDV), motorcycles (MC), heavy-duty gasoline buses (HDGB), heavy-duty diesel transit and urban buses (HDDBT), and heavy-duty diesel school buses (HDDBS).
Table 7.3 Description of Mobile6.2 emission types

<table>
<thead>
<tr>
<th>Emission</th>
<th>Description</th>
<th>Addressed in</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exhaust running</td>
<td>Refer to emissions which exit a vehicle’s tailpipe while the vehicle is operating in a warmed-up condition. Exclude emissions occurring during a vehicle start and warm-up.</td>
<td>USEPA, 2004a, USEPA, 2003a, USEPA, 2002a, USEPA, 2001k, USEPA, 2001m, USEPA, 2001x</td>
</tr>
<tr>
<td>Start</td>
<td>Refer to engine start emissions. Two types of starts exist: cold and hot starts.</td>
<td>USEPA, 2004a, USEPA, 2003a, USEPA, 2002c, USEPA, 2001w, USEPA, 2001x</td>
</tr>
<tr>
<td>Hot soak emissions</td>
<td>Refer to hydrocarbon losses from fuel vapours in the intake manifold and fuel system, driven off the vehicle by the heat of the engine immediately after shut down. Usually due to small leaks in the evaporative emission control system (joints, lines, valves) and permeation of the fuel hoses and tank. Fuel tank temperature is usually close to ambient but can increase in fuel injected vehicles due to fuel returning from the hot engine compartment. Typically, tank temperatures in fuel injected vehicles can exceed ambient temperatures by 5 to 15°F. Hot soak emissions are not a direct function of ambient temperature. If the vehicle is restarted, the full hot soak effect is interrupted, resulting in fewer hot soak emissions.</td>
<td>USEPA, 2004a, USEPA, 2003a, USEPA, 2001f, USEPA, 2001h, USEPA, 2001i</td>
</tr>
<tr>
<td>Diurnal emissions</td>
<td>Refer to hydrocarbon losses from fuel vapors driven off the vehicle from the increasing temperature of the fuel in the tank and other locations on the vehicle while the engine is shut down and during times of day when the ambient temperature is rising. If the vehicle is restarted, the full diurnal effect is interrupted, resulting in fewer diurnal emissions.</td>
<td>USEPA, 2004a, USEPA, 2003a, USEPA, 2001c, USEPA, 2001d, USEPA, 2001e, USEPA, 2001g, USEPA, 2001n</td>
</tr>
<tr>
<td>Resting losses</td>
<td>Small but continuous seepage and minor leakage of gasoline vapor through faulty connections, permeable hoses, and other components of the fuel system.</td>
<td>USEPA, 2004a, USEPA, 2003a, USEPA, 2001c, USEPA, 2001g</td>
</tr>
<tr>
<td>Running losses</td>
<td>Evaporative emissions which have escaped from a vehicle while the engine is operating. May appear from the evaporative canister, the fuel inlet, the top of the gas tank, and other spots where the integrity of the evaporative system has broken down or the purge system has become inoperative. May be an artifact of a particular evaporative system design or the result of poor maintenance. Because of greater heating of the fuel and evaporative system on longer trips, running loss emissions are not constant throughout a trip. The rate is assumed to continually increase as a function of trip length until it reaches a plateau at a trip length of about 50 to 60 minutes.</td>
<td>USEPA, 2004a, USEPA, 2003a, USEPA, 2001i, USEPA, 2001m</td>
</tr>
<tr>
<td>Crankcase emissions</td>
<td>Evaporative blow-by emissions, resulting primarily from defective positive crankcase ventilation (PCV) systems.</td>
<td>USEPA, 2004a, USEPA, 2003a</td>
</tr>
<tr>
<td>Refuelling emissions</td>
<td>Vapours that escape into the atmosphere when incoming liquid fuel displaces vapours in the vehicle fuel tank.</td>
<td>USEPA, 2004a, USEPA, 2003a</td>
</tr>
</tbody>
</table>
Table 7.4 Mobile6.2 vehicle classification (USEPA, 2003a)

<table>
<thead>
<tr>
<th>Number</th>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>LDGV</td>
<td>Light-Duty Gasoline Vehicles (Passenger Cars)</td>
</tr>
<tr>
<td>2</td>
<td>LDGT1</td>
<td>Light-Duty Gasoline Trucks 1 (0-6,000 lbs. GVWR, 0-3,750 lbs. LVW)</td>
</tr>
<tr>
<td>3</td>
<td>LDGT2</td>
<td>Light-Duty Gasoline Trucks 2 (0-6,000 lbs. GVWR, 3,751-5,750 lbs. LVW)</td>
</tr>
<tr>
<td>4</td>
<td>LDGT3</td>
<td>Light-Duty Gasoline Trucks 3 (6,001-8,500 lbs. GVWR, 0-5,750 lbs. ALVW)</td>
</tr>
<tr>
<td>5</td>
<td>LDGT4</td>
<td>Light-Duty Gasoline Trucks 4 (6,001-8,500 lbs. GVWR, greater than 5,751 lbs. ALVW)</td>
</tr>
<tr>
<td>6</td>
<td>HDGV2b</td>
<td>Class 2b Heavy-Duty Gasoline Vehicles (8,501-10,000 lbs. GVWR)</td>
</tr>
<tr>
<td>7</td>
<td>HDGV3</td>
<td>Class 3 Heavy-Duty Gasoline Vehicles (10,001-14,000 lbs. GVWR)</td>
</tr>
<tr>
<td>8</td>
<td>HDGV4</td>
<td>Class 4 Heavy-Duty Gasoline Vehicles (14,001-16,000 lbs. GVWR)</td>
</tr>
<tr>
<td>9</td>
<td>HDGV5</td>
<td>Class 5 Heavy-Duty Gasoline Vehicles (16,001-19,500 lbs. GVWR)</td>
</tr>
<tr>
<td>10</td>
<td>HDGV6</td>
<td>Class 6 Heavy-Duty Gasoline Vehicles (19,501-26,000 lbs. GVWR)</td>
</tr>
<tr>
<td>11</td>
<td>HDGV7</td>
<td>Class 7 Heavy-Duty Gasoline Vehicles (26,001-33,000 lbs. GVWR)</td>
</tr>
<tr>
<td>12</td>
<td>HDGV8a</td>
<td>Class 8a Heavy-Duty Gasoline Vehicles (33,001-60,000 lbs. GVWR)</td>
</tr>
<tr>
<td>13</td>
<td>HDGV8b</td>
<td>Class 8b Heavy-Duty Gasoline Vehicles (&gt;60,000 lbs. GVWR)</td>
</tr>
<tr>
<td>14</td>
<td>LDDV</td>
<td>Light-Duty Diesel Vehicles (Passenger Cars)</td>
</tr>
<tr>
<td>15</td>
<td>LDDT12</td>
<td>Light-Duty Diesel Trucks 1 and 2 (0-6,000 lbs. GVWR)</td>
</tr>
<tr>
<td>16</td>
<td>HDDV2b</td>
<td>Class 2b Heavy-Duty Diesel Vehicles (8,501-10,000 lbs. GVWR)</td>
</tr>
<tr>
<td>17</td>
<td>HDDV3</td>
<td>Class 3 Heavy-Duty Diesel Vehicles (10,001-14,000 lbs. GVWR)</td>
</tr>
<tr>
<td>18</td>
<td>HDDV4</td>
<td>Class 4 Heavy-Duty Diesel Vehicles (14,001-16,000 lbs. GVWR)</td>
</tr>
<tr>
<td>19</td>
<td>HDDV5</td>
<td>Class 5 Heavy-Duty Diesel Vehicles (16,001-19,500 lbs. GVWR)</td>
</tr>
<tr>
<td>20</td>
<td>HDDV6</td>
<td>Class 6 Heavy-Duty Diesel Vehicles (19,501-26,000 lbs. GVWR)</td>
</tr>
<tr>
<td>21</td>
<td>HDDV7</td>
<td>Class 7 Heavy-Duty Diesel Vehicles (26,001-33,000 lbs. GVWR)</td>
</tr>
<tr>
<td>22</td>
<td>HDDV8a</td>
<td>Class 8a Heavy-Duty Diesel Vehicles (33,001-60,000 lbs. GVWR)</td>
</tr>
<tr>
<td>23</td>
<td>HDDV8b</td>
<td>Class 8b Heavy-Duty Diesel Vehicles (&gt;60,000 lbs. GVWR)</td>
</tr>
<tr>
<td>24</td>
<td>MC</td>
<td>Motorcycles (Gasoline)</td>
</tr>
<tr>
<td>25</td>
<td>HDGB</td>
<td>Gasoline Buses (School, Transit and Urban)</td>
</tr>
<tr>
<td>26</td>
<td>HDDBT</td>
<td>Diesel Transit and Urban Buses</td>
</tr>
<tr>
<td>27</td>
<td>HDDBS</td>
<td>Diesel School Buses</td>
</tr>
<tr>
<td>28</td>
<td>LDDT34</td>
<td>Light-Duty Diesel Trucks 3 and 4 (6,001-8,500 lbs. GVWR)</td>
</tr>
</tbody>
</table>
Table 7.5 Mobile6.2 composite vehicle classes (USEPA, 2003a)

<table>
<thead>
<tr>
<th>Number</th>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>LDV</td>
<td>Light-Duty Vehicles (Passenger Cars)</td>
</tr>
<tr>
<td>2</td>
<td>LDT1</td>
<td>Light-Duty Trucks 1 (0-6,000 lbs. GVWR, 0-3,750 lbs. LVW)</td>
</tr>
<tr>
<td>3</td>
<td>LDT2</td>
<td>Light-Duty Trucks 2 (0-6,000 lbs. GVWR, 3,751-5,750 lbs. LVW)</td>
</tr>
<tr>
<td>4</td>
<td>LDT3</td>
<td>Light-Duty Trucks 3 (6,001-8,500 lbs. GVWR, 0-5,750 lbs. ALVW)</td>
</tr>
<tr>
<td>5</td>
<td>LDT4</td>
<td>Light-Duty Trucks 4 (6,001-8,500 lbs. GVWR, 5,751 lbs. and greater ALVW)</td>
</tr>
<tr>
<td>6</td>
<td>HDV2B</td>
<td>Class 2b Heavy-Duty Vehicles (8,501-10,000 lbs. GVWR)</td>
</tr>
<tr>
<td>7</td>
<td>HDV3</td>
<td>Class 3 Heavy-Duty Vehicles (10,001-14,000 lbs. GVWR)</td>
</tr>
<tr>
<td>8</td>
<td>HDV4</td>
<td>Class 4 Heavy-Duty Vehicles (14,001-16,000 lbs. GVWR)</td>
</tr>
<tr>
<td>9</td>
<td>HDV5</td>
<td>Class 5 Heavy-Duty Vehicles (16,001-19,500 lbs. GVWR)</td>
</tr>
<tr>
<td>10</td>
<td>HDV6</td>
<td>Class 6 Heavy-Duty Vehicles (19,501-26,000 lbs. GVWR)</td>
</tr>
<tr>
<td>11</td>
<td>HDV7</td>
<td>Class 7 Heavy-Duty Vehicles (26,001-33,000 lbs. GVWR)</td>
</tr>
<tr>
<td>12</td>
<td>HDV8A</td>
<td>Class 8a Heavy-Duty Vehicles (33,001-60,000 lbs. GVWR)</td>
</tr>
<tr>
<td>13</td>
<td>HDV8B</td>
<td>Class 8b Heavy-Duty Vehicles (&gt;60,000 lbs. GVWR)</td>
</tr>
<tr>
<td>14</td>
<td>HDBS</td>
<td>School Buses</td>
</tr>
<tr>
<td>15</td>
<td>HDBT</td>
<td>Transit and Urban Buses</td>
</tr>
<tr>
<td>16</td>
<td>MC</td>
<td>Motorcycles (All)</td>
</tr>
</tbody>
</table>

LVW = Loaded Vehicle Weight
ALVW = Alternative Loaded Vehicle Weight: The adjusted loaded vehicle weight is the numerical average of the vehicle curb weight and the gross vehicle weight rating (GVWR)
GVWR = Gross vehicle weight rating

7.4.4 Basic emission rates

Mobile6.2 basic emission rates (BER) are based on the federal test procedure (FTP) which has been the standard vehicle test cycle adopted in the US to determine compliance of light duty vehicles and light duty trucks with federal emission standards. The FTP is conducted on preproduction vehicles during the motor vehicle certification process, as well as to test production line and in-use vehicles for compliance with emission standards. The principal test elements are designed to test the evaporative and exhaust emissions (HC, CO, NOx, CO2) under several simulated situations. Evaporative emissions are tested after heating the fuel tank to simulate heating by the sun (the diurnal test) and again after the car has been driven and parked with a hot engine (the hot soak test). Exhaust emissions are measured by driving the vehicle (placed on a dynamometer) on a simulated urban driving trip under two conditions: with a cold start designed to represent a morning startup after a long soak (a period of nonuse) and then following a hot start that takes place after the cold start test while the engine is still hot. In
addition to evaporative and exhaust emissions, the FTP is also used in evaluating fuel economy (USEPA, 1993a; b).

The driving cycle used for the FTP was derived in the 1960’s to simulate a vehicle operating over a road route in Los Angeles believed to be representative of typical home to work commuting. By trial and error, a specific street route in the vicinity of the California Vehicle Pollution Laboratory was found to match the average speed/load distribution on the commute trips. That 12 mile route was called the “LA4”. Following additional assessments of driving patterns in Los Angeles, the average trip length was estimated to be 7.5 miles. The shortened route, designated the LA4-S3, was 7.486 miles in length with an average speed of 19.8 mph. The final version of the cycle was designated the LA4-S4 cycle and is 7.46 miles in length with an average speed of 19.6 mph. Finally, this cycle was referred to as the “LA4” or the Urban Dynamometer Driving Schedule (UDDS). It has been the standard driving cycle for the certification of light-duty vehicles and light-duty trucks since the 1972 model year (USEPA, 1993a; b).

Developed in the late sixties, the FTP had been adopted for more than 20 years before a requirement was issued by the Clean Air Act (CAA) amendments in 1990 to revise it. The USEPA completed its review process and published its findings in 1993 (USEPA, 1993a). The research program included 1) vehicle monitoring to determine how vehicles were actually driven; 2) analysis of data from vehicle monitoring to determine cycle, trip information and the impacts of different factors on driving behaviour and to develop driving cycles that represent the complete range of actual driving behaviour; and 3) assessment of the emission impact of driving behaviour through the development of a computer simulation model and vehicle testing (USEPA, 1993b).

The analysis of data indicated that significant differences existed between actual driving behaviour and the FTP. As a result, the USEPA determined that it was necessary to revise the existing test procedures to ensure that motor vehicles were indeed tested under circumstances reflecting actual driving conditions. On October 22, 1996; the final rule of FTP revision was published in the US federal register (Federal Register, 1996). The rule had revised the tailpipe emissions portion of the FTP and would be applicable to all light-duty vehicles and light-duty
trucks starting with the 2000 model year (2002 for light trucks over 6000 Gross vehicle Weight Rating) (USEPA, 1996). The primary new element of the rulemaking was a supplemental FTP (SFTP) designed to address the shortcomings with the FTP in the representation of 1) aggressive driving including high speed (up to 80 mph as compared to 57 mph for the old test cycle) or high acceleration; 2) rapid speed fluctuations; 3) driving behaviour following start up; and 4) use of air conditioning. The proposed test procedure would not replace existing test procedures, but rather add to them (USEPA, 1993a). Mobile6.2 calculates adjustments to the BER for conditions that differ from FTP. Adjustments are used both to reflect how an in-use vehicle population is different from the tested samples and for conditions different from those used in the testing program (USEPA, 2001j).

7.4.5 Input data

Mobile6.2 estimates emissions based on a wide range of input data including 1) external conditions, 2) environmental effects on air conditioning, 3) vehicle fleet characteristics, 4) activity data, 5) state programs, and 6) fuel data. The components of the six input categories are listed in Table 7.6 and detailed in Appendix B.

Table 7.6 Mobile6.2 input data

<table>
<thead>
<tr>
<th>External conditions</th>
<th>Environmental effects on A/C</th>
<th>Vehicle fleet characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calendar year</td>
<td>Cloud cover</td>
<td>Vehicle registrations</td>
</tr>
<tr>
<td>Evaluation month</td>
<td>Peak sun</td>
<td>Diesel fractions</td>
</tr>
<tr>
<td>Min/max daily temp.</td>
<td>Sunrise/sunset</td>
<td>Annual mileage</td>
</tr>
<tr>
<td>Hourly temp.</td>
<td>Hourly relative humidity</td>
<td>Natural gas vehicles fractions</td>
</tr>
<tr>
<td>Altitude</td>
<td>Barometric pressure</td>
<td>Emission factors for Natural Gas vehicles</td>
</tr>
<tr>
<td>Absolute humidity</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Vehicle activity</th>
<th>State programs</th>
<th>Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>VMT by vehicle class/facility/hour/speed</td>
<td>Inspection and Maintenance</td>
<td>Fuel program</td>
</tr>
<tr>
<td>Average speed</td>
<td>Anti-tampering</td>
<td>Sulfur content of gasoline</td>
</tr>
<tr>
<td>Starts per day</td>
<td></td>
<td>Sulfur content of diesel</td>
</tr>
<tr>
<td>Soak distribution</td>
<td></td>
<td>Oxygenated fuels</td>
</tr>
<tr>
<td>Hot soak activity</td>
<td></td>
<td>Gasoline Reid Vapor Pressure</td>
</tr>
<tr>
<td>Diurnal soak activity</td>
<td></td>
<td>Season for reformulated gasoline calculation</td>
</tr>
<tr>
<td>Weekday trip length distribution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weekend trip length distribution</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
7.5 Scope of emissions modelling

In this study, Mobile6.2C is used to estimate emissions of HC, CO, NOₓ, and CO₂ for light-duty private vehicles which encompass light-duty gasoline vehicles (LDGV), as well as minivans and sports utility vehicles, together referred to as light-duty gasoline trucks (LDGT). There are many reasons associated with the focus on light-duty private vehicles, namely; a) data concerning commercial vehicles especially heavy-duty trucks is very fragmented and often confidential; b) the highest proportion of transport-related emissions of CO, CO₂, and HC and nearly half of transport-related emissions of NOₓ are generated by light-duty vehicles (EC, 2008a); and c) the most widely available data such as the Transportation Tomorrow Survey (TTS) (a large-scale travel survey conducted on a five year basis in the GTA) and TASHA pertain to private vehicles thereby providing a wider understanding of car ownership and travel patterns of households.

The methodology for emissions estimation involves three main components, namely; 1) development of EFs for exhaust and evaporative emissions; 2) generation of travel activity data; and 3) combination of EFs with travel data. The output is hourly link-based exhaust and start emissions in the GTA, and hourly zone-based evaporative emissions for each traffic analysis zone (TAZ) within the GTA. Figure 7.1 illustrates the overall modelling methodology. Clearly, travel activity data are used both as an input into Mobile6.2C and are linked with EFs derived from Mobile6.2C to generate total emissions. For example, the distribution of soak times allows Mobile6.2C to develop EFs for vehicle starts based on the amount of time vehicles are soaking thus enabling the model to account for hot and cold starts. Moreover, the number of vehicles soaking in every TAZ is linked with soak-based EFs to generate total evaporative emissions. Other data input in Mobile6.2C include attributes of fuels, I/M program, vehicle fleet, and external conditions. Look-up tables for EFs are divided into 1) exhaust and running losses, 2) starts, 3) hot soaks, and 4) other evaporative emissions. Exhaust emissions and running losses are generated as a function of road type, average link speed, and hour of the day. All EFs and travel activity data are developed for the year 2001, in conformity with the calendar year of the Mobile6.2C simulation.
Figure 7.1 Scope of emissions modelling
7.6 Development of emissions factors for the GTA fleet

The different emission types rely on EFs derived from Mobile6.2C, the Canadian version of Mobile6.2. Since the Mobile6.2 model was originally developed by the USEPA for estimation of US nationwide fleet emissions, it has default values reflecting the characteristics of the US vehicle fleet. As such, prior to the use of Mobile6.2, the model was retrofitted to reflect Canadian conditions in general and the GTA fleet in particular. Such an effort involved an alteration of the Mobile6.2 source code in addition to supplementing it with input data. Fundamental changes, referred to as coding changes, were conducted by Environment Canada to reflect Canadian differences in emission control technology for pre-1988 model year vehicles (EC, 2004). This section describes the input data describing the GTA vehicle fleet as well as the resulting EFs. Data for Mobile6.2C inputs listed in Figure 7.1 are generated. In a sensitivity analysis conducted for Mobile6.0, speed, registration distribution, mileage for individual vehicle classes, temperature, and fuel characteristics were found to be the most important inputs affecting emissions (USEPA, 2002d).

7.6.1 External conditions and environmental effects on air conditioning

Mobile6.2 can model EFs for calendar years 1952-2050 inclusive and evaluation months January or July reflecting winter and summer seasons. In this study, a winter scenario is modelled for 2001. As such, a distribution for hourly temperatures was input for January, 2001 as published by the National Climate Data and Information Archive (Climate Data Online) which is part of the Weather Office at Environment Canada. Beside ambient temperature, hourly distributions for relative humidity were extracted from the same source and input. Both temperature and humidity are significant external parameters. Humidity mostly affects NOX emissions since water vapour absorbs some of the heat of combustion in the engine, which in turn results in a reduction in NOX formation. Moreover, both humidity and temperature are combined by Mobile6.2 to create a heat index which is used to estimate air conditioning usage. As such, high humidity on hot days increases air conditioning usage which indirectly increases HC and CO emissions. Other external effects include cloud cover, peak sun, and sunrise/sunset. In this case, default values were used, as recommended by the USEPA (since such values are consistent with conditions for ozone formation).
7.6.2 Vehicle fleet characteristics

Vehicle fleet characteristics include age distribution, mileage accumulation rates, as well as diesel and natural gas vehicle fractions. Since only gasoline vehicles are modelled, the fractions of both diesel and natural gas fuelled vehicles are assumed to be zero. Mobile6.2 covers a 25-year range of vehicle ages. Age is a significant input and the USEPA recommends the development of local age distributions. In fact, the age distribution of the fleet affects estimates of the deterioration of vehicle emission control effectiveness as well as determines the fractions of the fleet that meet different emission standards. Local vehicle age distributions for the GTA were obtained from the 2001 Drive Clean data as presented in Figure 7.2.

![Vehicle age distribution for the GTA](drive-clean-age-distribution.png)

Figure 7.2 Vehicle age distribution for the GTA (starting from 0 to ≥24 years; all fractions add-up to 1) (Drive Clean Ontario, 2002)

The annual mileage accumulation rate reflects the number of miles driven per year; Mobile6.2 divides it by 365 to obtain the mileage driven per day. Depending on the type and age of a vehicle, the accumulation rate varies; in fact, older vehicles tend to be driven fewer miles per year than newer ones. Annual mileage accumulation affects the rate at which vehicle emission controls deteriorate as well as the relative emissions contributions of newer and older vehicles. Local mileage accumulation rates were also obtained from the 2001 Drive Clean data as presented in Figure 7.3.
7.6.3 Vehicle fuel characteristics

Vehicle fuel characteristics affecting Mobile6.2 emissions include sulphur content of gasoline, sulphur content of diesel fuel, oxygenated fuels, gasoline Reid Vapour Pressure (RVP), and effective season for reformulated gasoline (RFG) calculation.

Sulphur is a naturally occurring contaminant in petroleum used to refine gasoline. It is typically associated with a reduction in the performance of catalytic converters. Mobile6.2 explicitly accounts for the effects of the sulphur content of gasoline on the emission estimates for gasoline fuelled vehicles. Average and maximum gasoline fuel sulphur content values for calendar years 2000-2015 were input as obtained from EC (2002). In addition, one single value illustrating pre-1999 gasoline sulphur levels was input as 514.6ppm. Since diesel-fuelled vehicles are not modelled, then diesel sulphur levels were not input.

Typically, either ethers or alcohols are added to gasoline in order to add oxygen to the engine during combustion. This would moderate rich AFRs thus reducing exhaust emissions. According to the USEPA, if, together, oxygenated blends account for less than 2 percent of total gasoline sales within an inventory area, and if there is no mandatory or locally endorsed voluntary program for ether blends, then oxygenated fuels need not be explicitly modelled (USEPA,
For the purpose of this modelling exercise, gasoline oxygenates are assumed negligible in the GTA. The volatility of gasoline in Mobile6.2 is indicated by the RVP of the dispensed fuel. In the GTA, the RVP for the gasoline sold in 2001 was 14.7 pounds per square inch (psi) in the winter and 10.4 psi in the summer (EC, 2002). RFG is a US federal fuel emission performance specification program and assumed to be non-existent in the GTA.

7.6.4 Vehicle activity input data
Mobile6.2 default input data on trip lengths and activity factors were collected through an instrumented vehicle study. In this study, data loggers were installed on randomly selected vehicles to monitor vehicle usage (including starts, ends, and trip lengths throughout the day). These characteristics allowed for the derivation of several vehicle activity distributions namely; 1) VMT by vehicle class, 2) VMT by facility, 3) VMT by hour, 4) speed VMT, 5) starts per day, 6) distribution of vehicle starts during the day, 7) weekday trip length distribution, 8) soak distribution, 9) hot soak activity, and 10) diurnal soak activity. The availability of TASHA, a disaggregated activity-based microsimulation model of travel demand, provides vehicle activity parameters that would otherwise have to be collected through instrumented vehicle studies.

7.6.4.1 Problem formulation
TASHA microsimulates a 24-hour schedule formation process for residents of the GTA and outputs a list of individual trips (and associated trip chains) per household. The most significant characteristics of each person-trip are: purpose of origin, purpose of destination, origin zone, destination zone, start time, mode, and number of household vehicles. For the purpose of emissions estimation, only car trips were selected from TASHA output. The database of auto trips contains 61,777 households with a total number of 260,221 person-trips. Recent model validation has shown considerable conformity between TASHA and TTS data (Roorda et al., 2007). While TASHA predicts the mode for each conducted trip, it does not attempt to allocate the different cars owned by a household to specific trips. For the purpose of extracting distributions on a per vehicle basis; there is a need to attach specific household cars to person-trips in order to convert the list of person-trips into a list of vehicle-trips.
7.6.4.2 Car allocation module

The car allocation module attempts to decide “which car” was used for “which trip” by “which individual” based on the total number of cars available per household as well as the start and end times of the individual trips. The boundary of the car allocation is considered to be the household where decisions are assumed to occur. The module was developed using a deterministic rule-based approach due to the lack of information on vehicle attributes. While this initial version of the car allocation module relies on a set of rules governing car sharing on a household level, a better behavioural representation could be incorporated in this module when TASHA is fitted with the capability of predicting the types of vehicles owned by households (Roorda et al., 2006b). At that stage, the car allocation module could attempt to link person attributes with vehicle attributes to improve the car allocation process.

The car allocation process is based on the following assumptions:

- Cars are allocated on the basis of entire trip chains (starting and ending at home).
- In the absence of information on the types of vehicles owned by households, all cars are assumed to be the same (type, age, model, fuel, etc.) only differentiated by a specific ID.
- The first car driven by an individual becomes the “preferred car” whereby on subsequent trip chains, this specific car will be requested first and, if in-use, another car will be released. This respects the principle of car ownership within households whereby typically people drive their “own car” and do not choose randomly any available car.
- Each individual will drive his/her preferred car unless it is not available; in this case, he/she will drive the first car on the list.

The car allocation module is developed in an object-oriented platform using the Python programming language. The module includes two classes namely, a person class and a car class. The person class has two attributes: the number of household vehicles and a preferred car. The attributes of the car class include: an ID, a list of trips defined by start and end times, and availability. The functions of the car class include: request a car and release a car. For each of the two classes, person objects and car objects are instantiated based on the total number of persons and cars in the household and stored in lists: a list of persons and a list of cars. The TASHA data

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on trips for each individual (in each household) is read as a list of lists whereby each household contains a list of trip chains with their associated start times, end times, and persons. Next, the list of trip chains is converted into a list of events whereby the start of a trip is considered as an event and the end of a trip is considered as a separate event. This doubles the number of items on the list. The last step in data manipulation includes the sorting of events by time of day into an events queue. As a result, starts or ends of trips (corresponding to requests or releases of cars) are arranged in increasing order of time. The simulation starts by reading the first event in the events queue; this event is always a car request. The person is allocated the first car on the car list; this car’s availability attribute is then set to “False” or unavailable. This car also becomes the person’s preferred car whereby if the same person places another request for a car during the day; this specific car will be released from the list, if available. The second event in the queue may be a car release (or end of a trip chain) from the first person or a car request by another person. In the case of a car release, the car’s availability attribute will be set to “True” whereby this car will be available for other trip chains. The process of requesting and releasing cars will continue until the last event in the queue; this event is always a car release. For one household; the module outputs for each car, a list of trip chains and their associated persons. As such, the TASHA output of trip chains, is converted into a list of car chains. In order to run the module for multiple households, a list of households is created and the car allocation module is run for each household on the list. Model output is printed on the screen and written into an ASCII file.

The module was verified through different checks; 1) all cars, at the end of the simulation, must have a status of “available” since TASHA imposes that at the end of the day “everyone goes home”; 2) the number of times and types of households for which the driven car is the same as the preferred car; and 3) the car availability attribute must turn to “True” every time a car is released. Following car allocation, soak times are calculated for each car and trip. An engine soak time is defined as the time interval between 2 subsequent trips.

7.6.4.3 Vehicle activity distributions
Vehicle activity distributions were derived from both an EMME/2, 24-hour assignment of trips (weekday trip length distributions) and by allocating individual vehicles to trips in the database and post-processing the list of vehicles into start and soak distributions.
Vehicle Miles Travelled (VMT) fractions by vehicle class specify the fractions of total VMT that are accumulated by each of the vehicle classes. These fractions do not affect the EF of a specific vehicle class but only affect the weight of the emissions of a specific vehicle class on the average EF from all classes combined. Due to the lack of travel data for different vehicle classes, every car in TASHA is assumed to be an average between a LDGV and a LDGT based on Mobile6.2 defaults (USEPA, 2003a).

Weekday trip duration distributions are described by the percentage of VMT corresponding to different trip lengths (<10 min, 10-20min, 21-30 min, 31-40 min, 41-50 min, >51 min) for each hour of the day. These distributions are extracted from the EMME/2 trip assignment (Figure 7.4).

Soak time affects exhaust starts and exhaust running emissions; it is the time between engine turn-off and the next time it is started. The soak distribution is described by the fraction of vehicle starts following 69 soak time intervals (starting from 0.01-1min to >720min) for each hour of the day. For each hour, the 69 values should add-up to one. After constructing the list of vehicle-trips from the TASHA output, soak times were calculated for each vehicle as the end time minus the subsequent start time. Following the calculation of soak times, each vehicle was counted in the corresponding soak time/start time bin (Figure 7.5).
Hot soaks occur when fuel vapours escape from a hot vehicle that has just been turned off. In Mobile 6.2, the hot soak duration spans from a minimum of one second (instantaneously after the engine is off) to a maximum of one hour after which, the engine is assumed to attain ambient temperature. The emissions are highest immediately after the engine is shut down and decrease over time, reaching a baseline level in about an hour. The hot soak distribution describes the fraction of vehicles experiencing a hot soak of a given duration (1 to 60 minutes) at each hour of the day. Each value is a fraction between 0 and 1, and the 60 values must add up to one for each time period. A given hot soak could potentially be classified into one or two hourly groups depending on the duration of the hot soak, and whether it crossed a group interval boundary. For example, if a hot soak was from 8:20am to 8:40am, it is simply classified as a twenty-minute hot soak in hourly group 8-9am. If it was from 7:51 to 8:51, it is classified as a 9min hot soak.
between 7 and 8am and a 51min soak between 8 and 9am. Figure 7.6 presents the total number of hot soaks throughout the day; clearly most of the hot soaks occur around 8am and 6pm corresponding with the arrival time to work in the morning and home in the evening.

![Figure 7.6 Distribution of hot soaks throughout the day](image)

**Diurnal soaks** refer to HC losses from fuel vapours driven off the vehicle from the increasing temperature of the fuel in the tank and other locations on the vehicle while the engine is shut down and during times of day when the ambient temperature is rising. Due to the lack of multi-day activity information from TASHA, Mobile6.2 default diurnal soak distributions were used in this study.

**Engine start** emissions, especially those occurring after a cold start, account for a significant fraction of the emissions over a vehicle trip. Following the development of a list of trips and associated vehicle ID from TASHA, the number of trips for each vehicle is counted and an average number of trips/vehicle is calculated for the entire database. Mobile6.2 associates one start and one end for each trip therefore, the number of trips per vehicle is equal to the number of starts, on average: 2.34 starts per vehicle. The same database provides the distribution of vehicle starts throughout the day simply by grouping trip start times into 24 hourly bins and dividing the
number of starts for each hour by the total number of starts to obtain 24 fractions adding-up to one.

Figure 7.7 Fraction of vehicle starts throughout the day (the small "bump" at 3am is a result of the TASHA formulation which "forces everyone to go home" at the end of the day which is defined at 3:00-3:59am)

7.6.5 State programs
Mobile 6.2 can model two main types of programs namely, I/M and anti-tampering programs. The GTA vehicle fleet is subject to the Drive Clean I/M program. While the Drive Clean program includes a visual inspection of the emission control equipment, it may not be classified as an anti-tampering program per se. As such, the effects of an anti-tampering program are disregarded in the following model. The Drive Clean program consists of a mandatory exhaust emission test for both light duty and heavy duty vehicles. Light duty vehicles over 3 and under 20 years of age are subject to biennial inspections at 1,771 decentralized accredited facilities (68 test only, 1,435 test/repair, and 268 repair only). The emission test is an acceleration simulation mode (ASM), dynamometer test, coupled with a two-speed idle test for vehicles that cannot be tested on the dynamometer. If a vehicle fails it must be repaired; waivers are granted at the discretion of I/M authorities to vehicles that are unable to pass the test even after repairs exceeding 450$ are made (Drive Clean Ontario, 2002; ERG, 2005).
7.6.6 Development of emission factors

As illustrated in Figure 7.1, four look-up tables for EFs were developed by running Mobile6.2C for various scenarios and using the GTA-specific inputs described above. The first look-up table contains EFs for exhaust emissions and running losses. Exhaust emissions refer to emissions which exit a vehicle’s tailpipe while the vehicle is operating in a warmed up condition; running losses refer to evaporative emissions which have escaped from a vehicle while the engine is operating. The second look-up table contains EFs for start emissions which refer to engine emissions during start up. Those three types of emissions are assumed to occur on roadways and are output in grams per vehicle mile travelled (g/VMT). The third look-up table contains EFs for hot soaks which occur immediately after engine shut down due to small leaks in the evaporative emission control system. The fourth look-up table contains EFs for all other evaporative emissions: 1) diurnal emissions which occur during times of day when the ambient temperature is rising; 2) resting losses which include small but continuous seepage of gasoline vapour through faulty connections and other components of the fuel system; 3) crankcase emissions which occur from defective positive crankcase ventilation systems; and 4) refuelling emissions which occur when incoming liquid fuel displaces vapours in the vehicle fuel tank. Hot soaks and all other evaporative emissions include all types of HC emissions that do not depend on engine operation and are attributed to TAZs rather than roadway links; they are output in grams per vehicle (g/veh).

7.6.6.1 Exhaust and running losses emission factors

For exhaust emissions and running losses, the AVERAGE SPEED command in Mobile6.2C was used whereby one specific speed attributed to a specific roadway type was input as a scenario. A total of 60 speed-roadway type scenarios were modelled for each hour of the day, emission type, and pollutant. Speed categories amount to 15 and include: 2.5 miles per hour (mph), 5mph, 7.5mph, and 10 to $\geq 65$ mph in 5 mph increments. Roadway type categories amount to four and include: freeway, arterial, local, and ramp. Pollutants include HC (as VOC), CO, NOx, and CO2. A total of 11,520 EFs were calculated (15 speeds * 4 roadway types *24 hours * 4 pollutants * 2 emission types). These were grouped into one large look-up table. Note that Mobile6.2C assumes one speed for local roads and ramps and as such, their EFs are constant with respect to speed. Selected EFs are presented in Figure 7.8.
7.6.6.2 Start emission factors

A look-up table for start EFs was also developed. Since start emissions are neither roadway-specific nor speed-dependent, their look-up table was solely based on hour of the day and pollutant (VOC, CO, and NOx). Start emissions were modelled using additional vehicle activity data such as trip length distributions and soak durations. The trip chains derived from TASHA were used to construct soak duration distributions for each vehicle and therefore differentiate cold and hot starts for each TAZ and time of day (Section 7.6.4.3).

7.6.6.3 Evaporative emission factors

Soak based EFs (in grams/vehicle) per hour, reflect evaporative emissions that occur during soaking of vehicles. Since they only occur while the engine is off, they do not depend on speed or roadway type. Also, since they are only composed of HC, this reduces the dimension of the soak EF matrix to a single row with 24 columns, representing the different hours of the day. The difference between each hourly EF is mainly due to 1) ambient temperature, affecting fuel evaporation, and 2) soak time distribution within each hour. The latter entailed the development of soak time durations for the GTA within each hour of the day as described in Section 7.6.4.3. Earlier research has recognized the importance of developing regional and zone-specific soak-time duration distributions (Nair and Bhat, 2000). A total of two tables for soak EFs were developed in Mobile6.2C, namely; one table for hot soak EFs; and another table for all other evaporative emissions.
7.7 Generation of travel activity data

As illustrated in Figure 7.1, travel activity data, to be combined with EFs, was derived from TASHA (number of vehicles soaking and hot soaking) and EMME/2 (link based speeds and volumes). While Figure 7.1 shows output from TASHA -namely Origin-Destination matrices-used as input in EMME/2 for assignment; in fact, auto-based trip distribution matrices for the GTA were extracted from 2001, TTS data; accessible through the Joint Program in Transportation (JPINT) at the University of Toronto (DMG, 2003). These matrices could have been extracted from TASHA just as well. Recent model validation has shown considerable conformity between TASHA and TTS data (Roorda et al., 2007).

7.7.1 Link-based data

A total of 24 auto-trip matrices, representing each hour of the day were extracted from TTS data and assigned on the GTA network using EMME/2 (INRO, 1998); as such, 24 traffic assignments were conducted. The EMME/2 network representation for the GTA includes the same roadway classification as Mobile6.2C, namely: freeways, arterial roads, local roads, and freeway ramps. Trips originate and end at centroids of TAZs and local roads are only used as centroid connectors. The GTA auto network is composed of a total of 38,301 links including: 1,507 freeways; 27,287 arterials; 7,534 local roads; and 1,973 freeway ramps. Figure 7.9 presents the network and highlights the City of Toronto and the four regional municipalities which together make up the GTA. In addition, the City of Hamilton is represented and considered as part of the GTA for the purpose of this study.

The output of the EMME/2 assignment comprises speeds and volumes for each link on the network and each hour of the day taking into account interzonal trips only. Speeds obtained by EMME/2 were not post-processed. While research into different types of speed post-processors has shown that they generally reduce speeds generated by the travel demand model in already congested situations (thus increasing emissions) (Helali and Hutchinson, 1994; Dowling and Sakabardonis, 1993) different post-processors have had dissimilar impacts on mobile emission inventories (Bai et al., 2007) thus stressing the need for further research into the most appropriate post-processing method for computing on-road emission inventories. The current version of EMME/2 used for the GTA uses a modified Bureau of Public Roads (BPR) function that better
handles oversaturated travel times (Miller, 2004). Limited validation of the outputs indicated that the EMME/2 times are generally reasonably close to observed travel times within the GTA.

Travel data show the highest traffic volumes during morning and afternoon peak hours and lower volumes during off-peak. During the morning peak hour, arterial roads carry most of the VMT (around 51%) followed by freeways (around 39%), local roads (around 6%), and freeway ramps (around 4%). Figure 7.10 illustrates selected aggregated travel data extracted from EMME/2 and converted from VKT to VMT in order to make it compatible with Mobile6.2C EFs in g/VMT.
Figure 7.10 Selected aggregated travel data
7.7.2 Zone-based data

Using the same list of vehicle trips extracted from TASHA and used to develop soak duration distributions input into Mobile6.2C; the number of vehicles soaking in each zone and during each hour was calculated in addition to the length of the soak (derived from trip chaining information). Since TASHA predicts intrazonal trips, the resulting soak emissions take into account the effect of those trips while EMME/2 does not. For the purpose of this Chapter, this discrepancy was allowed to occur and intrazonal soaks were not discounted from the analysis. In addition, a list of vehicle hot soaks was developed whereby the number of vehicles undergoing a hot soak was estimated in each zone and each hour. Note that a given soak (or hot soak) could potentially be classified into one or two hourly groups depending on its duration, and whether it crosses a group interval boundary. For example, if a soak is from 7:51 to 8:51, it is classified as a 9min soak between 7 and 8am and a 51min soak between 8 and 9am. The number of zones in the GTA network is 1,677; each TAZ has a centroid. As discussed above, the zone centroid is considered to be the point of departure and end of trips.

7.8 Combining EFs with travel data

Following the generation of EF look-up tables and link-based speed and VMT, each link on the network is attached to an EF based on its type (freeway, arterial, local, ramp) and speed. This procedure is conducted for the 24 assignment matrices each of which is linked to its corresponding look-up table based on the hour of the day. A total of four exhaust and running EFs are associated with each link, thus representing the EFs for the four pollutants (HC, CO, NOx, and CO2) for each hour of the day. The next step involves multiplying each link-based EF (in g/VMT) by the total VMT on that link thus resulting in hourly emissions (in grams) for each pollutant and for each link. The development of link-based emissions has many advantages. Rather than using speed distributions over an entire area, this methodology assigns an EF for each link based on its average speed and type. This bottom-up approach has been shown to yield a much different spatial distribution of emissions than the one obtained when allocating emissions using spatial surrogates (Cook et al., 2006). Also, the link by link approach allows results to be presented graphically, facilitating the determination of emission “hot spots” in the transportation network. The main thrust in developing link-based emissions is the fact that such a representation of emissions will set the stage for dispersion modeling to be conducted in the
GTA, whereby every roadway link is considered as line source of pollution thus allowing for the development of air quality concentration contours within the GTA.

The procedure for start emissions is slightly different as they are assumed to occur only on local roads and only in the direction of the zone centroid to link node. The rationale behind this is that local roads in that same direction carry vehicles that have just started a trip in a zone centroid and are leaving their origin to reach the road network. Start emissions occur at the start position but also during this short period when the vehicle is on the local road. As such, vehicle volumes on local roads in the direction of the zone centroid to link node are multiplied with the start EF and considered responsible for all the start emissions occurring in the zone. For the purpose of dispersion modelling, start emissions in each zone will be attributed to the whole zone and treated as area sources of pollution.

Following the development of a list of hot soaks and a list of soaks; the number of vehicles soaking (or hot soaking) in each zone and hour was multiplied with the corresponding soak (or hot soak) EF. Note that, the EFs (in grams/vehicle) were multiplied by the number of vehicles in each hour interval irrespective of the soak or hot soak durations since these were taken into account within the Mobile6.2C estimation of the EFs. Recall that soak duration distributions were developed and input in order to derive EFs.

7.9 Emission results
Three main types of emissions were generated for light-duty private vehicles in the GTA, these include: 1) running emissions which refer to exhaust emissions of HC (as VOC), CO, NO\textsubscript{x}, CO\textsubscript{2} and running losses of HC (as VOC); 2) start emissions of HC (as VOC), CO, and NO\textsubscript{x} which occur at vehicle start up and last for approximately the first 2 minutes of the trip; and 3) evaporative emissions of HC (as VOC) which include hot soaks and all other evaporative emissions.
7.9.1 Running emissions

Total daily emissions from all links in the GTA are around 43 tons for HC; 1,094 tons for CO; 94 tons for NO\textsubscript{x}; and 21,489 tons for CO\textsubscript{2}. Hourly profiles for total emissions are presented in Figure 7.11 and Figure 7.12. Clearly, peaks in emissions correspond with peak periods of travel namely the morning and afternoon peaks. The contributions of the four roadway categories to total emissions of CO and NO\textsubscript{x} are illustrated in Figure 7.13 and Figure 7.14. Arterial roads have only a slightly higher (and sometimes lower) contribution to total emissions than freeways although they carry around 1.3 times the VMT carried on freeways, thus indicating the greater effect of freeway driving on emissions.

![Figure 7.11 Hourly profiles for total emissions of HC, CO, NO\textsubscript{x}](image-url)
Figure 7.12 Hourly profile for CO₂ emissions

Figure 7.13 Contribution of roadway types to total CO emissions
By estimating the contribution of each GTA region to total CO₂ emissions, the highest contributor is the City of Toronto (around 40 percent) followed by the Region of Peel (Figure 7.15). Note that, such estimation only takes into account emissions occurring within different areas on the network; in fact, a large amount of the City of Toronto traffic is caused by vehicles originating from outside the City. For this purpose, future work should focus on attaching emissions to specific trips while keeping track of their path throughout the network. This will allow associating specific trips with an emission load and hence design policies that can control the “highest polluters”.

Figure 7.14 Contribution of roadway types to total NOx emissions
Figure 7.15 Contribution of GTA zones to total CO$_2$ emissions

Figure 7.16 presents link-based emissions in the GTA during the hour 7:00-7:59 AM. Since the VMT affects total emissions; all emissions on this map are presented in Kg/mile in order to avoid the effect of link length on the total emissions and as such to be able to highlight the highest emitting links based on type, location, speed, and volume. The results show that the highest emitting links are major highways within the GTA. The highest emitting arterials are mainly in the City of Toronto and extending North towards York region; in addition to the City of Mississauga in Peel region and the City of Hamilton. Indeed, these are major urban centres; yet, emissions from links within the City of Toronto are by far higher due to the large number of vehicles entering the City during the morning peak as well as the low traffic speeds on the City’s network.
By looking at the evolution of emissions within the City of Toronto throughout the day (Figure 7.17), one can clearly see the peaks in emissions as they are associated with peaks in daily travel. The most emitting highway is Highway 401 running East-West, North of the City. Other links associated with high emissions include the Don Valley Parkway close to the intersection with Highway 401 Northeast of the City as well as the links surrounding the interchange of Highway 401, Highway 427, and Highway 409 Northwest of the City. In addition, South of the City, along the Gardiner expressway, a few “hotspots” are observed but they are localized: at the interchange of Highway 427 and the Gardiner expressway, and when the Gardiner expressway enters downtown Toronto. Emissions along the Gardiner expressway are lower than emissions on Highway 401. Arterial roads in the City of Toronto have significantly lower emissions per mile than highways despite the lower traffic speeds expected on arterials especially in downtown Toronto at peak hours. This may be due to the average speed assumption of Mobile6.2C which captures only to a certain extent idling, acceleration, and deceleration. Note in Figure 7.13 that the contribution of arterial roads in the GTA is slightly higher than the contribution of freeways.
However, the contribution of highways to emissions on a “per-mile of road length” basis is significantly higher than that of arterial roads thus resulting in a “concentration of emissions” along freeways and “spreading-out” of emissions on arterial roads. Recall that this inventory does not include the contribution of buses, trucks, and other commercial vehicles. As a result, it is expected that freeway emissions are even higher thus posing local air quality concerns in the areas surrounding highways.
Figure 7.17 Evolution of daily link-based CO emissions (Kg/mile) in the City of Toronto
7.9.2 Start emissions

Figure 7.18 presents HC start emissions (which are only assigned on local roads in the direction of the zone centroid to the link node) for selected hours throughout the day in the GTA; start emissions for all hours between 5am and 11pm are presented in Appendix C. Start emissions are highest during peak hours and decrease significantly off-peak. They are most significant West and Northwest of the City of Toronto as well as Northeast. Start emissions within the City and especially the downtown are not significant, again indicating that “hot spots” of emissions are located North of the City.
Figure 7.18 Evolution of start HC emissions (Kg/mile) in the City of Toronto in the morning
7.9.3 Evaporative emissions

Total soak emissions in the GTA are around 14 tons per day; which constitutes around 25 percent of total HC emissions. This percentage is expected to be lower if intrazonal trips were taken into account by EMME/2. Soak emissions can be decreased through reducing the prevalence of short trips. Note that in this study, hot soak emissions were found to be minimal because the scenario modelled is winter. January ambient temperatures in Toronto are significantly low and they do not cause hot soak emissions to be a concern. However, a summer scenario would substantially increase both hot soak and other evaporative emissions. During the summer, soak-related emissions contribute to more than half of the total HC emissions. For the purpose of this exercise, the winter scenario was chosen only because the start emissions generated are higher and better represented visually.

Both hot soak and other evaporative emissions (in grams) in each GTA zone were added up and presented on a GIS platform (Figure 7.19). Clearly, the peaks in soak emissions follow the peaks in travel yet they remain high between noon and 4pm. This is both the effect of 1) decreased travel which means that more engines are off and soaking; and 2) rising daytime temperature which enhances evaporation of HC. Beyond 10pm, soak emissions decrease considerably since as the time for engine-off increases, evaporation of HC decreases. Overnight soaks are practically minimal.
Figure 7.19 Evaporative emissions occurring in GTA zones throughout the day.

Legend:
- HC (grams)
  - 0-319
  - 320-619
  - 620-1019
  - 1020-7000
7.10 Comparison of emissions with an existing inventory

In 2007, the City of Toronto published an inventory of GHGs and CACs from major sources (ICF International, 2007). The inventory was conducted for the year 2004. It was observed that road transportation resulting from light-duty vehicles (LDGV, LDGT) and diesel trucks (HDDT) movements was responsible for 73 percent of the NO\textsubscript{x} emissions that occurred directly within the City; the rest was attributed to space heating. The results also indicate that diesel trucks are responsible for 45 percent of all NO\textsubscript{x} emissions inside the City itself (although they only contribute to 13 percent of vehicle traffic in Toronto). Emissions of VOCs were attributed almost exclusively to gasoline powered cars and light trucks (LDGV, LDGT). Regarding CO\textsubscript{2} emissions, transportation fuels were found to be responsible for 36 percent of CO\textsubscript{2} emissions (28 percent generated by LDGV and LDGT) while natural gas accounted for 37 percent and electricity use making up the rest.

A comparison between the total yearly emissions in the City of Toronto for LDGV and LDGT obtained from this study and the City of Toronto study (ICF International, 2007) is presented in Table 7.7. Note that the City’s study accounts for emissions of passenger cars and light-trucks separately while the current study assumes an “average car” which is a combination of a LDGV and a LDGT. Based on Table 7.7, there is a significant discrepancy between the City of Toronto estimates and the estimates generated by this study. Yearly emissions for HC, CO, and CO\textsubscript{2} are lower in the current study; NO\textsubscript{x} emissions are higher than the City of Toronto’s estimates.

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Current Study</th>
<th>(City of Toronto inventory: ICF International, 2007)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tons/year</td>
<td>Tons/year</td>
</tr>
<tr>
<td></td>
<td>light-duty vehicles &amp; trucks</td>
<td>light-duty vehicles &amp; trucks</td>
</tr>
<tr>
<td>HC as (VOC)</td>
<td>6,158</td>
<td>6,028</td>
</tr>
<tr>
<td>CO</td>
<td>144,831</td>
<td>106,014</td>
</tr>
<tr>
<td>NO\textsubscript{x}</td>
<td>13,027</td>
<td>6,417</td>
</tr>
<tr>
<td>CO\textsubscript{2}</td>
<td>2,976,128</td>
<td>2,838,506</td>
</tr>
</tbody>
</table>

An overview of the methodology and input data for the City of Toronto inventory provides useful insight into the discrepancy between the two studies. In fact, the City’s study uses one EF
for each pollutant and vehicle type irrespective of the roadway type, link speed, or time of day. EFs are derived from Mobile6.2C using default USEPA distributions and assuming an average vehicle age (8 years) rather than a distribution of vehicle ages. A comparison of the EFs used in the City’s study with the range of EFs adopted in this study is presented in Table 7.8. Clearly EFs adopted in the context of the City of Toronto study are significantly lower than EFs derived for this study, this is due to the inaccurate assumption of all vehicles having the same age and attributes. Vehicle age is a significant input in Mobile6.2 affecting emissions. Typically, around 10 percent of the vehicle fleet composed of older vehicles is responsible for about 50 percent of emissions. According to the USEPA (2002d), a 20 percent shift in vehicle fractions among age classes can lead to a change in emissions of up to 50 percent. The average age assumption of the City of Toronto study is expected to underestimate EFs. In addition, speed dependency is not represented by the single EF used by the City whereby all vehicle speeds are assumed to generate the same amount of emissions. This is clearly inaccurate considering that emissions generated during idling and at low vehicle speeds amount to a significant portion of emissions generated throughout the entire trip. Despite the lower EFs adopted within the City of Toronto inventory, total emissions are significantly higher than emissions generated by the current study (Table 7.7) which indicates the need to inspect travel activity data used for both studies in order to better understand this discrepancy.

Table 7.8 Comparison of emission factors used for the City of Toronto study and the current study

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Current Study</th>
<th>(City of Toronto inventory: ICF International, 2007)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EF (g/VKT) for freeways at 7am light-duty vehicles &amp; trucks</td>
<td>EF (g/VKT) light-duty vehicles</td>
</tr>
<tr>
<td>HC as (VOC)</td>
<td>5.50 @ 4Km/h - 0.35 @ 104+ km/h</td>
<td>0.471</td>
</tr>
<tr>
<td>CO</td>
<td>47.37 @ 4Km/h - 13.90 @ 104+ km/h</td>
<td>8.287</td>
</tr>
<tr>
<td>NOx</td>
<td>1.97 @ 4Km/h - 1.07 @ 104+ km/h</td>
<td>0.502</td>
</tr>
<tr>
<td>CO2</td>
<td>232.30 (independent of speed)</td>
<td>70 Kg/Giga Joules</td>
</tr>
</tbody>
</table>

Recall that VKT obtained in the context of the current study were output by EMME/2. The network representation in EMME/2 is surely expected to differ from the “real” road network. Local roads in EMME/2 are represented as centroid connectors which could underestimate their real length. In addition, only household vehicles are taken into account and as a result, commercial light-duty vehicles and trucks are not considered within this study. The City of
Toronto study uses traffic counts to generate the VKT. Mean traffic volumes by street segment are obtained from the City of Toronto’s Transportation Services Division while mean traffic volumes for provincial highways in Toronto are obtained from the Ministry of Transportation (MTO). Based on the traffic count and road length data, the City of Toronto estimates a total of 24.6 billion VKT in 2004. The City of Toronto project allocates 87 percent of this VKT or 21.4 billion for light-duty vehicles and trucks (52 percent for LDGV and 35 percent for LDGT). The current study estimates approximately 93 million VKT per day (on a weekday) for the LDGV and LDGT in the GTA. Extracting the VKT for the City of Toronto (approximately 35 million per day) and multiplying by 365 (no information is available on weekend travel at this stage) leads to a total of 12.9 billion VKT per year for LDGV and LDGT; nearly half the City of Toronto estimate. Note that the estimate for the VKT in this study is for 2001 while the City’s estimate is for 2004. This large difference may not be completely explained by the growth in travel within a 3-year timeframe. Other variables affecting this difference include 1) the fact that the City of Toronto study accounts for commercial light-duty vehicle movements while EMME/2 only generates VKT for household travel; 2) the City of Toronto vehicle counts are not obtained by vehicle type; but rather, the authors have allocated 87 percent of the total VKT to light-duty vehicles simply because light-duty vehicles account for 87 percent of the vehicle fleet.

Clearly this large difference in VKT has caused total emissions to be higher in the City of Toronto estimate despite the lower EFs. There is no doubt that the estimate for the VKT used by the City of Toronto inventory better reflects the “real” VKT within the City than the estimate generated by EMME/2. A more fair comparison would have to look at the VKT estimate for household travel only in order to ensure a level playing field for both studies. In this case, emissions generated by the current study would be significantly larger simply due to the more comprehensive EFs modelled. This is not to undermine the importance of a VKT estimate that accounts for all vehicles on the road. However, modelling of commercial vehicle travel and transit buses is beyond the scope of this study which mainly aims at developing a framework that can assess the environmental impact of long-range transport policy scenarios primarily targeting household travel patterns.
7.11 Conclusion

This Chapter has presented the methodology for and results of an inventory for vehicle-induced emissions in the GTA. This was done by interfacing the activity-based travel demand model TASHA with Mobile6.2C as well as with a traffic assignment model (EMME/2) and a GIS tool. The outputs are link-based vehicle emissions and zone-based evaporative emissions. Both types of emission representations set the stage for dispersion modelling to be conducted by treating links as line sources and zones as area sources of pollution.

The use of TASHA for the purpose of generating vehicle activity parameters rather than a conventional 4-stage model has enabled the achievement of more comprehensive emission results. In fact, the major strength of Mobile6.2 is its ability to estimate and report emissions for the entire day, on an hourly basis. This allows the model to provide more accurate output that accounts for the time of day that vehicle emissions occur. This, however, requires hourly vehicle activity inputs. TASHA models 24-hour travel on a five-minute increment basis and provides a much better internal consistency across time periods than is the case for conventional models. In addition, by microsimulating individual trips and tours, TASHA provides information on vehicle engine on-off patterns thus allowing for the estimation of start and soak emissions which are variable both in space and time. Local input data was generated for Mobile6.2C whereby distributions of vehicle ages and mileage accumulation were generated for the GTA. These two variables are most important from an emission perspective. Finally, the generation of speed-dependent emissions provides the model with sensitivity not only to vehicle volumes but also to roadway type and speed.

The importance of generating local input data for Mobile6.2C rather than USEPA defaults was discussed by Cook et al. (2006) who developed an emission inventory of highway vehicles in Philadelphia by comparing a top-down and a bottom-up approach. The bottom-up approach used vehicle activity data at the link level and hourly EFs to generate emissions while the top-down approach relied on more aggregated information and default inputs. An example of a top-down approach in Canada is the National Pollutant Release Inventory (EC, 2008a). Cook et al. (2006) used Mobile6.2 to generate seasonal fleet average EFs for Philadelphia, the same speed distribution was used for all links of the same type in the bottom-up approach. The travel demand model used was TRANPLAN (TRANsportation PLANning integrated model),
developed by Citilabs. Results show 1) more refined spatial distribution of emissions in the bottom-up approach whereby emissions are distributed along major roadways and at highway intersections as opposed to being allocated to a gridcell or census tract; 2) county benzene emissions using the bottom-up approach are about half of the emissions derived from using the top-down approach; and 3) the total top-down benzene inventory for the entire modeling domain is 12 percent higher than the bottom-up approach.

Recall the City of Toronto emission inventory developed by ICF International (2007) and described in the previous section. In that inventory a single EF was used to describe all light-duty vehicles irrespective of age, mileage accumulation, speed, or time of day. Clearly emissions derived by such an approach are lower than emissions derived using distributions of vehicle and link attributes; they are also insensitive to changes in variables affecting these attributes. The current study provides a much more comprehensive treatment of vehicle emissions by explicitly representing most variables affecting the level of emissions in addition to their spatial and temporal variation. The spatial and temporal variation in emissions not only better reflects real emission patterns occurring in a day but also becomes crucial for dispersion modelling. Wind and turbulence patterns will transport and disperse emissions thus affecting certain areas while other areas are unaffected. This may either accentuate the spatial variability in emissions by causing areas with the highest emissions to become the areas with the highest concentrations or may “wipe-out” the spatial variability in emissions by transporting emissions from the highest emitting areas to the lowest emitting areas. The temporal variation in meteorological conditions, typically characterized by poor dilution at night and strong turbulence at sunrise, tends to accentuate the temporal variation in emissions by accumulating emissions generated during the evening peak period in the atmosphere throughout the night and diluting the accumulated pollutants in the morning. Without a temporal variation in emissions, extreme high-concentration events occurring at night will be underpredicted.

Despite the comprehensiveness of the approach for estimating emissions described in this Chapter, it is associated with various limitations. While light-duty vehicles are responsible for the major part of emissions in urban areas, light-duty commercial vehicle movements, trucks, and buses are increasingly becoming a concern and future research should attempt to address them. The focus on household vehicles solely will significantly underpredict total emissions
expected in the GTA. This would be unacceptable if the purpose of this study was to conduct an emission inventory of road transportation in the GTA. However, the purpose of this study is to compare long-range policy scenarios mostly affecting household travel patterns. In addition, due to the limited information on the types of vehicles owned by households, arbitrary distributions were assumed in this study. Additional information on the types of household vehicles (sedan, minivan, sports utility vehicle, etc) and the daily VKT for each vehicle type is needed (for example, the household minivan may be driven less during a typical weekday than the other vehicle owned). This information is especially important when assessing the effect of increased market penetration of sports utility vehicles. One final limitation associated with Mobile6.2 is the “Average Speed” assumption. While Mobile6.2 estimates slightly different emissions for the same average speed for freeways and arterials (assumes that average speeds on arterial reflect more idling, acceleration, and deceleration than highways); it seems to undermine emissions on arterial roads within the City of Toronto especially downtown Toronto whereby average link speeds cannot be considered representative of driving patterns. The development of microscopic emissions for the whole of the GTA is a daunting task, data-hungry, and hard to validate (most validations focus on traffic counts and speeds but not on acceleration and deceleration). A proposed approach to refine the emission estimates could involve categorizing links (especially arterials) based on their acceleration-deceleration profiles and using a microscopic emission model to derive EFs for the “refined” link types.
Chapter 8
Air Dispersion of Road Emissions: Methodology

8.1 Introduction
Understanding vehicle-induced emissions alone is not sufficient to understanding the problem of air pollution in an urban area. Since emissions relate to the amount of chemicals being released into the atmosphere, a study of emissions can only tell that areas in which significant sources of emissions exist are at a higher risk of air pollution than areas which are remote to sources of emissions. Air quality however, relates to the concentrations of contaminants that people are exposed to; these concentrations result from the transport and dilution of emissions into the atmosphere. The focus of an urban air quality assessment is the “characterization of air quality” or the quantification of air pollutant concentrations under different atmospheric conditions.

This Chapter and the following are dedicated to the establishment of a CALPUFF-based air quality model for the City of Toronto which estimates the contribution of road emissions to local air pollution. This Chapter discusses the methodology adopted for the air dispersion exercise. A review of methods and applications of air pollution dispersion is initially conducted. Following the literature review, selection of the modelling system, pollutant of concern, and the modelling domain are provided. Subsequently, the inputs and methods for both the meteorological modelling and dispersion modelling are explained in detail. While this chapter is dedicated to the methodology adopted for air dispersion modelling, the next Chapter discusses the resulting concentrations.

8.2 Review of air dispersion modelling
In an attempt to set the stage for a discussion on the selected model and overall methodology for air dispersion of road emissions in the GTA, a literature review of air dispersion modelling methods and applications is conducted and presented in this section. The review starts with a brief description of meteorological parameters with most relevance to air dispersion modelling, in light of the importance of meteorology to the dispersion of pollutants. Indeed, meteorology determines the potential of the atmosphere to dilute and transport pollutants released: pollutants
are transported by the wind, spread by diffusion, mixed or trapped by turbulence, and removed by rain. Following the discussion on air pollution meteorology, an overview of the fundamentals for air pollution dispersion is provided. While it is not within the scope of this research to elaborate on atmospheric dispersion modelling, a summary of the mathematical formulation for air pollution dispersion is important especially in order to contrast traditional methods with the more sophisticated methods applied in the context of this work. Beyond the first two subsections, this section summarizes recent efforts at developing/implementing air pollution dispersion models in urban areas with special emphasis on integrated tools that have been used for modelling policy scenarios.

8.2.1 Air pollution meteorology
Most air pollution dispersion phenomena occur in the Planetary Boundary Layer (PBL) or Atmospheric Boundary Layer (ABL), which is the lowest part of the atmosphere where the wind is influenced by surface friction through vertical mixing. Characterization of the PBL is typically of interest to air pollution modellers. Beyond, the PBL, surface effects are negligible and winds are generated as a response to temperature and pressure.

8.2.1.1 Characteristics of the Planetary Boundary Layer
Due to the friction exerted on the wind by the ground surface and objects on the surface (or roughness elements), wind speeds are slow at ground level. The relationship between wind speed and elevation above ground is frequently approximated by the power law, presented in Equation 1 and described in Turner (1994). The gradient wind, or free-stream flow, occurs at the height above the surface where the effects of the surface are no longer felt.

\[ u_z = u_a \left( \frac{z}{z_a} \right)^p \]  

Equation 1

Where  
- \( u_z \) Wind speed, m s\(^{-1}\), at vertical height \( z \) above ground  
- \( u_a \) Wind speed, m s\(^{-1}\), at anemometer height  
- \( z \) Vertical height above ground, m  
- \( z_a \) Anemometer height above ground, m  
- \( p \) Exponent dependent primarily on atmospheric stability which varies from around 0.07 for unstable conditions and to about 0.55 for stable conditions.
The PBL can be divided into three major sub-layers, namely: 1) the “laminar sub-layer”; 2) the “surface layer”; and 3) the “transition layer” (Zanetti, 1990). The “laminar sub-layer” is the region above the ground in which turbulence is intermittent or not fully developed. It extends from the ground up to the height of the surface roughness length. The surface roughness length ($z_0$) is typically used to signify the frictional effect on the wind due to both the height and spacing of roughness elements. Typical values for $z_0$ are: 1-3 meters for urban areas; 1.3 meters for coniferous forests; 0.2 meters for swamps; and 0.0001 for water bodies (Turner, 1994). According to Zanetti (1990), $z_0$ can also be interpreted as the “eddy size at the surface”. The “surface layer” extends from $z_0$ to a height of 10-200 meters; and is characterized by strong vertical gradients of wind, temperature, and moisture. The “transition layer” extends from the top of the “surface layer” to $z_i$ which defines the top of the PBL and ranges from 100 meters to 2 kilometres (Zanetti, 1990). Between $z_0$ and $z_i$, turbulence prevails over molecular phenomena.

The most notable meteorological factors characterizing the PBL and affecting air pollution are: 1) horizontal wind speed (generated by the geostrophic wind component and altered by surface friction and local winds) mainly responsible for transport of pollutants; and 2) turbulence, mainly responsible for dispersion. Note that turbulence can be mechanical or buoyant. Mechanical turbulence occurs as a result of wind moving past vegetation or other structures. Buoyant turbulence is generated as a result of heating or cooling of air near the earth’s surface. At one extreme, during midday with clear skies and light wind, the sun heats the air near the ground which in turn creates an upward heat flux heating air in the lower layers. Large convective eddies are formed thus creating positive buoyant turbulence; atmospheric conditions are considered unstable. The opposite occurs at night with light winds, whereby outgoing infrared radiation cools the ground thus creating a downward heat flux at the surface (or negative buoyancy). This situation is referred to as an inversion, because the vertical temperature structure is inverted from the usual decrease of temperature with height. The inversion causes the atmosphere to become stable and resist vertical mixing; it also diminishes mechanical turbulence. This in turn is detrimental to the vertical spread of pollutants. A third atmospheric condition exists between the two extremes: neutral or when the net heat flux close to the ground is zero. This condition occurs during periods of winds that provide good mixing, or during cloudy periods which inhibit incoming and outgoing radiation, or during sunrise and sunset. In this case, the vertical temperature structure follows a decrease in height at a rate of about 0.0098 Celsius / meter; also
referred to as the dry adiabatic lapse rate (Tuner, 1994). While stability conditions (neutral, stable, and unstable) are the most common way of characterizing the dispersion properties of the atmosphere, other ways include the height of the PBL and the depth of the mixed layer (also known as mixing height) or the height above the ground where strong mixing occurs. In neutral and unstable conditions, the mixing height is approximately equal to the length of the PBL ($z_i$), while in stable conditions, the mixing height is smaller than $z_i$.

8.2.1.2 Meteorological modelling

As discussed in the previous section, the two most important atmospheric characteristics for air pollution modelling are wind speed and atmospheric stability. As such, in order to provide input for dispersion modelling, meteorological modelling is conducted. As discussed later on in this Chapter, this research has devoted significant efforts to the generation of meteorological input data for dispersion modelling in light of the significance of meteorology to the dispersion process. Note that meteorological models of interest in this context are numerical models rather than analytical or physical models as they constitute powerful tools for meteorological and air quality simulation. Zanetti (1990) describes two types of numerical models namely, diagnostic and prognostic models. Diagnostic models rely on available meteorological measurements and have no time-dependency (i.e. they simulate every time period based on data for that specific time period). Prognostic models on the other hand, have time-dependent equations (i.e. the simulation for every time period is based on past time periods). While diagnostic models include little physics in their calculations; they have the advantage of incorporating available measurements hence rendering their output highly dependent on the quality and density of available measurements. The output is a three dimensional field of meteorological parameters derived from interpolation and extrapolation of available meteorological data thus providing a best-guess for every time period. Prognostic models rely on meteorological physics (mainly using equations of conservation of mass, heat, motion, and water) but they cannot incorporate available data to modify the forecasts. A future challenge for meteorological modellers is to link prognostic and diagnostic models.
8.2.2 Estimates of air pollution dispersion

The basis for estimating air pollutant concentrations from a continuous source to a receptor is the Gaussian dispersion equation. Most air pollution models used for regulatory purposes around the world are based on Gaussian dispersion or modified versions of it; they are commonly referred to as Gaussian models. More advanced models that overcome some of the limitations of Gaussian models, have also been developed; these include puff, particle, and grid models as well as combinations of these approaches (MFE, 2004); these and the Gaussian formulation are discussed in this section. Zanetti (1990) classifies air pollution models into three categories namely, Eulerian models, Lagrangian models, and Gaussian/puff models. Because the Gaussian and puff formulations can be derived from either the Eulerian or Lagrangian dispersion equations, they are considered by Zanetti (1990) as a separate category. The most common Eulerian model is the single (or multiple) box model which is based on the mass conservation of a pollutant inside an Eulerian box. The multiple box model approach has been implemented in most grid models discussed in this section. The most common application of the Lagrangian formulation is in the complex particle models, also discussed below.

8.2.2.1 Gaussian steady-state dispersion

The Gaussian plume model is the most common air pollution model in which cross-wind, vertical, and horizontal dispersion of a pollutant released by a point source is described by the Gaussian dispersion equation. The generalized form of the Gaussian plume model is illustrated in Figure 8.1 and presented in Equation 2.

\[
C(x, y, z; H) = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp \left[ -\frac{y^2}{2\sigma_y^2} \right] + \exp \left[ -\frac{(H - z)^2}{2\sigma_z^2} \right]
\]  

Equation 2

Where

- \(C\)  Air pollutant concentration, usually g m\(^{-3}\)
- \(Q\) Pollutant emission rate, usually g s\(^{-1}\)
- \(u\)  Horizontal wind speed at the point of release, m s\(^{-1}\)
- \(\sigma_y\) Standard deviation of the concentration distribution in the crosswind direction at the downwind distance \(x\), m
- \(\sigma_z\) Standard deviation of the concentration distribution in the vertical direction at the downwind distance \(x\), m
- \(H\)  Effective height of the plume centerline, m
This equation estimates the concentration at a receptor located away from a source at a position: x downwind, y crosswind, and with a height of z above the ground; in a wind-oriented coordinate system. Equation 2 is a multiplication of four general terms giving rise to the concentration at each receptor; these terms include 1) emission rate; 2) horizontal wind speed; 3) crosswind dispersion; and 4) vertical dispersion (Table 8.1). In addition to the four basic terms; additional terms are typically added to take into account reflection, deposition/decay, and chemical transformation. Note that while the most general form of the dispersion equation reflects a point source of emission; Equation 2 can be spatially integrated to simulate the effects of line, area, and volume sources. Other effects that are typically taken into account in most Gaussian plume models include: fumigation, plume downwash, plume trapping, plume tilting, as well as coastal and complex terrain effects. Discussions of these effects are found in most air dispersion modelling textbooks (Zanetti, 1990).
Table 8.1 Factors affecting pollutant in the Gaussian dispersion equation (Turner, 1994)

<table>
<thead>
<tr>
<th>Factor</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q$</td>
<td>The concentration at the receptor is directly proportional to the emission rate, $Q$.</td>
</tr>
<tr>
<td>$\frac{1}{u}$</td>
<td>In the direction of the plume, or x axis, the concentration is inversely proportional to the wind speed, $u$.</td>
</tr>
<tr>
<td>$\frac{1}{2\pi 0.5 \sigma_y} \exp \left[ -\frac{y^2}{2\sigma_y^2} \right]$</td>
<td>In the crosswind direction, concentrations are inversely proportional to the spread of the plume in the y direction, $\sigma_y$. The greater the downwind distance $x$, the larger the horizontal spreading and the lower the concentration.</td>
</tr>
<tr>
<td>$\frac{1}{2\pi 0.5 \sigma_z} \exp \left[ -\frac{(H-z)^2}{2\sigma_z^2} \right]$</td>
<td>In the vertical direction, concentrations are inversely proportional to the spread of the plume in the z direction, $\sigma_z$. The greater the downwind distance $x$, the larger the vertical spreading and the lower the concentration. The exponential term represents the distance between the receptor and the plume centerline.</td>
</tr>
</tbody>
</table>

The validity of the concentrations derived from Equation 2 strongly depends on a correct calculation of the dispersion parameters $\sigma_y$ and $\sigma_z$. Both $\sigma_y$ and $\sigma_z$ are a function of the stability of the atmosphere. Zanetti (1990) discusses two general methods for calculating $\sigma_y$ and $\sigma_z$. In the first method, $\sigma_y$ and $\sigma_z$ are calculated using non-dimensional functions $S_y$ and $S_z$ which are in turn functions of diffusion time and Lagrangian time scale. In the second method, $\sigma_y$ and $\sigma_z$ are estimated based on semi-empirical calculations that mainly depend on atmospheric stability classes and downwind distance.

The simplicity of the Gaussian plume model made it popular. Zanetti (1990) shows how the Gaussian equation can be derived from different assumptions and justified by semi-empirical considerations. The author describes that despite irregular instantaneous plume concentrations, a typical averaging time of one hour generates “bell-shaped concentration distributions that can be well approximated by the Gaussian distribution in both the horizontal and (to a lesser degree) the vertical”. Gaussian models do not require significant computing resources, are fairly easy to use, and have simple meteorological data requirements. While computationally attractive, the Gaussian plume model has many limitations. As can be seen in Equation 2, it refers to a stationary state since the concentration is not a function of time; it also uses meteorological conditions (wind speed and dispersion parameters) that are stationary and homogeneous in the entire modelled domain; and it does not work in calm wind conditions ($u \to 0$). Emissions and meteorological conditions can vary from hour to hour but the model calculations in each hour do not depend on the previous hours. One consequence of this formulation is that every hour, the
plume extends to infinity and hence pollutants concentrations can be found at points that are too far to have been reached by the plume within that hour; as such, Gaussian models typically overestimate concentrations in the far-field. The Gaussian model has no memory of pollutants released in the previous hours. Due to their assumption of constant meteorology throughout the modelling domain, plume models are typically used for near-field applications (up to 10Km source-receptor distance) as meteorology is expected to change beyond the near-field (MFE, 2004). The constant meteorology also implies that sea breezes as well as slope and valley flows (leading to plume channelling) in complex terrain are not modelled.

8.2.2.2 Puff models

Gaussian puff models overcome the Gaussian model limitations of stationary emissions and steady-state meteorology and can handle calm wind situations. In this case, a plume is simulated as a series of puffs. Each puff represents a mass of pollutant $\Delta M$ injected into the atmosphere during a time duration $\Delta t$ in a time-varying emission rate $Q$ ($\Delta M = Q \Delta t$). The center of the puff is advected according to the time-varying wind vectors. The pollutant concentration due to that puff at receptor $r$ and at time $t$ is expressed by the basic Gaussian puff formula presented in Equation 3; the total pollutant concentration at receptor $r$ and time $t$ is found by summing the contributions of all puffs from all sources (Zanetti, 1990).

\[
\Delta c = \frac{\Delta M}{(2\pi)^{3/2} \sigma_z^2 \sigma_h^2} \exp \left[ -\frac{(x_p - x_r)^2}{2\sigma_h^2} \right] \exp \left[ -\frac{(y_p - y_r)^2}{2\sigma_h^2} \right] \exp \left[ -\frac{(z_p - z_r)^2}{2\sigma_z^2} \right] 
\]  

Equation 3

Where

- $\Delta c$  Concentration at receptor $r$
- $\Delta M$  Mass of pollutant released during $\Delta t$
- $\sigma_z$  Vertical dispersion coefficient
- $\sigma_h$  Horizontal dispersion coefficient
- $x_p, y_p, z_p$  Coordinates of the puff center
- $x_r, y_r, z_r$  Coordinates of the receptor

As can be seen in Equation 3, the puff formulation is time-dependent and does not include the horizontal wind component $u$ (substituted by an extra horizontal dispersion term) which makes this formulation able to handle calm wind situations. Even with the use of single point meteorological data, the “memory” capability of the puff formulation generates more sensible
concentrations contours (Figure 8.2). Additional components can also be added to Equation 3 to reflect; deposition/decay and reflection. Other features of puffs have been analyzed in detail including puff splitting and puff merging. The puff dispersion parameters $\sigma_h$ and $\sigma_z$ are typically determined similarly to plume dispersion parameters (discussed in the previous section) except in special cases (Zanetti, 1990). A traditional drawback of puff models is the need to release a large number of puffs to adequately represent a continuous plume close to the source. Scire et al. (2000a) suggest in the discussion of their puff model that puff should overlap sufficiently (no more than one $\sigma_h$ between any two puffs) so that concentrations of receptors located between puffs are not underestimated and concentrations at receptors located at puff centers are not overestimated.

Figure 8.2 Illustrating the "memory" capability of the puff model
8.2.2.3 Particle models

Lagrangian particle models compute trajectories of particles (not necessarily representing real particles, they could represent small parcels of air) in a turbulent flow, given a statistical description of the random velocity field. Each particle’s acceleration is computed for every time step. Currently, particle modelling is the most powerful computational tool for the description of atmospheric processes especially transport and diffusion of air pollutants (Wilson and Sawford, 1996). The main disadvantage of particle models is their enormous requirement for computing time hence making their use impractical when a large number of emission sources and simulation days are involved (Schwere et al., 2002). Particle models take into account the three basic dispersion coefficients namely; transport due to the mean fluid velocity; the random turbulent fluctuations of wind components; and molecular diffusion (if not negligible). While every particle is modelled individually, particle models are not concerned with following each molecule but only in defining algorithms that provide accurate overall density distributions or ensemble averages.

Zanetti (1990) illustrates in, Equation 4, the mathematical formulation for the position of a particle at a time $t_2$, taking into account its previous position $x(t_1)$ at a time $t_1$ where $u$ is the “instantaneous” wind vector in each point $x(t)$ between $t_1$ and $t_2$. Atmospheric turbulent properties make it impossible to know $u$, because of the random nature of turbulent eddies, an effective wind vector $u_e$ (Equation 5) can be considered as responsible for moving the particle from $x(t_1)$ to $x(t_2)$ in the interval $(t_1, t_2)$. Zanetti (1990) defines $u_e$ as in Equation 6 whereby $\overline{u}$ is the best estimate of the average Eulerian wind vector which is known based on wind measurements or provided by a meteorological model and represents our deterministic understanding of the average transport process; whereby $u'$ is an artificial numerical perturbation related to the turbulence intensities of the smaller eddies not included in $\overline{u}$. The computation of $u'$ is at the heart of Lagrangian particle modelling; two fundamental approaches are used to estimate it: a numerical procedure for solving the diffusion equation and a statistical approach for modelling the randomness of fluid trajectories.

\[
x(t_2) = x(t_1) + \int_{t_1}^{t_2} u(x(t), t) \, dt
\]

Equation 4
\[
\frac{\delta c_i}{\delta t} + \frac{\delta(u c_i)}{\delta x} + \frac{\delta(v c_i)}{\delta y} + \frac{\delta(w c_i)}{\delta z} = 0
\]

Equation 7

\[
= \frac{\delta}{\delta x} K_x \left( \frac{\delta c_i}{\delta x} \right) + \frac{\delta}{\delta y} K_y \left( \frac{\delta c_i}{\delta y} \right) + \frac{\delta}{\delta z} K_z \left( \frac{\delta c_i}{\delta z} \right) + R_i + S_i + D_i + W_i
\]

Where:
- \( c_i \) Concentration of pollutant i, a function of space \((x,y,z)\) and time \(t\)
- \( u, v, w \) Horizontal and vertical wind speed components
- \( K_x, K_y \) Horizontal turbulent diffusion coefficients
- \( K_z \) Vertical turbulent exchange coefficients
- \( R_i \) Net rate of production of pollutant i by chemical reactions
- \( S_i \) Emission rate of pollutant i
- \( D_i \) Net rate of change of pollutant i due to surface uptake processes
- \( W_i \) Net rate of change of pollutant i due to wet deposition processes

8.2.2.4 Grid models

Grid or multiple cell models divide the modelling domain into a three dimensional grid, whereby each cell is treated separately from the others. The model starts with an initial distribution of pollutants in all of the cells then for each time step, calculates the change in concentration of the pollutant of interest and its precursors in each cell by numerically integrating Equation 7. Equation 7 is the basis for grid models; it is referred to as the atmospheric diffusion or species continuity equation (or advection/diffusion equation) and it represents a mass balance in which emissions, transport, diffusion, chemical reactions, and removal processes are expressed in mathematical terms (SAI, 1999).

A typical application of grid models is in airshed modelling systems. Airshed models divide the modelling domain into a set of three dimensional grid cells whereby pollutants are moved from one cell onto the next (as opposed to being dispersed as plumes). Airshed models allow for modelling pollutant transport over large domains by setting grid cell sizes to hundreds of kilometres. They also have the cheapest computational demands among advanced models. However, one significant challenge of airshed models is in the allocation of emissions to grid
cells. An emission inventory of all sources in the modelling domain needs to be conducted in addition to “gridding of emissions” especially roadway emissions. Meteorological input data is of particular concern for airshed models mainly because of their grid-based approach. If the wind direction in one cell is inaccurate, then emissions can either add to or completely miss emissions in a nearby grid cell. A major difficulty arising in airshed modelling is when the scale of the pollutant release is smaller than the grid point spacing. MFE (2004) recommends the use of airshed models when assessing air quality of entire regions while incorporating all the relevant emissions; in such applications, air shed models can reveal long-term air quality trends, provide data for exposure assessment, and assess the effect of new sources.

8.2.3 Spatial scales of meteorology and air pollution phenomena

Atmospheric phenomena occur at various scales ranging from localized turbulence and air flow around buildings to cyclones and global circulation patterns. Moussiopoulos et al. (2003) distinguish nine general types of atmospheric phenomena: turbulence (few meters to tens of meters), building wakes (up to 100 meters), thermals (100 to few hundred of meters), deep convection (few kilometres), urban heat island and thunderstorms (few kilometres up to 50 kilometres), land-sea breeze circulation (tens to hundreds of kilometres), fronts and mesocyclones (1000 to a few thousand kilometres), cyclones (up to 10,000 kilometres), and global circulation (tens of thousands of kilometres). Atmospheric phenomena at the local and urban scales have a spatial extent ranging between a few meters to about 500 kilometres. Clearly an accurate representation of air pollutant transport and dispersion needs to take into account the multi-scale character of the atmosphere. However, as Moussiopoulos et al. (2003) indicate, the approach to air pollution modelling has focused on scale separation whereby models have been developed for specific scales rather than for a range of scales. Specific scales include: local scale, urban scale, mesoscale, macroscale, and global climate scale. According to the authors, this scale separation has proven to be a useful approach to air dispersion modelling, whereby every modelling scale includes parameterizations of lower scale phenomena. For example, an urban-scale model should be capable to simulate in detail the urban heat island and land-sea breeze circulations while the smaller scale phenomena such as street-level turbulence are parameterized. As such, a street-canyon model, which can resolve the size and shape of buildings and accounts for traffic-induced turbulence and wind circulation within the canyon and around buildings, has a
domain the size of the street canyon. On the other hand, an urban scale model would not explicitly treat buildings and hence urban canyons, but it would take into account the effect of buildings through the roughness length \((z_0)\) discussed in Section 8.2.1; the roughness length in-turn affects the calculation of atmospheric stability. Any air pollution modelling application should start with a decision regarding the modelling scale and move on to the type of formulation that best fits the application at hand. The modelling scale essentially determines the effects that will be explicitly treated in the model and those that will be implicit.

8.2.4 Recent advances in urban air quality modelling

Recall in Chapter 7, Section 7.3.1.2, the overview of studies that have extended IUMs and activity-based travel demand models with emission estimation capabilities. This section looks beyond the integration of transport models with emissions models by studying linkages with dispersion models and capabilities for population exposure assessment. This section is divided into two subsections; first a review of dispersion models linked with IUMs is conducted in light of the interest in integrated models and their use to assess the environmental and sustainability impacts of land-use and transport policies. This section also reviews another type of studies; which, despite their lack of land-use and transport interactions, have developed sophisticated approaches for coupling traffic emissions with dispersion and exposure assessments. Examples of such approaches are discussed in the second subsection.

8.2.4.1 Integrated Urban Models and air quality assessment

In the context of the SPARTACUS (System for Planning and Research in Towns and Cities for Urban Sustainability) project conducted within the Environment and Climate Research Program of the European Commission, a land-use and transport model, MEPLAN, was combined with a set of sustainability indicators which include transport emissions and air quality. SPARTACUS includes a raster module which uses GIS techniques to calculate spatially disaggregate indicators of emissions, air quality and noise in addition to a tool for analysis of results and a module for the evaluation of policy alternatives. The raster module, of special interest to emissions and dispersion, converts the output of the zone-based MEPLAN model, to raster cells. Roadway emissions are attributed to raster cells which in turn become input into the dispersion model. Emission functions for PM, \(\text{NO}_x\), and CO are combined with the VKT in every raster cell in
order to generate total emissions. Concentrations of pollutants are then linked with population
counts to estimate the number of people exposed to concentrations of different levels (Lautso and
Toivanen, 1999). Based on the methodology developed in the SPARTACUS project, the
PROPOLIS project (Planning and Research of Policies for Land Use and Transport for
Increasing Urban Sustainability) was initiated to address air quality and other sustainability
impacts of various policies within selected case study cities (Lautso et al., 2004).

Potoglou and Kanaroglou (2005) have mapped CO concentrations in the Hamilton area in
Canada by linking the IUM IMULATE with emission and dispersion models. Mobile5.C was
used to estimate EFs by average speeds which were then linked with link-based traffic flows to
estimate total CO emissions. The Gaussian dispersion model, CALINE-4, was then used to
estimate CO concentrations at predefined point locations within 500 m of the roadway. Because
CALINE-4 can only accommodate 20 links and 20 receptor points at each run, a generalized
network including major roads was considered for dispersion and the area was subdivided into
five zones. Following the estimation of 1-hour CO concentrations at localized receptors,
universal kriging was used in order to generate a surface map of CO concentrations for the
Hamilton area. In a more recent study, the authors refined their CO emission and dispersion
system by linking Mobile6.2C and CALINE-3 with IMULATE. Mobile6.2C was used to
develop speed-based EFs. CALINE-3’s source code was altered to accommodate 4,000 roadway
links and 3,500 discrete receptors; receptor locations were chosen to correspond with residential
locations of individuals. Average meteorological data for the four seasons in 1991 and 2001 were
used as input in CALINE-3 in addition to emissions. Morning peak CO concentrations were
estimated for 1991 and 2001. Results showed a decline in CO concentrations, between 1991 and
2001, which the authors attributed to a decline in CO EFs due to vehicle technology
improvements (Kanaroglou et al., 2006).

8.2.4.2 Integrated traffic emissions and dispersion studies
This section summarizes relevant studies that have integrated traffic, emission, and dispersion
models to assess urban/regional scale air quality as well as studies that have assessed local,
street-level pollution. In this context, it is worth mentioning the SATURN (Studying
Atmospheric Pollution in Urban Areas) project which is part of the European EUREKA project
studying the transport and chemical transportation of air pollutants over Europe. SATURN has grouped researchers from 19 European countries with the objective of improving the understanding of air pollution in urban areas and establishing source-receptor relationships at the urban scale. SATURN is structured into three research clusters: 1) the local cluster dealing with microscale and local scale air dispersion investigated through field data collection as well as wind tunnel experiments and numerical modelling; 2) the urban cluster addressing urban and regional air pollution which excludes a resolution of individual obstacles and street-canyon effects; and 3) the integration cluster which focuses on integrating the various air quality models into air quality management systems to be used for various applications. The SATURN approach to investigating local scale, mesoscale, and regional scale effects on urban air quality is through “multi-scale model cascades” whereby coupling of different scale models is conducted with the aim of expressing the interactions between the various scales. This is done for example by using local scale modelling results to develop parameters for the urban scale application. Examples of regional-to-urban and urban-to-local coupling of models in the context of the SATURN project are presented in the final project report (Moussiopoulos, 2003).

**Urban/regional scale**

The TEMMS (Traffic Emission Modelling and Mapping Suite) project in the UK is an example of a modelling system that integrates traffic emissions and air dispersion. Currently, the model is linked to a traffic assignment model, SATURN (Simulation and Assignment of Traffic to Urban Road Networks); a vehicle emissions model, ROADFAC; and air pollution dispersion models, Airviro or ADMS. As a result of this integration, TEMMS determines traffic flow on road networks in urban areas, models traffic emissions from the road networks (based on average speed), combines these emissions with stationary source emission estimates, and inputs these combined emissions to a dispersion model. Both dispersion models applied in the context of the TEMMS project, can calculate NO₂ from NOₓ emissions, and have street canyon models for simulating air quality for a particular street segment surrounded by buildings. Air quality is mapped on a 0.01-1 km² area basis. In a later stage, TEMMS will be integrated with the START/DELTA land-use strategic transport model (Still and Simmonds, 1997) thus creating a land-use/transport/air quality/health interaction package to support land-use and transport policy assessment (Namdeo et al., 2002). TEMMS was used to evaluate the air quality impact of cordon and distance-based charges in Leeds, UK. The authors tested a range of charge scenarios as well
as network scenarios (road building), and clean fuel vehicle technologies. Results showed that the growth in trips between 2005 and 2015 would outweigh most of the emission benefits of clean technology; emissions would continue to decrease but at a slower rate than what was experienced in the nineties. The study also showed that road pricing can significantly reduce road emissions however, its use as an air quality management tool is affected by the prevailing air quality in the urban area of concern and emission characteristics of the fleet (Mitchell et al., 2005).

In Finland, Karppinen et al. (2000a) developed a modelling system for evaluating traffic volumes, emissions from stationary and vehicular sources, and atmospheric dispersion in urban areas. The dispersion modelling is based on the Finnish urban dispersion model UDM-FMI and the road network dispersion model CAR-FMI. Implementation of the model in the Helsinki Metropolitan Area and generation of annual average NO$_2$ concentration contours, showed that 80-95 percent of ground-level NO$_x$ concentrations originated from traffic sources (despite the fact that the contribution of traffic emissions is not as high). The concentrations of NO$_2$ were highly distributed around roads with higher vehicle speeds. The authors also compared the NO$_2$ and NO$_x$ concentrations with data from the urban measurement network in Helsinki and found better agreement for the suburban stations than for urban ones (Karppinen et al. 2000b).

Peace et al. (2004) conducted a source apportionment of road emissions to estimate the contribution of different vehicle types to NO$_x$ ground-level concentrations in a 1552 Km$^2$ area in the Northwest of England. Emissions were estimated for heavy duty vehicles, light-duty gasoline and diesel vehicles, buses, and motorcycles, using EFs obtained from the “Exhaust Emission Factor 2001: Database and Emission Factors Report” for Euro standard engines and engine sizes. Road emissions were then input into the Gaussian dispersion model ADMS-Urban. Since the maximum number of sources allowed by ADMS is 1,000 line sources and 3,000 gridded sources, the authors included major roadways as line sources and other sources as aggregated volume sources contained in 1Km$^2$ grids. Gridded receptors were located 300 meters apart in the whole area except close to major roads whereby receptors were placed 20 meters apart to improve the resolution of the final concentrations. NO$_x$ emissions were found to be highest close to major arterial roads; 55 percent of ambient NO$_x$ concentrations close to major roads were attributed to
goods vehicles and 15 percent of ambient NO$_x$ was found to come from car journeys over 8 kilometres. Authors found road traffic to be the major source of air pollution in the urban area.

**Local scale**

A wide range of local scale air pollution applications exist; they aim at assessing the effect of street-level emissions on air pollution and exposure in the vicinity of the road. These applications are based on earlier research into wind flow and dispersion patterns in urban canyons. Their accuracy depends on the level of understanding of air dispersion phenomena in geometrically simple or complex urban configurations. Prior to describing various local scale applications, selected studies of urban canyon flow measurements and modelling are outlined.

Tsai and Chen (2004) conducted measurement of air pollutants and modelling of the three dimensional air flow and dispersion in an urban street canyon in cases where the wind flow is normal to the street. The authors found that the concentrations of pollutants on the leeward side are usually higher than those on the windward side. This happens because air is trapped and recirculated in an urban canyon when the wind is normal to the street. As such, the windward side faces relatively fresh air while the leeward side receives polluted recirculated air. The difference between leeward and windward concentrations normal to the street axis increases with the wind speed. Traffic-induced turbulence produces further mixing in the street canyon but its effect was not quantified in this study. Simulated wind fields indicate a clockwise circulation vortex with the vortex center located slightly above the mid-height and close to the windward side. Wind blowing normal to the street was observed to enter the canyon both from the top and from the street outlet/inlet. Simulated pollutant concentrations show results consistent with measurements: concentrations decline as the height increases and are higher on the leeward side than on the windward side. Differences of 20 to 35 percent were found between concentrations at ground level and at the top of the canyon. Using a passive tracer, Caton et al. (2003) studied experimentally the concentration transfer between the street and the external flow when the wind is normal to the street axis. As in the previous study, the authors observed a large recirculation within the street canyon; they also observed that except close to the source or the walls/buildings, the concentrations of pollutants are uniform inside the canyon. The authors also observed a fairly turbulent shear layer at the top of the canyon responsible for the transfer between the canyon and the external flow. Albergel and Jasmin (1998) also observed the same eddy structure within the
canyon observed in the other two studies. When wind speeds are low, moving cars were observed to have a significant effect on the flow.

Recently, a European network of researchers developed the OSCAR air quality assessment system which includes a suite of models for studying street-level air quality problems; including traffic, emissions, meteorological pre-processing, and dispersion. Two different dispersion models are integrated in the OSCAR framework: CARII which is a simple model that performs annual statistics, and CAR-FMI which is more suited for the estimation of hourly concentrations (Sokhi et al., 2008).

Keller et al. (2008) studied the impact of reducing the maximum speed limit on motorways in Switzerland to 80 km/hour on vehicle emissions and ozone concentrations. For this purpose the Eulerian air quality model CAMx (Comprehensive Air Quality Model with extensions) was coupled with the MM5 prognostic meteorological model and an emission inventory whereby model runs were performed for 4 days in the month of August 2003. Gridded hourly emissions were estimated for 2 scenarios namely, a regular scenario with maximum speed limit of 120km/hour and a scenario based on a reduced maximum speed limit of 80 km/hour using a database of EFs for Swiss, German, or Austrian vehicle fleets. Major arterial roads and highways were considered as line sources whereas dense networks of small urban roads were considered as area sources. The emissions of each grid cell in the model were considered as the sum of the emissions of the area sources and those of the line sources located within the grid cell. A 4 percent decrease in NOx emissions was found to be significant in the reduced speed scenario; VOC and CO emissions were not significantly affected. Photochemical modelling was also conducted to determine ozone concentrations under the two emission scenarios. With a 4 percent decrease in NOx, the decrease in ozone levels under the speed reduction scenario was found to be lower than 1 percent.

In Portugal, Borrego et al. (2003) developed a modelling system linking the TREM (Transport Emission Model for Line Sources) emission model with the VADIS Lagrangian dispersion model. The TREM/VADIS system was used mainly to assess dispersion conditions in street canyons as VADIS can incorporate buildings. TREM estimates emissions for individual roadway links using an average speed approach and is connected with the VISUM transportation model.
Recognizing exposure as a better indicator of the health effects of air pollution than emissions or concentration of air pollutants, the DAPPLE (Dispersion of Air Pollution and Penetration into the Local Environment) research project, developed in the UK, aims at assessing the sustainability of urban road transport in terms of exposure to traffic-related air pollution. The project seeks to identify situations (e.g. street canyons) where exposure fails to follow the same trend as fixed-point air quality as evidence that ambient air quality is a poor indicator of sustainability. Such an assessment will shed new light on the effect of human exposure to vehicular air pollution on the sustainability of development of urban transport systems (Colvile et al., 2004).

8.3 Model selection
In order to select the most appropriate model for the dispersion of road emissions in the GTA, a review of selected operational models, of potential applicability, was conducted. Based on the main objective of this research, which is to assist decision making of transport plans in the GTA, the models of interest are those that reflect urban scale phenomena and air dispersion. While local scale, especially street-canyon air pollution is of particular interest in urban areas especially in dense city centers such as downtown Toronto, it can only be envisaged in combination with urban scale air dispersion modelling in the GTA. On its own, it is not useful as a policy-support tool. This research will consider urban scale effects solely whereby local scale effects are reflected by the roughness length \((z_0)\). This exercise is expected to highlight areas of interest that could be the object of further local-scale air pollution modelling. In this respect, both Gaussian plume models and more advanced models were considered as part of this exercise. Several criteria were taken into account when assessing the different models some of these criteria are standard to most modelling exercises and generally looked at by air dispersion modellers when investigating the viability of a model to a specific application and other criteria are inherent to the “modelling philosophy” and general modelling direction of the ILUTE/TASHA framework.

8.3.1 Review of selected operational models
Models considered as viable to air quality modelling of road emissions in the GTA include the Gaussian Industrial Source Complex (ISC), AERMOD, and CALINE-4 models as well as the more advanced models; CALPUFF, Urban Airshed Model (UAM), The Air Pollution Model
(TAPM), and the Community Multiscale Air Quality (CMAQ) model. This section provides a short description of these models. Note that the purpose of this section is not to conduct a detailed review and comparison of existing models but rather to provide a brief overview of existing operational models as a basis for the next section which discusses the selection of the final model.

Various authors have conducted reviews of air dispersion models based on model formulations as well as comparison of the results obtained form different models applied to the same dispersion case. Holmes and Morawska (2006) reviewed a wide range of dispersion models, including simple box models, Gaussian models, Lagrangian/Eulerian models, and models that include aerosol dynamics, with emphasis on their applicability to the dispersion of particles. CALTRANS (2006) conducted a survey of air quality dispersion models for project-level conformity analysis. Caputo et al. (2003) conducted a comparison of Gaussian, Gaussian segmented plume, and Lagrangian atmospheric dispersion models. Moussiopoulos et al. (1996) conducted a review of a wide range of dispersion and transport models. Comparisons and evaluations of line-source models for highway dispersion were conducted by Sharma et al. (2004) and Marmur and Mamane (2003). Sharma and Khare (2001) conducted a review of highway dispersion studies. The results of the model reviews indicate that considerable differences exist between the different models and it is impossible to rank models from best to worst since the performance of each largely depends on the application it is intended for. Holmes and Morawska (2006) propose some factors to be considered when choosing a dispersion model, these include: complexity of the environment, model dimensions, computing power, and accuracy and timescale of the calculated concentrations.

8.3.1.1 Gaussian steady-state models
AERMOD is a near-field steady-state Gaussian dispersion model, based on planetary boundary layer turbulence structure and scaling concepts, and including treatment of both surface and elevated sources over both simple and complex terrain. It is able to model multiple sources of different types including point, area and volume sources. AERMOD was developed by the American Meteorological Society/Environmental Protection Agency Regulatory Model Improvement Committee. It includes a meteorological pre-processor, AERMET that accepts
surface meteorological data and upper air meteorology and a terrain pre-processor AERMAP which provides information that allows the dispersion model to simulate the effects of air flowing in complex terrain (USEPA, 2004b). Similar to AERMOD, the Industrial Source Complex 3 (ISC3) is a Gaussian plume dispersion model which operates in both a long-term and short-term mode (USEPA, 1995). As of December 2005, ISC3 was replaced by AERMOD on the USEPA’s “preferred models” list. The USEPA recommends the use of AERMOD for appropriate application as a replacement to ISC. A common model used to calculate the dispersion of vehicle emissions is CALINE4, developed by the California Department of Transportation. CALINE4 is a Gaussian plume model and so suffers from the inherent limitations of the Gaussian equations to urban dispersion modelling over long distances and within complex environments. Despite this, it has been applied in a large number of studies and for regulatory purposes due to its ease of use and low computational requirements (Coe et al., 1998). Although not relevant to the scope of the current study, it is worth mentioning CAL3QHC, the California Line Source Model 3 with Queuing and Hot Spot Calculation. CAL3QHC has been developed is an enhancement to the CALINE-3 line source dispersion model (the earlier version of CALINE-4); it estimates CO and PM concentrations from both moving and idling vehicles near intersections and has been recommended by the USEPA for estimating concentrations near intersections.

8.3.1.2 Advanced models
Currently the most commonly used puff model is CALPUFF which is recommended by the USEPA as the guideline model for applications involving long-range transport of pollutants. CALPUFF was developed by Earth Tech Inc. It is a non steady-state Lagrangian Gaussian puff dispersion model which can handle time- and space-varying meteorological conditions. The latter are generated by CALMET, its meteorological pre-processor. CALPUFF can also be driven by single-point meteorological observations used in steady-state plume models in the same format as the ISC3 model; however, this option does not allow CALPUFF to take advantage of its spatially varying meteorological fields. CALPUFF includes algorithms for

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12 Up until 2006, CALPUFF was owned by Earth Tech Inc. after which, ownership of the model switched to the TRC Environmental Corporation
complex terrain effects, over-water transport, coastal interactions effects, building downwash, wet and dry removal, and simple chemical transformation. It can model point, line, buoyant areas, and volume sources (Scire et al., 2000a).

Another advanced model is The Air Pollution Model (TAPM) developed by the Atmospheric Science Group at the Common Wealth Scientific and Industrial Research Organization (CSIRO) in Australia. Instead of relying on a Gaussian plume or puff approach, TAPM solves approximations to the fundamental fluid dynamics and scalar transport equations to predict meteorology and pollutant concentrations. While CALMET is a diagnostic meteorological model that relies on significant input data, TAPM uses a prognostic model for meteorological modelling which minimizes its meteorological data needs. Instead, the model predicts the flows important to local-scale air pollution, such as sea breezes and terrain induced flows. The air pollution component of TAPM, which uses the predicted meteorology and turbulence from the meteorological component, has an Eulerian grid module and a Lagrangian particle module which can be used to represent near-source dispersion more accurately. In TAPM, emissions can be input either as points, lines, and areas, or can be grid-based; in fact, TAPM has a grid-based emission file specification for “vehicle petrol exhaust emissions”. TAPM also runs in a chemistry mode and specifically represents chemical reactions between pollutants emitted and background pollutants (Hurley, 2005a; b).

One example of a grid model considered is the Urban Airshed Model (UAM) developed and maintained by Systems Applications International (SAI), a subsidiary of ICF International. The Urban Airshed Model - Variable grid (UAM-V), which is the most current operational version of the UAM, *is a “three-dimensional photochemical grid model designed to calculate the concentrations of both inert and chemically reactive pollutants by simulating the physical and chemical processes in the atmosphere that affect pollutant concentrations”* (SAI, 1999). Concentrations of pollutants are calculated by solving the terms of the advection/diffusion equation at time intervals of the order of a few minutes using numerical integration. The UAM-V uses hourly three dimensional meteorological inputs (generated by diagnostic or prognostic meteorological models); emission inputs include gridded, hourly estimates of gaseous pollutants including VOC, NO\textsubscript{x} as NO and NO\textsubscript{2}, and CO for all sources. In addition, the model needs air quality data as an input to specify the initial concentration fields and the concentrations on
boundaries of the domain. The model outputs a three-dimensional array of concentrations for all pollutants for averaging periods specified by the user and for each advection time step (SAI, 1999). A popular application of the UAM-V is to simulate the processes involved in the production and fate of tropospheric ozone from emissions of NO\textsubscript{x}, VOC, and CO.

Another photochemical model considered is the Community Multiscale Air Quality (CMAQ) modelling system, developed by the USEPA’s Atmospheric Science Modelling Division. It consists of a suite of programs for conducting air quality simulations. The model can address a wide range of atmospheric chemistry phenomena including the generation of tropospheric ozone, acid deposition, visibility, and fine particulates. The approach taken by model developers is that of a “one atmosphere” whereby all interactions occurring between the different pollutants and their precursors are modelled simultaneously and holistically at a regional or urban scale. Air quality modeling is viewed as an integral part of atmospheric modeling and the governing equations are consistent and compatible. The CMAQ system has three main components: it incorporates output fields from an emission model as well as a meteorological model, which together are fed into the CMAQ Chemical Transport Model (CCTM). The CCTM then performs chemical transport modeling for multiple pollutants. Currently, the Models-3 Emission Projection and Processing System (MEPPS) produces the emissions and the Fifth Generation Penn State University/ National Center for Atmospheric Research Mesoscale Model (MM5) provides the meteorological fields needed for the CCTM (Ching and Byun, 1999; Byun, 1999).

8.3.2 Decision-making

In order to make a decision on the most appropriate model for the dispersion of road emissions in the GTA, various issues were taken into account when assessing the different models. While a more sophisticated methodology than the traditional Gaussian plume approach is preferred, an important consideration is whether the data available justifies the use of a sophisticated model. For example, a model like CMAQ, which involves significant chemistry, would require the incorporation of all sources of emissions and background pollutant concentrations (especially ozone) to provide accurate concentrations. While most advanced models address the limitations of Gaussian plume models, it is not necessary that their results are more accurate especially if an application primarily aims at looking at the near-field under wind speeds greater than 1 m/s.
Another issue taken into consideration is the flexibility of the modelling system itself to accommodate different types of sources should future research directions lead to the incorporation of not only roads but other sources of emissions in the GTA. These issues and others considered during the model selection process are listed below:

1. The need to look at both near-field and far field impacts. Near field impacts are important in light of the expected high populations in proximity of roadways. Far-field impacts are important from a policy point of view whereby one can estimate the contributions of regions within the GTA to air pollution in other regions. This is mostly important in assessing the effect of emissions generated in the City of Toronto on air pollution in the surrounding municipalities.

2. The need to take into account the transport time of pollutants from source to receptor especially that sub-hourly emissions are considered as a future extension of the current model.

3. The need to capture the effect of low wind speeds and stagnation events that occur during the summer season in Toronto.

4. The need to model the effect of Lake Ontario on the generation of land/sea breezes.

5. The need to maintain the shape of the road network and the distances between roads and centroids of traffic analysis zones. This criterion leads to a very large number of sources if every roadway link is modelled individually. CALPUFF allows for the assignment of emissions to specific roadway links. Indeed, a main drawback of current modelling approaches for large urban areas is the allocation of emissions to grid cells. This process uniformly spreads road emissions throughout a grid cell rather than to a specific link. This reliance on spatial surrogates runs the risk of underestimating emission density and hence pollutant concentrations along and in the vicinity of roadways.

6. The ability to disperse sub-hourly emissions that are generated by microsimulation models of traffic and vehicle emissions.

7. The ability to handle an extremely large number of individual sources (up to 60,000).

8. The ability to model up to one year of meteorology and emissions thus respecting the one year time step in ILUTE. This is not considered a hard constraint as representative days can also be selected for modelling.

9. Invariability with respect to advanced chemistry. It is beyond the scope and policy relevance of ILUTE to model advanced chemical processes. The resulting concentrations will serve as a basis for comparing different policy scenarios.

10. Invariability with respect to treatment of complex terrain as the GTA is generally flat.
Based on items 1 through 4 in the above list and taking into account the fact that current emissions estimated for the road network in the GTA are time-varying, a steady-state Gaussian plume model was ruled out. According to MFE (2004), as a rule of thumb, Gaussian plume models are generally applicable when only first order chemistry is required, the terrain is not steep, the meteorology may be considered spatially uniform, and there are few periods of calm winds. Advanced models, on the other hand, should be used when meteorological conditions vary across the modelling domain, modelling is conducted in a complex terrain, calm conditions are frequent, pollutants accumulate during calm conditions and can recirculate when winds change, and if chemical transformations are important. While complex terrain is not an issue in the GTA, uniformity of the meteorology across the modelling domain cannot be considered as a valid assumption. This is mainly due to the effect of Lake Ontario that should be taken into account. Item 5 rules out the use of grid-models such as the UAM-V which involve “gridding” of emissions. Beyond, the fact that they adopt a grid approach, both UAM-V and CMAQ are photochemical models which makes their use inappropriate for modelling road emissions exclusively since all sources as well as background air quality need to be incorporated in photochemical models to obtain sensible concentrations of air pollutants. While different in their theoretical approaches to dispersion, both CALPUFF and TAPM generally satisfy most of the objectives and constraints of the current application. The open-source nature of CALPUFF, its validation and use in the United States and Canada, are considered as highly valuable assets of the model; CALPUFF is also the “preferred” model used by the City of Toronto for dispersing road and other emissions. Being an open-source model, CALPUFF can be recompiled to increase array sizes for the numbers of sources and other variables. For these and all reasons cited in the numbered list, CALPUFF was selected as the dispersion model for this research. One main disadvantage of CALPUFF is its inability to estimate ground-level ozone concentrations; indeed CALPUFF is not a “chemistry model” per se. As stated in item 9, advanced chemistry is not an objective at this stage. This is mainly because road emissions are modelled exclusively and due to the nature of this exercise, which is to develop a transport policy assessment tool rather than an urban air quality management tool.
8.4 Overview of selected model (CALMET/CALPUFF)

The original development of CALPUFF and its related meteorological pre-processor CALMET was sponsored by the California Air Resources Board (CARB). Currently, CALPUFF is owned by TRC Environmental Inc. and managed by its Atmospheric studies group (ASG). The CALPUFF modelling system has three main components: 1) a meteorological modelling package, CALMET; 2) a Gaussian puff dispersion model with chemical removal, wet and dry deposition, building downwash, and complex terrain effects; and 3) a set of pre- and post-processors for land-use, terrain, concentrations, and deposition fluxes. Part of the CALPUFF model system, two models were also developed that can interface with CALMET for meteorological information and share the pre- and post-processors, these include; 1) a photochemical model, CALGRID which was developed as an improvement over the UAM (described in Section 8.3.1.2); and 2) a Lagrangian particle model, the Kinematic Simulation Particle (KSP) model which uses explicit kinematic simulation of transport and dispersion eddies in the atmosphere (Scire et al., 2000a). Neither CALGRID nor KSP were used in the present study, hence they will not be discussed further. This section provides a description of CALPUFF and CALMET and refers to some of the relevant pre- and post-processors.

8.4.1 CALMET meteorological model

CALMET is a meteorological model which uses a grid system of vertical and horizontal grid cells and operates in a terrain-following vertical coordinate system. CALMET develops three dimensional hourly gridded fields of wind and temperature. Other meteorological fields generated by the model include gridded, two-dimensional fields of surface friction velocities, convective velocity scales, mixing heights, Monin-Obukhov lengths, stability classes, and precipitation rates. Output from CALMET is used to drive the dispersion of pollutants in CALPUFF. This section briefly describes the diagnostic wind field module in CALMET (Figure 8.3); detailed descriptions of this and other modules can be found in Scire et al. (2000b).
As seen in Figure 8.3, the wind field module uses a two step approach to the computation of wind fields. In the first step, an initial guess field is adjusted for terrain effects thus producing the Step 1 winds. In the second step, the Step 1 winds are refined through the introduction and processing of observational data thus resulting in the Step 2 or final wind field.

8.4.1.1 Generation of Step 1 wind field

The initial guess field can be a three-dimensional wind field or a constant (domain mean) wind used throughout the grid. The latter can be computed internally by vertically averaging and time-interpolating upper air sounding data or obtained from meteorological station observations which in turn can be extrapolated vertically using similarity theory to determine the initial guess field. Typically, and if available, a three-dimensional gridded wind field is used as the initial guess field. Generally, the three-dimensional wind field is generated by a prognostic wind field model executed on a relatively coarse grid. Prognostic models for example, can reflect the vertical structure of a lake breeze circulation that may not be captured by surface observations and provide information for areas of the modelling domain that lack observational data. When output from prognostic models is used as the initial guess field, winds are first interpolated to the fine
scale CALMET grid. A model commonly used as a source of input data for the CALMET initial guess field is the Pennsylvania State University / National Center for Atmospheric Research (PSU/NCAR) mesoscale model known as MM5 (Grell et al., 1994). Chandrasekar et al. (2003) discuss the advantage of using a blend of mesoscale prognostic model output (MM5) and a diagnostic model (CALMET). The prognostic model has a high enough resolution to capture topographically forced wind flows such as lake/sea breezes and mountain/valley winds while the diagnostic model has an even finer resolution so that it can refine prognostic model winds.

Following the setup of the initial guess field, CALMET simulates the kinematic effects of terrain, slope flows, and terrain blocking effects in order to generate the Step 1 wind field. Mathematical formulations for the three modules are presented in Scire et al. (2000b). Alternatively, MM5 data can be input as the Step 1 wind field whereby the simulation of terrain effects is bypassed.

### 8.4.1.2 Generation of Step 2 (final) wind field

This second step starts with the introduction of data from surface stations and/or upper air soundings into the Step 1 gridded wind field. Following the input of observations, CALMET performs an inverse distance method to interpolate observations. This scheme allows for observational data to be heavily weighed in the vicinity of the observational station while the Step 1 wind dominates in areas of the modelling domain where observations are lacking. The weighing procedure is applied independently for the surface layer and the layers aloft. This allows for inputting different weights to surface observational data and upper air data. An observation is excluded from interpolation if the distance between the observation and a particular grid point exceeds a maximum radius of influence. In addition to horizontal spatial interpolation, CALMET performs a vertical extrapolation of surface winds into higher layers as an option. Following the addition of observational data, CALMET performs a smoothing of the wind field whereby the $x$ and $y$ wind components after smoothing are estimated as a function of the $x$ and $y$ wind components of the four grid points surrounding a particular point on the grid. The computation of vertical velocities is computed using one of two methods, mass conservation, and the O'Brien procedure which forces the vertical velocity at the top of the modelling domain to be zero. Finally, three-dimensional divergence in the wind field is
minimized at every grid point. For this purpose, CALMET performs an iterative procedure to gradually reduce divergence throughout the modelling domain. Mathematical formulations for the different steps leading to the generation of the Step 2 wind field are presented in Scire et al. (2000b).

8.4.2 CALPUFF dispersion model
CALPUFF is a transport and dispersion model that advects puffs of emitted pollutants while simulating chemical transformation processes along the way. It contains algorithms for near-source effects such as building downwash, transitional plume rise, partial plume penetration, subgrid scale terrain interactions, and longer range effects such as wet and dry deposition, chemical transformation, vertical wind shear, over-water transport, and coastal interaction effects. Typical output from CALPUFF includes hourly concentrations and deposition fluxes at receptor locations. Scire et al. (2000a) provide a comprehensive technical discussion of the different CALPUFF modules; some of which are summarized in this section.

8.4.2.1 Technical discussion of selected CALPUFF modules and formulations
CALPUFF follows the general puff formulation presented in Section 8.2.2.2. However, in order to overcome the drawback of having to generate an extremely large number of puffs to accurately represent concentrations in the near-field, CALPUFF also incorporates a “slug” formulation. While a puff is radially symmetric, a slug is a non-circular puff, elongated in the direction of the wind during release, to eliminate the need for frequent releases of puffs. An advantage of these two sampling schemes is through the use of a slug formulation for the near-field and puff in the far-field. Equation 8 illustrates the basic equation for the contribution of one puff at one receptor and at a specific snapshot in time. Equation 9 describes the slug formulation in CALPUFF whereby the concentration at a receptor from one slug at a specific point in time, is illustrated. Equation 9, represents a slug as a continuous emission of puffs having very small puff separation distances, and each containing an infinitesimal mass of \( q \, dt \). As with circular puffs, each slug is free to evolve independently in response to dispersion, chemical transformation, etc. As with the puff approach, the slug formulation is robust with respect to low wind speeds. In fact, the factor \( (u/u') \) in Equation 9 allows low winds and calm conditions to be treated properly. As \( u \) approaches zero, the exponential crosswind term becomes 1 and the radial concentration
depends on $F$, the “causality function”. When $u$ is greater than a few meters per second, the ratio $(u/u')$ is 1 and becomes unimportant. According to Scire et al. (2000a), the slug formulation is more “puff-like” than segmented plume models which do not perform very well under low wind speeds and do not treat well segment edge effects.

\[
C = \frac{M}{2\pi \sigma_x \sigma_y} g \exp\left[-\frac{d_a^2}{2 \sigma_x^2}\right] \exp\left[-\frac{d_c^2}{2 \sigma_y^2}\right]
\]

whereby

\[
g = \frac{2}{(2\pi)^{1/2} \sigma_z} \sum_{n=-\infty}^{+\infty} \exp\left[-\frac{(H+2nh)^2}{(2\sigma_z^2)}\right]
\]

Where

- $C$ ground-level concentration
- $M$ pollutant mass in the puff
- $\sigma_x$ dispersion coefficient at the receptor in the along-wind direction
- $\sigma_y$ dispersion coefficient at the receptor in the crosswind direction
- $\sigma_z$ dispersion coefficient at the receptor in the vertical direction
- $d_a$ distance from puff center to the receptor in the along-wind direction
- $d_c$ distance from the puff center to the receptor in the crosswind direction
- $H$ effective height above the ground of the puff center
- $h$ mixing height
- $g$ vertical term that takes into account multiple reflections (ground or ceiling)

\[
C = \frac{FQ}{(2\pi)^{1/2} u' \sigma_y} g \exp\left[-\frac{d_a^2}{2 \sigma_y^2} \frac{u^2}{u'^2}\right]
\]

whereby

\[
F = \frac{1}{2} \left\{ \text{erf}\left[\frac{d_{a2}}{2 \sigma_y^2}\right] - \text{erf}\left[\frac{d_{a1}}{2 \sigma_y^2}\right] \right\} + g \text{ as in Equation 10}
\]

Where

- $Q$ emission rate
- $u$ vector mean wind speed
- $u'$ scalar mean wind speed defined as $u'=(u^2+\sigma_v^2)^{1/2}$ with $\sigma_v$ defined as the wind speed variance
- $\sigma_y$ dispersion coefficient at the receptor in the crosswind direction
- $\sigma_{y1}$ dispersion coefficient at the oldest end of the slug in the crosswind direction
- $\sigma_{y2}$ dispersion coefficient at the youngest end of the slug in the crosswind direction
- $d_c$ cross-slug distance to the receptor
- $d_{a1}$ along-slug distance from end 1 (oldest end) to the receptor
- $d_{a2}$ along-slug distance from end 2 (youngest end) to the receptor ($d_{a2}>0$ in the direction of end 1)
- $F$ “causality” function, it takes into account edge effects near the end points
of a slug, for long emission times and receptors inside the body of the slug \( F=1 \)
(no edge effects), for receptors outside the slug \( F=0 \) (pollutant has not reached
the receptor), near the end points, \( F \) produces a leading/trailing Gaussian trail

A key consideration for either the puff or slug dispersion is the estimation of the horizontal and
vertical Gaussian dispersion coefficients \( \sigma_y \) and \( \sigma_z \) at the start and end of each sampling step, and
at each receptor location. CALPUFF provides various methods for estimating the dispersion
coefficients as detailed in (Scire et al., 2000a). The model also allows for puff-splitting due to
vertical wind shear. The change of wind speed and direction in height may cause a differential
advection of pollutant whereby shear across a single puff may transport the upper portion of a
puff in a different direction than its lower portion. Other effects estimated by the model include:

- Building downwash and plume rise (buoyant and momentum)
- Overwater and coastal dispersion which significant due to the differences in structure
  between the marine and land environments. In fact, water has a relatively low diurnal
  temperature change, the sea surface is aerodynamically less rough that land surfaces, and
  there is constant moisture in marine environments. This leads to a sensible heat flux over
  water which is significantly less than that over land; this absence of a strong sensible heat
  flux and the relatively smooth water surface result in relatively low mixing heights which can
  lead to plume trapping in marine environments. CALPUFF also includes a Thermal Internal
  Boundary Layer (TIBL) module when coastal effects need to be resolved on a sub-grid scale.
- Dispersion in complex terrain whereby CALPUFF simulates changes in the flow of pollutant
  in the vicinity of terrain features. A central feature of the complex terrain module is the
  dividing-streamline concept whereby a flow is composed of two layers. The upper layer of
  the flow has sufficient energy to transport pollutants up and over a hill, while in the lower
  layer, the flow travels around a hill.
- Linear chemical transformation which can either be in the form of a pseudo first order
  chemical reaction mechanism for the conversion of \( \text{SO}_2 \) to \( \text{SO}_4^{2-} \) and \( \text{NO}_x \) \((\text{NO}+\text{NO}_2) \) to \( \text{NO}_3^- \)
or can treat the \( \text{NO} \) and \( \text{NO}_2 \) conversion process and the \( \text{NO}_2 \) to total \( \text{NO}_3 \) and \( \text{SO}_2 \) to \( \text{SO}_4 \),
  conversions with equilibrium between gaseous HNO\(_3\) and ammonium nitrate aerosol. Those
two options necessitate the input of background ozone concentrations (as a surrogate for the
OH concentration during the day when gas phase free radical chemistry is active).
- Changes in regional visibility whereby CALPUFF provides hourly concentrations of
  sulphates and/or nitrates and/or other particulates and the post-processor CALPOST
  computes a light extinction coefficient relative to the background light extinction. The light
  extinction coefficient includes both scattering and absorption and measures the attenuation of
  light over a unit distance.
- Adjustments to the dispersion algorithms when wind speeds are less than a user-specified
  value (default is 0.5m/s)
8.4.2.2 Overview of selected CALPUFF implementations

Typically, applications of CALPUFF involve long-range transport in complex terrain due to its ability to capture terrain effects and its non-steady-state nature; examples of such applications include estimating exposure to power plant emissions (Levy et al., 2002; Zhou et al., 2003) and predicting the impact of industrial and domestic heating sources (Elbir, 2003). Due to its extensive expertise and computational requirements, applications of CALPUFF for near-field analysis and in urban areas have been limited. Two studies of interest to the current research illustrate the potential of CALPUFF and its advantage in near-field and urban area applications.

Recent air quality modelling in Portland has used CALPUFF to assess the impact of vehicle emission on concentrations of three hazardous air pollutants: benzene, 1,3-butadiene, and diesel particulate matter. The resulting concentrations were used to develop a regression model that links roadway proximity with air pollutant concentrations, and to estimate the area of influence around roadways. The advantage in the use CALPUFF was the ability to treat roadway links as line sources rather than use a grid cell approach for the dispersion of hazardous air pollutants. Emissions for link segments were obtained from EMME/2 and Mobile6.2 data. The regression results showed limited capability to predict CALPUFF concentrations. However, the authors found the zone of influence around a roadway to be between 200 and 400 meters, thus suggesting that in order to capture localized impacts, the need to include individual roadway links is crucial (Cohen et al., 2005).

The implementation of CALPUFF for a near-field analysis in the Alpine Lakes Wilderness Area, has shown improved ability to calculate chemical transformation and deposition as well as to incorporate terrain effects, as opposed to ISC3 and CALPUFF-Lite (CALPUFF driven by ISC single point meteorology) (Carper et al., 2003). The authors found that the implementation of CALPUFF has reduced the overestimation of concentrations that is typically associated with steady-state Gaussian dispersion models and resulted in a more realistic dispersion representation.
8.5 CALMET meteorological modelling

A CALMET run was conducted to obtain hourly data for 2001 that can be input into CALPUFF which in turn will estimate hourly average pollutant concentrations. The most recent version of CALMET was used (Version 6.112). This section describes the modelling domain, input data for CALMET, and discusses as well as validates the results of the CALMET scenario for 2001. The development of sensible meteorological data is crucial for air dispersion modelling. Special emphasis is devoted to wind fields due to their importance in the transport of pollutants.

8.5.1 Modelling domain

While the emission sources are restricted to the GTA and Hamilton, the modelling domain for CALMET (and CALPUFF) is significantly larger. The reason for that is to allow for dispersion of emissions beyond the near-field. The modelling domain, presented in Figure 8.4, has an area of 252 x 252 Km. It includes the GTA and Hamilton but also most of Lake Ontario (which is expected to have an effect on meteorology and dispersion), Lake Simcoe, the Niagara Escarpment, Nottawasaga Bay, and extending all the way East to the town of Brighton North of Lake Ontario.

The lower left corner has the following coordinates in Universal Transverse Mercator (UTM) (datum NAD83, zone 17 N): UTM Easting (Km) = 520 and UTM Northing (Km) = 4760. The domain is divided into 210 grid cells in the X direction (Easting) and 210 grid cells in the Y direction (Northing); the size of every grid cell is 1.2 x 1.2 Km. The grid spacing is indeed a compromise between processing time and resolution of the results, due to the large number of sources and size of the domain, a smaller grid spacing would significantly increase the processing time and was not considered. Recall, that the aim of the current application is to look at air pollution at the level of the whole of every TAZ rather than in microenvironments such as roadway intersections. Any application that aims at assessing the impact of traffic on urban environments in the vicinity of the roadways should decrease the grid spacing; and focus on small sub-areas of the modelling domain. Vertically, in the z direction, the domain consists of 10 levels, the elevations of each level 1 to level 10 are: 20m, 40m, 80m, 160m, 320m, 700m, 1300m, 1700m, 2300m, and 3000m.
8.5.2 Input data

A flow chart of inputs and outputs for the CALMET/CALPUFF system, specific to the current modelling application, is presented in Figure 8.5. As illustrated in Figure 8.5, significant data gathering and processing was conducted in order to set up a CALMET run for the modelling domain and year 2001. These data include 1) terrain, 2) land cover, 3) surface and 4) three-dimensional meteorology.
Terrain elevation data for the modelling domain were obtained from the Shuttle Radar Topography Mission (SRTM) mainly conducted by the National Aeronautics and Space Administration (NASA) and the National Geospatial-Intelligence Agency (NGA). The SRTM data are organized into rasterized cells, or tiles, each covering one degree by one degree in...
latitude and longitude. Sample spacing for individual data points is 1 arc-second, 3 arc-seconds, or 30 arc-seconds, referred to as SRTM1, SRTM3 and SRTM30, respectively. The data for the modelling domain is in SRTM3 which roughly corresponds to 90 meters in resolution. A description of the SRTM mission can be found in Farr et al. (2007). SRTM3 data were input into the terrain processor TERREL which allocates the raw terrain elevation data to the modelling grid. Output from TERREL for the modelling domain is presented in Figure 8.6. Land cover data for the modelling domain were obtained from the United States Geological Survey (USGS) Global Land Cover Characteristics (GLCC) Database V2.0. The resolution of the data is 1Km, which is acceptable concerning the resolution of the modelling domain is 1Km as well. The data legend follows the USGS Land Use/Land Cover general scheme. Documentation on the GLCC Database in addition to the Land Use/Land Cover system legend is available online: (http://edcsns17.cr.usgs.gov/glcc/globdoc2_0.html#app3). Land cover data were input in the CTGPROC land-use processor which computes the fractional land-use for each grid cell in the modelling domain. Output from CTGPROC for the modelling domain, overlaying the terrain elevations is presented in Figure 8.7.
Figure 8.7 3D terrain overlaid by land-use for the modelling domain (source for land-use: USGS GLC Res: 30 arc-sec ~ 1Km). Map features surface meteorological stations (1: Burlington, 2: Buttonville, 3: Hamilton airport, 4: Toronto Island Airport, 5: Pearson Airport, 6: Port Weller).

Surface meteorological data were obtained from the National Climate Data and Information Archive (Climate Data Online) which is part of the Weather Office at Environment Canada. Hourly data for 2001 for six meteorological stations within the modelling domain were extracted. The meteorological stations are listed in Table 8.2; their locations are presented in Figure 8.7. Hourly data extracted include Temperature, Dew Point Temperature, Relative Humidity, Station Pressure, Wind Direction, Wind Speed, and Visibility (Table 8.3). Note that the data were not in the proper format for processing by the modelling system; hence, a macro was developed to convert Environment Canada data into the US National Climatic Data Center (NCDC), Hourly US Weather Observations (HUSWO) format and to handle missing data. Formatted data was input into SMERGE which processes hourly observations from various meteorological stations into a single file with the data sorted by time rather than station.

Three dimensional hourly meteorological data for 2001 was extracted from an MM5 run that encompasses the modelling domain; MM5 data was kindly provided by Mr. Joseph Scire, Vice President and Group Manager of the Atmospheric Studies Group at TRC Inc., owner of the CALPUFF modelling system. The data was pre-formatted and could be directly used by
CALMET. The resolution for the MM5 data is 36Km and consists of 29 vertical layers. For every grid cell, surface pressure, total rainfall for the past hour, and a snow cover indicator are contained in the MM5 file. In addition, for every grid cell and every vertical layer; pressure, elevation, temperature, wind direction, and wind speed are included. These data are provided for every hour and for the year 2001; thus generating a very large meteorological file. The availability of MM5 data for the modelling domain is crucial considering the lack of upper air data in the modelling domain (the nearest upper air sounding is located in Buffalo, approximately 50Km South-West of the modelling domain).

Table 8.2 Description of surface meteorological stations in modelling domain

<table>
<thead>
<tr>
<th>Meteorological Station Name</th>
<th>Latitude, Longitude</th>
<th>Elevation (m)</th>
<th>WMO identifier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burlington Piers (WWB)</td>
<td>43.3, -79.8</td>
<td>77.4</td>
<td>71437</td>
</tr>
<tr>
<td>Toronto Buttonville A (YKZ)</td>
<td>43.86, -79.37</td>
<td>198.1</td>
<td>71639</td>
</tr>
<tr>
<td>Hamilton A (YHM)</td>
<td>43.7, -79.93</td>
<td>237.7</td>
<td>71263</td>
</tr>
<tr>
<td>Toronto Island A (YTZ)</td>
<td>43.63, -79.4</td>
<td>76.5</td>
<td>71265</td>
</tr>
<tr>
<td>Toronto Lester B. Pearson Int'l A (YYZ)</td>
<td>43.68, -79.63</td>
<td>173.4</td>
<td>71624</td>
</tr>
<tr>
<td>Port Weller (WWZ)</td>
<td>43.25, -79.22</td>
<td>79.0</td>
<td>71432</td>
</tr>
</tbody>
</table>

Table 8.3 Environment Canada’s description of surface observation data fields (from The Climate Glossary: http://www.climate.weatheroffice.ec.gc.ca - Climate Glossary)

<table>
<thead>
<tr>
<th>Data field</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>The temperature of the air</td>
</tr>
<tr>
<td>Dew Point Temperature</td>
<td>A measure of the humidity of the air. It is the temperature to which the air would have to be cooled to reach saturation with respect to liquid water. Saturation occurs when the air is holding the maximum water vapour possible at that temperature and atmospheric pressure.</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>The ratio of the quantity of water vapour the air contains compared to the maximum amount it can hold at that particular temperature</td>
</tr>
<tr>
<td>Station pressure</td>
<td>Atmospheric pressure or force per unit area exerted by the atmosphere as a consequence of the mass of air in a vertical column from the elevation of the observing station to the top of the atmosphere.</td>
</tr>
<tr>
<td>Wind direction</td>
<td>The direction (true or geographic, not magnetic) from which the wind blows: 90 degrees means an east wind, and 360 degrees means wind blowing from the geographic north pole.</td>
</tr>
<tr>
<td>Wind speed</td>
<td>The speed of motion of air, usually observed at 10 meters above the ground.</td>
</tr>
<tr>
<td>Visibility</td>
<td>The distance at which objects of suitable size can be seen and identified. Atmospheric visibility can be reduced by precipitation, fog, haze or other obstructions to visibility such as blowing snow or dust.</td>
</tr>
</tbody>
</table>
8.5.3 Setup of CALMET run
Beyond the processing of input data, described in the previous section, setting up the CALMET run involved testing and making decisions with respect to different parameters and algorithms embedded in the model; the most important of which include: wind field module, calculation of mixing heights and lapse rates, terrain effects and radius of influence of terrain features, radii of influence of surface stations and weighing of step1 wind fields versus observations, and surface wind extrapolation. CALMET was run in a diagnostic wind field module whereby MM5 data was set up as the initial guess field and surface observations were introduced in Step 2 (cf. Section 8.4.1). The weight given to the surface observations versus the Step1 wind field is extremely important factor. A high weight given to a surface station would force winds to follow the wind vector recorded at the station thereby wiping out terrain effects since only the Step1 wind field is adjusted for terrain. In addition MM5 data can capture sea and land breezes which may not be captured by surface stations. Surface stations are believed to accurately represent “microenvironments” and therefore care was taken when weighing observations. Appendix D illustrates the effect of weighing of surface observations and radii of influence of surface stations.

An input file CALMET.INP, containing all the different inputs and links to input data files, was prepared and is presented in Appendix E. A total of two CALMET runs were conducted to simulate the whole of 2001; the first run was for January to June 2001 and the second run covered July to December 2001. The run time for each of the two runs was 18 hours; thus amounting to a total runtime of 36 hours for the meteorological simulation. The two resulting output files CALMET_1.dat and CALMET_2.dat were further used as inputs into CALPUFF. Meteorological data generated by CALMET include wind vectors, temperature, precipitation, mixing height, stability class, and relative humidity.

8.5.4 Validation of wind fields
Wind vectors generated by CALMET were extracted from the CALMET output file using PRTMET and plotted using the SURFER V8.0 contouring and gridding software as a way of visualizing wind speeds and directions in the modelling domain. Figure 8.8 illustrates wind fields on July 17, 2001 at 6pm and on January 5, 2001 at 10am.
Figure 8.8. Wind vectors for selected hours (6pm on July 17 and 10am on January 5)
Clearly, wind fields are significantly different. On July 17 at 6pm, wind fields show what could probably be the generation of a lake breeze, this is mainly because environmental winds are low (ranging between 0.06 and 2.97 m/sec) which makes the lake breeze detectable; while on January 5 at 10am, wind speeds are much higher especially over the lake.

In light of the importance of wind fields to the transport of pollutants, wind vectors generated by CALMET should be validated against surface observations. Note that, while winds are generated on an hourly basis, it is beyond the scope of the meteorological model to replicate every hour. Instead, aggregated wind vectors over a period of time are expected to reflect existing conditions. For this purpose, time series files for hourly wind speeds and directions for 2001, were extracted at three locations (Hamilton Airport, Pearson Airport, and the Toronto Island Airport) using PRTMET. A macro was developed that constructs monthly windroses (combines wind speeds and directions with frequencies of occurrence) from hourly data. As a result, monthly windroses were constructed and plotted for the three locations for both modelled and measured data. For every month and location, windroses for measured and modelled winds were compared; the most important discrepancies are discussed next.

For illustration purposes, Figure 8.9 presents four windroses extracted for Pearson Airport and comparing measured and modelled winds for the months of March and September. The full set of windroses for the three locations and twelve months are presented in Appendix F. Based on the monthly windroses developed for the three locations, some general trends are observed. In general, CALMET captures well the most frequent winds in the GTA, which are Westerly, Southwesterly, or Northwesterly. Northern winds are somehow under-represented by the model especially the Northern wind gusts which occur in the winter season. CALMET predicts overall lower wind speeds and under-represents winds higher than 10m/s. Since there are only 6 surface stations in the domain, the model relies heavily on the Step 1 wind fields which are based on MM5. It is expected that MM5 would predict overall seasonal or monthly trends but not low frequency extreme weather events. In an application of CALMET to wind resource assessment and forecasting, a comparison of annual windroses for CALMET and observed winds at Nantucket Airport in 2003; revealed similar results to the ones observed in this study. Overall wind directions and speeds are well captured by CALMET but the frequency of high wind speeds is higher among measured data (Klausmann and Scire, 2005).
Figure 8.9 March and September windroses (modelled and observed) for Pearson Airport
With this in mind, note that the objective of this modelling application is to compare policy scenarios rather than forecast air quality episodes, as such, meteorology is important in the sense that the general meteorological patterns are captured on a monthly basis. Changes during the day, especially day-night distinctions are also important in terms of temperature and atmospheric stability changes on a 24-hour basis. While it is not necessary that predictions for a certain day match the reality on that specific day, it is important to capture “typical days” in every month or season, that reflect both average conditions and extreme events occurring during that month even if their frequency of occurrence is not exactly replicated. The rationale behind the development of a yearly meteorology file is because a year of meteorology is expected to cover approximately the whole range of typical atmospheric conditions that may prevail thereby allowing for the computation of yearly pollutant concentrations. This is of special concern when chronic exposure to a particular contaminant is an issue.

This 2001 CALMET run will serve as a basis for most air quality analyses conducted for the GTA. The CALMET file can be called from CALPUFF and depending on the air dispersion simulation days, CALPUFF will read the corresponding meteorological information.

### 8.6 CALPUFF air dispersion modelling

Following the generation of three dimensional meteorological data for the modelling domain, the CALMET output file was used to drive the CALPUFF dispersion model. Meteorological data and link-based emissions (Chapter 7) were combined, along with other inputs, to estimate base-case 2001 pollutant concentrations. Recall from Chapter 7 that emissions were estimated solely for private autos (excluding, buses, trucks, and other commercial vehicles). As such, the concentrations resulting from a dispersion of these emissions are expected to reflect the contribution of private autos to air pollution. In the GTA and especially in the City of Toronto, road transportation contributes to a significant fraction of total emissions and private autos constitute the majority of road transport emissions (ICF International, 2007). As such, an assessment of the contribution of private autos to air pollution can provide valuable information on the patterns of air quality in the urban area. This section describes the method adopted for the development of concentration profiles using the CALPUFF dispersion model. Pollutant
selection, input data, and model setup are discussed. Results of the dispersion model are presented and examined in the next chapter.

8.6.1 Pollutants and standards
In Chapter 7, the selected CACs for which emissions were computed for the road network in the GTA include: VOCs, CO, and NO\textsubscript{x} which are mainly composed of nitrogen dioxide (NO\textsubscript{2}) and nitric oxide (NO) (in addition to other minor compounds: nitrous oxide, N\textsubscript{2}O; nitrate, NO\textsubscript{3}; dinitrogen trioxide, N\textsubscript{2}O\textsubscript{3}; dinitrogen tetroxide N\textsubscript{2}O\textsubscript{4}; and dinitrogen pentoxide N\textsubscript{2}O\textsubscript{5}). For the purpose of the present CALPUFF dispersion application for the GTA, only NO\textsubscript{x} emissions, with emphasis on modelling the ambient NO\textsubscript{2} concentrations, are addressed.

8.6.1.1 Formation of NO\textsubscript{2} and ozone
Most atmospheric NO\textsubscript{2} is emitted as NO which has some harmful effects on health but these effects are substantially less than those of an equivalent amount of NO\textsubscript{2}. Yao et al. (2005) conducted long tunnel experiments to characterize primary vehicular NO\textsubscript{2}/NO\textsubscript{x} ratios. They observed NO\textsubscript{2}/NO\textsubscript{x} ratios of less than 2 percent in sections of the tunnel where ozone (O\textsubscript{3}) concentrations were at a minimum. The authors conclude that directly emitted NO\textsubscript{2} from vehicles does not have a significant impact on atmospheric NO\textsubscript{2} concentrations.

NO is converted to NO\textsubscript{2} through a number of reactions, NO\textsubscript{2} in turn goes through various reactions thus producing O\textsubscript{3} (Zanetti, 1990; De Nevers, 1995). Ambient NO\textsubscript{2} is decomposed by a photon to produce NO and the oxygen radical O, the latter reacts with O\textsubscript{2} to form O\textsubscript{3}; the O\textsubscript{3} molecule then reacts with NO to form NO\textsubscript{2}:

\begin{align*}
(1) \quad & NO_2 + h\nu \rightarrow O + NO \\
(2) \quad & O + O_2 + M \rightarrow O_3 + M \quad \text{(where M represents any molecule, usually N\textsubscript{2} or O\textsubscript{2}, which carries some of the energy released in the reaction)} \\
(3) \quad & NO + O_3 \rightarrow NO_2 + O_2
\end{align*}

Reaction (3) is generally fast, Yao et al. (2005) cite an NO\textsubscript{2} formation rate of 27% min\textsuperscript{-1} under specific ambient temperature and O\textsubscript{3} concentration. In the absence of VOC, the three reactions
(1), (2), and (3) lead to an equilibrium between NO, NO$_2$, and O$_3$ that depends on the intensity of the solar radiation. Every NO$_2$ molecule that is split produces both an NO and an O$_3$ molecule which can then react to reverse the reaction. The role of VOCs is to convert NO to NO$_2$ without using O$_3$ so that there is not enough NO to use all the O$_3$ thus leading to an accumulation of O$_3$:

(4) OH + VOC $\rightarrow$ RO$_2$ + H$_2$O (where R stands for any hydrocarbon)
(5) RO$_2$ + NO $\rightarrow$ NO$_2$ + RO
(6) RO + O$_2$ $\rightarrow$ RCHO + HO$_2$
(7) HO$_2$ + NO $\rightarrow$ NO$_2$ + OH

Reactions (4), (5), (6), and (7) can be represented by an overall reaction where NO$_2$ is formed without use of O$_3$ and generating an aldehyde (RCHO):

(8) VOC + 2NO + O$_2$ $\rightarrow$ H$_2$O + RCHO + 2NO$_2$

Added complexity to the process is generated by the fact that NO$_2$ also reacts with an OH radical to produce nitric acid thus reducing the availability of OH radicals. This reaction means that in some instances, adding NO$_2$ can reduce atmospheric O$_3$:

(9) OH + NO$_2$ $\rightarrow$ HNO$_3$

8.6.1.2 Importance of NO$_2$

There are various reasons associated with the focus on NO$_2$, as listed below:

- NO$_x$ are emitted from high-temperature combustion processes, such as those occurring in trucks, cars, and power plants. Indoor, home heaters and gas stoves also produce substantial amounts of NO$_x$. In urban areas, road transportation is considered as the primary source of NO$_x$ amounting to approximately 50 percent of total NO$_x$ emissions (De Nevers, 1995). In the City of Toronto, transportation is responsible for 73 percent of NO$_x$ emissions (the rest being generated by natural gas in space heaters) (ICF International, 2007):

> Local air quality is particularly sensitive to NOx. The formation of ground level ozone, for instance, is dependent on the availability of NOx as well as heat and sunlight, and local sources of NOx are dominated by the emissions from vehicle
tailpipes and building chimneys. On an annual basis as well as during summer months, vehicle tailpipe NOx emissions predominate over building emissions.

- NO₂ plays a central role in tropospheric chemistry; it reacts with VOCs and ultraviolet light generating tropospheric O₃ and nitrate (NO₃). The latter is an important contributor to the secondary formation of respirable PM₂.₅ in the ambient air.

- NO₂ is a serious respiratory irritant which aggravates respiratory and cardiovascular problems. It is typically absorbed by the moisture coating the airways, forming nitric and nitrous acid. NO₂ also impairs visibility, and interferes with plant growth.

8.6.1.3 Ambient air quality standards for NO₂

There are ambient air quality standards for NO₂ to protect human health. Most regulations for NOₓ emissions base their numerical values on the assumption that the entire NO is converted to NO₂; this is typically expressed as “NOₓ expressed as NO₂”. A summary of the most recent NO₂ standards in selected countries/jurisdictions is presented in Table 8.4. Clearly Canadian and US standards are more lenient than UK and the World Health Organization (WHO) standards. The US National Ambient Air Quality Standards (NAAQS) developed by the USEPA as well as the Canadian and Ontario standards, set an allowable NO₂ level equal to 400 µg m⁻³ for a 1-hour exposure. In contrast, the hourly standard set by the UK Air Quality Objectives for protection of human health and the WHO, is exactly half of the North American Standard (200 µg m⁻³). The Canadian and US annual standard (100 µg m⁻³) is more than twice the UK and WHO standard (40 µg m⁻³). According to the WHO, in population studies, NO₂ was associated with adverse health effects even when the annual concentrations complied with the 40 µg m⁻³ standard. This was especially the case for children and infants. Despite this fact, available evidence to lower the standard was not considered sufficient (WHO, 2005).
Table 8.4 Summary of selected NO2 standards

<table>
<thead>
<tr>
<th>Agency, Location</th>
<th>NO2 concentration</th>
<th>Averaging time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Quality Objectives and Standards, Canada</td>
<td>400 µg m⁻³</td>
<td>Hourly</td>
</tr>
<tr>
<td><a href="http://www.env.gov.bc.ca/air/airquality/pdfs/aqotable.pdf">http://www.env.gov.bc.ca/air/airquality/pdfs/aqotable.pdf</a></td>
<td>200 µg m⁻³</td>
<td>Daily</td>
</tr>
<tr>
<td></td>
<td>100 µg m⁻³</td>
<td>Annual</td>
</tr>
<tr>
<td>Ambient Air Quality Criteria, Ministry of Environment, Ontario</td>
<td>400 µg m⁻³ standard for NOx based on NO2</td>
<td>Hourly</td>
</tr>
<tr>
<td><a href="http://www.ene.gov.on.ca/envision/gp/2424e04.pdf">http://www.ene.gov.on.ca/envision/gp/2424e04.pdf</a></td>
<td>200 µg m⁻³ standard for NOx based on NO2</td>
<td>Daily</td>
</tr>
<tr>
<td>National Ambient Air Quality Standards, Environmental protection Agency (EPA), US</td>
<td>100 µg m⁻³</td>
<td>Annual</td>
</tr>
<tr>
<td><a href="http://www.epa.gov/air/criteria.html">http://www.epa.gov/air/criteria.html</a></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ambient Air Quality Standards, California Air Resources Board (CARB), California</td>
<td>0.18 ppm (approximately 370 µg m⁻³ at standard temperature and pressure)</td>
<td>Hourly</td>
</tr>
<tr>
<td><a href="http://www.arb.ca.gov.research/aaqs/caaqs/no2-1/no2-1.htm">http://www.arb.ca.gov.research/aaqs/caaqs/no2-1/no2-1.htm</a></td>
<td>0.03 ppm (approximately 62 µg m⁻³ at standard temperature and pressure)</td>
<td>Annual</td>
</tr>
<tr>
<td>Air Quality Objectives for Protection of Human Health, UK</td>
<td>200 µg m⁻³ (not to be exceeded more than 18 times a year)</td>
<td>Hourly</td>
</tr>
<tr>
<td><a href="http://www.airquality.co.uk/archive/standards.php">http://www.airquality.co.uk/archive/standards.php</a></td>
<td>40 µg m⁻³</td>
<td>Annual</td>
</tr>
<tr>
<td>Air Quality Guidelines, World Health Organization</td>
<td>200 µg m⁻³</td>
<td>Hourly</td>
</tr>
<tr>
<td><a href="http://www.euro.who.int/Document/E87950.pdf">http://www.euro.who.int/Document/E87950.pdf</a></td>
<td>40 µg m⁻³</td>
<td>Annual</td>
</tr>
</tbody>
</table>

8.6.2 Input data
A flow chart of inputs and outputs for the CALMET/CALPUFF system, specific to the current modelling application, is presented in Figure 8.5. As illustrated in Figure 8.5, emissions and meteorology are the two most important inputs for dispersion modelling. The generation of meteorological data is discussed in Section 8.5. Emissions of NOx for the GTA road network are presented in Chapter 7. Significant effort was dedicated to preparing the CAPUFF emission file. In fact, CALPUFF requires the emissions of every source and every hour to be included in the same file in addition to a description of every source of emission including shape and coordinates. Recall that CALPUFF incorporates emissions from line, area, and volume sources. Typically, road emissions are treated as line sources in dispersion models. Both thermal and mechanical turbulence occurring behind a vehicle contribute to the mixing of emissions; in addition, buoyancy of the exhaust plume and turbulence generated by the wind and vehicle flow on a road segment contribute to further mixing thus generating a continuous line source of emissions. One drawback of CALPUFF is that the line source algorithm is set up to reflect
emissions from smelter buildings and narrow rectangular structures rather than roads. As such, road segments were input into CALPUFF as area sources. This was done through the development of the following macro:

- Divide every road link into n-segments of equal length, each segment with a length approximately equal to 0.5 Km. Roads that have an original length less than 0.5Km, do not get divided.
- Re-allocate link emissions equally among the generated segments
- Draw buffers around road segments with every segment acting as the centerline of the newly created area. Buffers are developed based on the number and width of roadway link lanes. Coordinates of the new areas are stored into the CALPUFF input emission file. The development of buffers is illustrated in Figure 8.10.

Recall that the total number of links in the GTA for which emissions are computed is slightly above 33,000. As such, after the segmentation of links, the resulting number of area sources is around 60,000. The advantage of CALPUFF is that it can be recompiled with a larger array size for the number of area sources. A major drawback however, is the computing time required. We estimated that to run one day of meteorology with the 60,000 area sources, for the CALMET modelling domain, and with gridded receptors covering the domain and located 1.2Km apart (210x210=44,100 receptors), the CPU time is around 6 weeks. Of course, this task can be divided onto several computers whereby each computer can handle a subset of the area sources and the resulting output files can be processed by CALSUM into a single concentration file for the entire domain and all area sources.

Beside the emission rate, the CALPUFF emission input file includes information on the effective height, base elevation, and initial vertical dispersion coefficient ($\sigma_z$) for each area source. A critical input is the initial vertical dispersion coefficient ($\sigma_z$) in meters since it takes into account traffic-induced mixing near the roadway as well as canyon effects, to a certain extent. Initial $\sigma_z$ values around 3 meters (and up to 30 meters) are commonly used for traffic dispersion modelling. As discussed in Section 8.2.4.2, recirculation eddies of the height of the canyon are often observed. A value of 3 meters for $\sigma_z$ on all roadways was used in the current study, except in downtown Toronto where a value of 10 meters was used based on recommendations from CALPUFF developers.
8.6.3 Setup of CALPUFF runs

Beyond the processing of input data, setting up the CALPUFF run involved making decisions with respect to the treatment of NO$_x$, the number and location of receptors, and ways to overcome the significant computing requirements of this application. CALPUFF does not estimate a rate for the conversion of NO to NO$_2$, instead it takes NO$_x$ emissions as input and requires the specification of the fraction of NO$_x$ that is treated as NO$_2$ as a set of NO$_2$/NO$_x$ ratios as a function of varying NO$_x$ concentrations. At this stage, information on conversion rates for NO into NO$_2$ in the context of the current application is not available. It was therefore decided to model all NO$_x$ as NO$_2$. This assumption is expected to overestimate the resulting NO$_2$ concentrations. Future work should address NO$_x$ chemistry.

A major drawback of the current study is the limited computing resources at hand. In fact, only one PC was available for both the CALMET and CALPUFF simulations. This situation has stressed the need for major simplifications of the problem:

- Instead of simulating dispersion from emissions for the entire GTA, it was decided to consider only the contribution of City of Toronto emissions on air pollution in the modelling domain, thus decreasing the number of area sources from around 60,000 to a total of 10,365.
Instead of modelling one year of meteorology, it was decided to select 12 days, each day representing a specific month, and simulate dispersion for each one of the selected days. The selection of the 12 days was done by inspecting output from the CALMET run and selecting days that were most representative of average and specific meteorological conditions. Also, the CALMET output on the selected days had a good agreement with surface station data. Selected days are: January 5, 2001; February 6, 2001; March 04, 2001; April 21, 2001; May 20, 2001; June 21, 2001; July 17, 2001; August 6, 2001; September 8, 2001; October 28, 2001; November 23, 2001; and December 30, 2001. Ideally, run lengths of a few days to one week are more informative because they can capture the accumulation of pollutants during overnight dispersion conditions and their effect on next-days’ concentrations.

While the calculation of concentrations on a receptor grid allows for the development of concentration contours, it is time consuming and computer intensive. It was therefore decided to simulate concentrations on gridded receptors for only one selected day: June 21, 2001. The runtime for this exercise was around 190 hours (approximately 8 days) for the City of Toronto emissions. For all of the other days, concentrations were computed for a set of discreet receptors; chosen as the centroids of TAZs; and amounting to a total of 463 in the City of Toronto. The runtime for each day was around 6 hours.

8.7 Conclusion
This Chapter has presented the methodology adopted for the implementation of dispersion modelling in the GTA, starting from model selection to the development of a 2001 meteorological scenario that is used as an input for dispersion. The CALMET/CALPUFF modelling framework was selected as the most adequate for the current application. CALMET is a diagnostic meteorological model that provides high resolution data for the modelling domain. It was used along with land-use, terrain, as well as surface and upper-air meteorology to generate an input file to be used by CALPUFF. The accuracy of dispersion estimates is highly dependent upon the accuracy of the meteorological inputs. As such, significant effort was devoted to the validation of wind fields obtained by CALMET to ensure that they adequately reflect observations from meteorological stations in the GTA. One of the many strengths associated with the use of CALPUFF is its ability to assign emissions to specific roadway links and treat links as line sources in dispersion. Indeed, a main drawback of existing modelling approaches for large urban areas is the allocation of emissions to grid cells. This process uniformly spreads road emissions throughout a grid cell rather than to a specific link. This reliance on spatial surrogates runs the risk of underestimating emission density and hence pollutant concentrations along and in the vicinity of roadways.
Chapter 9
Air Dispersion of Road Emissions: Results and Discussion

9.1 Introduction

In the previous Chapter, theories, contributions to, and applications of air dispersion modelling were described. Furthermore, the methodology for the present air dispersion application was discussed in addition to the major limitations, the most significant being the focus on the City of Toronto rather than the GTA. This Chapter presents and discusses the results of air dispersion of road emissions in the City of Toronto. It highlights the validity of conducting air dispersion of road emissions and the importance of this exercise to transport policy assessment in the GTA. Comparison of modelled concentrations with measurements at monitoring stations within the City of Toronto is conducted. In addition, an initial attempt at estimating population exposure to NO₂ concentrations generated by road transport is presented. The concentrations resulting from the dispersion of road emissions in the City of Toronto were looked at from different perspectives based on the CALPUFF runs presented in Section 8.6.3. The discussion of results in this Chapter follows Figure 9.1.

![Figure 9.1 Flowchart illustrating different results from CALPUFF runs](image)
9.2 Results of gridded NO\textsubscript{2} concentrations

Hourly concentration contours generated by the City’s road network were developed for June 21, 2001. Figure 9.2 illustrates the effect of the City of Toronto emissions on the modelling domain for 5pm and 6pm on June 21. The whole set of maps illustrating the concentration contours in the modelling domain for the 24 hours on June 21 is presented in Appendix G. Based on the wind direction on June 21, the emissions generated in the City have an impact West and Northwest of the City. Despite the fact that concentrations outside the City fall off to a level below 12 \( \mu \text{g m}^{-3} \), an account of all NO\textsubscript{x} transportation emissions could increase this level by about 50 percent. The Canadian standard for an annual average concentration is 100 \( \mu \text{g m}^{-3} \); as such, a daily contribution of the City to the background concentrations of surrounding regions could cause them to cross the annual ambient air quality standard.

A focus on concentration contours within the City of Toronto is presented in Figure 9.3 which features NO\textsubscript{2} concentrations for selected hours. Concentration contours within the City for the 24 hours on June 21, 2001 are presented in Appendix H. Clearly the peaks in concentrations within the City correspond to the peaks in travel and emissions. In addition, peak period concentrations are quickly dispersed away from the sources. Note that the meteorological conditions on June 21, 2001 (partial cloud coverage and moderate winds) were favourable for good mixing of pollutants and dispersion. This situation may not be generalized as will be seen later in this Chapter whereby specific meteorological conditions may cause “stagnation” and accumulation of pollutants in the City thus causing the peaks in pollution to occur after the peaks in travel. Figure 9.3 highlights various “hotspots” or areas that are most affected by transport emissions. These are mostly located North of the City, along Highway 401 in addition to the interchange of Highway 401 and the Don Valley Parkway (Northeast) as well as the interchange of Highway 401, Highway 427, and Highway 409 (Northwest). The latter is in close proximity to the Lester B. Pearson International Airport which itself is a major source of NO\textsubscript{x} due to the Landing and Takeoff Cycle (LTO) of aircraft in addition to ground support vehicles. The presence of the airport can significantly compound the NO\textsubscript{2} concentrations in the area. This area has various elements that are considered as “sensitive”; these include the West Humber Park, the Royal Woodbine Golf Club, the Woodbine Race track, the Humber Valley Golf Club, as well as a significant proportion of houses, schools, and community centers.
Figure 9.2 Effect of City of Toronto emissions on the surrounding regions in the modelling domain
Figure 9.3 Concentration contours within the City of Toronto
The other area affected, based on Figure 9.3, is located Northeast of the City, and includes a significant proportion of housing and local parks (e.g. Graydon Hall Park, Fenside Park). South of the City, along the Gardiner expressway, a few “hotspots” are also observed but they are localized: at the interchange of Highway 427 and the Gardiner expressway, between the South Kingsway and Parkside Drive, and when the Gardiner expressway enters downtown Toronto. Although localized, these three “hotspots” are of concern especially due to the presence of a large number of the population in these areas especially during the daytime. Based on Figure 9.3, all of the “hotspots” seem to be localized around the highways, while the effect of arterial roads does not appear to be significant. This may be due to the dispersion modelling formulation; in fact, the model does not capture urban canyon effects that typically occur in dense urban areas such as downtown Toronto. Despite this, the model shows the contribution of local and arterial roads to NO₂ concentrations within the City; this finding is similar to the observation made regarding emissions presented in Chapter 7, traffic within the City of Toronto is not as much a concern as traffic on highways and outside the City.

Note that in all of the concentration maps presented in Figure 9.3, NO₂ concentrations do not go beyond 120 µg m⁻³ which is much lower than the hourly Ontario standard equal to 400 µg m⁻³. However, this level is quite close to the WHO hourly standard equal to 200 µg m⁻³. Note that this assessment only accounts for private autos which are responsible for around half of the NOₓ transportation emissions. Accounting for all transport emissions may not cause concentrations to go beyond the Ontario standard however there is a high chance that they would violate the WHO standard which is half the Ontario limit. Also, as stated before, June 21 is a meteorologically favourable day for mixing and dispersing emissions. Assessment of other days is crucial in order to determine the range of impacts expected.
9.3 Hourly concentrations at zone centroids

Due to the limited computing resources, hourly concentrations were calculated at the centroids of TAZs within the City rather than on a receptor grid. The total number of TAZs in the City of Toronto is 463 thus amounting to 463 discrete receptors. The concentration at every centroid is assumed to represent the NO$_2$ concentration within the TAZ. This assumption is valid for downtown Toronto and a large portion of the City of Toronto whereby the size of the TAZs is smaller or slightly larger than the spatial resolution of the model. Outside the City, TAZs become significantly larger making this assumption invalid. Figure 9.4 illustrates the City of Toronto road network and centroids of TAZs overlaying concentration contours. This method has a significantly faster runtime than gridded receptors and can be a computationally efficient way of visualizing the distribution of concentrations within the City. Figure 9.5 and Figure 9.6 present the concentrations at zone centroids for selected hours and contrasts the results obtained for June 21, 2001 with the ones for July 17, 2001. The figures also present population estimates in every zone. The two sets of 24 maps each for June 21 and July 17 are presented in Appendix I.

Figure 9.4 Toronto road network and zone centroids overlaying concentration contours
Figure 9.5 Concentrations at zone centroids at 19:00 and 20:00 local standard time on June 21 and July 17, 2001
Figure 9.6 Concentrations at zone centroids at 21:00 and 22:00 local standard time on June 21 and July 17, 2001
Figure 9.5 and Figure 9.6 show a clear distinction in the NO₂ concentrations simulated for June 21 and July 17 between 7pm and 10pm. As discussed in Section 9.2, the peaks in NO₂ concentrations on June 21 follow the peaks in travel as such, after 7pm; the concentrations decline. The situation on July 17 is noticeably different. Due to the meteorological conditions that are unfavourable for mixing and dispersion of pollutants (very low wind speeds) occurring on that day, the NO₂ emitted during the evening peak period have accumulated within the City thus causing levels in most parts of the City to be high. This is especially the case for the Northeast part of the City, around the interchange of Highway 401 and the Don Valley Parkway. NO₂ levels in this area are in the range of 100 to 400 µg m⁻³ in the evening and they cross the 400 µg m⁻³ hourly standard in one TAZ. The WHO hourly standard (200 µg m⁻³) is clearly violated in several zones. Note that this is only taking into account the contribution of private autos.

The population estimates presented in Figure 9.5 and Figure 9.6 were developed using output from TASHA. Recall that TASHA microsimulates activities and derives trips for individuals thus keeping track of the location for every individual within the GTA. As such, output from TASHA was used to extract the activities, durations, and locations for individuals in the GTA at every hour of the day. A giant matrix was developed to aggregate the number of persons in every TAZ at each of the 24 hours of the day. These numbers were then combined with concentration maps as illustrated in Figure 9.5 and Figure 9.6. Note that the macro developed to perform this task was done for the whole of the GTA, taking into account people who commute into and out of the City. As such, the total population of the City varies throughout the day whereby it is highest between the hours of 8am and 4pm. Based on the population distributions in the City between 7pm and 10pm on July 17; 1.5-4.4 percent of the total City population is exposed to hourly NO₂ concentrations greater than 200 µg m⁻³ (not taking into account buses, trucks, and other commercial vehicle emissions). This percentage may not say much unless it is linked to the attributes of exposed persons. This information is available within TASHA but it was not retrieved for the purpose of this application. Note that, while outdoor NO₂ concentrations are calculated, it is not expected that indoor NO₂ concentrations follow the same pattern. As such, people present in zones with high levels over the span of an hour, may not be exposed to those same levels if they only spend a portion of this hour outdoors. This exercise is by no means a way of accounting for population exposure however; it is valuable in terms of relating pollution
profiles with population distribution and addressing questions such as: what are the attributes of people who live in the most polluted areas? Are the most polluted areas also the busiest in terms of population? Future work should look at the distribution of population attributes in affected areas. In addition, this setup allows for the computation of NO$_2$ concentrations around schools, community centers, parks, hospitals, and other facilities by incorporating locations of concern as discrete receptors.

9.4 24-hour average concentrations for selected days

Aggregation of hourly concentrations was conducted whereby an average daily NO$_2$ level was computed for every TAZ within the City. This exercise was conducted for the twelve selected days in 2001. Looking at 24-hour averages highlights the zones that are most affected over an entire day and allows for a comparison of different meteorological conditions thus pinpointing areas at risk of experiencing high NO$_2$ levels. From a policy point of view, it is important to simulate a broad range of meteorological conditions, taking into account their frequency, in order to come up with air quality contour maps associated with a frequency of occurrence. Policy-makers are expected to find it easier to deal with daily averages especially when different policy scenarios are compared. The only drawback of aggregating concentrations over a 24-hour period is the inability to link NO$_2$ levels with activities and trips of individuals over the span of a day and assess potential exposure. Figure 9.7 presents 24-hour average NO$_2$ concentrations for February 6, March 4, October 28, and November 23; the whole set of NO$_2$ concentrations for the twelve selected days is presented in Appendix J. Despite the choice of varying meteorological conditions among the selected days, all of the maps show that areas North, Northeast, and Northwest of the City are mostly affected by road emissions. Daily concentrations between 25 and 100 $\mu$g m$^{-3}$ are not uncommon; if all NO$_x$ emissions from road transport were accounted for, these levels may approach or even reach the NO$_2$ 24-hour standard for Ontario (200 $\mu$g m$^{-3}$); while a daily standard does not exist within the WHO guidelines, recall that 200 $\mu$g m$^{-3}$ is the hourly WHO standard. NO$_2$ concentrations away from highways, however, are not as high as the levels observed in the vicinity of highways. As discussed earlier, this may be a result of the model not taking into account urban canyon effects as well as the outcome of the lower emission levels from local and arterial roads generated by the emission model.
Figure 9.7 Daily concentrations at zone centroids
In parallel to estimating 24-hour average NO₂ concentrations, the time at which the highest concentration of the day occurred, was estimated for the twelve selected days (Figure 9.8 for January 5, and Appendix K for the twelve days). Results show that on most of the days considered (7 days), the maximum concentration occurs between 6am and 8am; the second most common time period is the one following the afternoon peak in travel, between 6pm and 8pm (3 days). The hour corresponding to the highest daily concentration and the highest concentration of the day in addition to the daily average NO₂ concentration could reveal to be more informative to policy-makers then hourly concentrations for the whole day. Note that the model time step does not change and is still 1 hour. However, a 24-hour aggregation of results provides enough information for policy decisions and could be more interesting to policy-makers. Note that, 24-hour average contours can also be generated using gridded receptors. An interesting way of looking at NO₂ concentrations could be through the development of 24-hour average contours as well as calculating concentrations at selected discrete receptors.

Figure 9.8 Hour corresponding to the maximum daily concentration (January 5, 2001)
9.5 Comparison of model predictions with monitoring data

Comparison of model predictions with data measured at air quality monitoring stations is a core element of dispersion model evaluation. Chang and Hanna (2004) recognize three components of model evaluation: scientific, operational, and statistical. Scientific evaluation involves a review of model algorithms and physics. In an operational evaluation, issues such as user friendliness and error checking are considered. In a statistical evaluation, agreement between model predictions and observations is tested through a wide variety of statistical measures. The latter range from exploratory data analyses (including scatter plots, quantile-quantile plots, residual plots, and plots of predicted and observed concentrations as a function of time and space) to statistical performance measures including: fractional bias, geometric mean bias, normalized mean square error, geometric variance, correlation coefficient, and the fraction of predictions within a factor of two of observations. For detailed discussions on the usefulness as well as advantages and disadvantages of each statistical measure in the context of air quality model performance evaluation, refer to Borrego et al. (2008) and Chang and Hanna (2004). Each modelling application starts with an evaluation objective. Based on model physics and the emission sources that are taken into account by the model, evaluation objectives differ and this is translated by the way pairing of observed and predicted concentrations is conducted. For example, pairing can occur in time only (no penalty is given if the model predicts the maximum concentration at a wrong place), in space only (no penalty is given if the model predicts the maximum concentration at the wrong time), or both in time and space. The latter is clearly the most stringent. For regulatory applications, the primary objective of the USEPA is the agreement between the measured and predicted maximum hour concentration anywhere in the domain.

In the current dispersion modelling of light-duty vehicle emissions in the GTA, a formal statistical evaluation of the model cannot be performed for two reasons namely: 1) the model does not account for all emission sources in the GTA (especially heavy-duty diesel vehicles which typically account for around 40 percent of NOx emissions) as such, it is expected to underpredict measured concentrations, and 2) only 2 sets of 24-hour values are output for June 21 and July 17 respectively while typically, hourly data for at least 3 consecutive days are used. Taking into account those limitations, of interest to the evaluation of CALPUFF in the context of the current modelling exercise, is the ability of the model to replicate trends in observed concentrations rather than actual values. This is assessed through plotting observed ambient
concentrations and estimated concentrations reflecting the contribution of LDGV to ambient NO\textsubscript{x} levels as a function of time as well as computing correlations between pairs of observed concentrations and estimated concentrations reflecting the contribution of LDGV. In air quality model evaluations, the spearman correlation coefficient (\(r_s\)) is suggested as a more robust measure than the pearson correlation coefficient (\(r\)) (Willmott, 1982). Since \(r_s\) correlates ranks of observed and predicted concentrations instead of their values, it is therefore not influenced by extreme outliers. Observed NO\textsubscript{x} concentrations in the City of Toronto were obtained from four monitoring stations managed by Environment Canada (Table 9.1) and compared with NO\textsubscript{x} concentrations reflecting the contribution of LDGV and estimated at the centroids of Traffic Analysis Zones containing the monitoring stations. Comparisons between observed NO\textsubscript{x} concentrations and estimated concentrations reflecting the contribution of LDGV were conducted at each of the four stations for both June 21 and July 17, 2007.

Table 9.1 Air pollution monitoring stations in Toronto managed by Environment Canada

<table>
<thead>
<tr>
<th>Station ID</th>
<th>Station Location</th>
<th>UTM Easting (Km)</th>
<th>UTM Northing (Km)</th>
<th>Traffic Analysis Zone</th>
<th>Pollutant</th>
<th>Date</th>
<th>Temporal variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>31103</td>
<td>Toronto Downtown Bay and Wellesley</td>
<td>630.031</td>
<td>4835.838</td>
<td>218</td>
<td>NO\textsubscript{x}</td>
<td>6/21/2001 7/17/2001</td>
<td>Hourly</td>
</tr>
<tr>
<td>33003</td>
<td>Toronto East Kennedy Ave./Lawrence Ave.</td>
<td>638.883</td>
<td>4845.460</td>
<td>413</td>
<td>NO\textsubscript{x}</td>
<td>6/21/2001 7/17/2001</td>
<td>Hourly</td>
</tr>
<tr>
<td>34020</td>
<td>Toronto North Yonge St./Hendon St.</td>
<td>627.501</td>
<td>4848.628</td>
<td>311</td>
<td>NO\textsubscript{x}</td>
<td>6/21/2001 7/17/2001</td>
<td>Hourly</td>
</tr>
<tr>
<td>35003</td>
<td>Toronto West Elmcrest Rd./Centennial park</td>
<td>613.844</td>
<td>4833.907</td>
<td>25</td>
<td>NO\textsubscript{x}</td>
<td>6/21/2001 7/17/2001</td>
<td>Hourly</td>
</tr>
</tbody>
</table>

Table 9.2 presents a summary of frequency distributions and correlations between observed concentrations and estimated concentrations reflecting the contribution of LDGV at the four monitoring locations in the City for both June 21 and July 17, 2001. Observed mean daily concentrations on June 21 range from 83.77 to 120.99 with standard deviations of 81.97 and 166.92 respectively. In Toronto East (Kennedy/Lawrence) for example, observed concentrations range from 10.27 to 431.25 on the same day. The variance in observed concentrations on July 17 is smaller at all locations. Spearman correlation coefficients range between 0.22 and 0.80. The
highest correlation ($r_s = 0.80$) is observed on July 17 at the Toronto North monitoring location (Yonge/Hendon), while the lowest correlation is observed at the same location on June 21 ($r_s = 0.22$).

Table 9.2 Summary of distributions and correlations between observed NO$_x$ concentrations and estimated NO$_x$ concentrations (in $\mu$g/m$^3$) reflecting the contribution of LDGV at monitoring stations across Toronto

<table>
<thead>
<tr>
<th>Station</th>
<th>Toronto Downtown</th>
<th>Toronto East</th>
<th>Toronto North</th>
<th>Toronto West</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed* $n=24$</td>
<td>Predicted** $n=24$</td>
<td>Observed $n=24$</td>
<td>Predicted $n=24$</td>
</tr>
<tr>
<td>June 21, 2007</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>115.37 2.91</td>
<td>120.99 3.39</td>
<td>112.46 6.52</td>
<td>83.77 10.03</td>
</tr>
<tr>
<td>Median</td>
<td>41.07 2.22</td>
<td>16.43 2.93</td>
<td>108.84 4.05</td>
<td>28.75 8.15</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>112.68 1.79</td>
<td>166.92 2.18</td>
<td>48.36 6.24</td>
<td>81.97 40.68</td>
</tr>
<tr>
<td>Min</td>
<td>30.80 0.87</td>
<td>10.27 1.02</td>
<td>49.28 0.24</td>
<td>20.53 2.56</td>
</tr>
<tr>
<td>Max</td>
<td>377.86 7.71</td>
<td>431.25 9.69</td>
<td>213.57 24.79</td>
<td>250.54 26.99</td>
</tr>
<tr>
<td>$r_s$</td>
<td>0.59 0.60</td>
<td>0.22 0.43</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

|         | Observed $n=24$ | Predicted $n=24$ | Observed $n=24$ | Predicted $n=24$ | Observed $n=24$ | Predicted $n=24$ |
| July 17, 2007 | | | | | | | |
| Mean    | 81.37 17.61  | 32.26 12.97  | 89.84 25.17  | 85.99 32.45  |
| Median  | 64.69 6.13   | 28.75 6.01   | 82.14 11.4   | 77.01 17.93  |
| Standard deviation | 46.71 25.14 | 19.96 15.87 | 45.29 30.89 | 36.49 37.15 |
| Min     | 24.64 1.37   | 10.27 0.75   | 24.64 1.02   | 34.91 3.88   |
| Max     | 209.46 97.15 | 80.09 75.00  | 170.45 101.59 | 147.86 110.02 |
| $r_s$   | 0.73 0.49    | 0.80 0.74    | | |

* Observed: NO$_x$ concentrations measured at monitoring stations
** Predicted: Estimated NO$_x$ concentrations reflecting the contribution of LDGV

Figure 9.10 and Figure 9.9 illustrate the observed concentrations and estimated concentrations reflecting the contribution of LDGV plotted as a function of time on July 17 and June 21 at the Toronto North location. Despite the poor correlation observed on June 21, Figure 9.9 shows that the model was able to pick-up the general trend in concentrations throughout the day except that the peaks in estimated concentrations reflecting the contribution of LDGV are slightly shifted compared to the observed ones. In addition, observed concentrations on June 21 are highest at the beginning of the day, in fact the maximum is at midnight. This was also observed on July 17 at the East, West, and Downtown monitoring locations (Figure 9.11, Figure 9.12, and Figure
9.13). Recall that currently CALPUFF is run for one day at a time, this clearly underestimates the NO\textsubscript{x} levels at the beginning at the day since in reality, they are affected not only by emissions generated in the same hour but also by “old” puffs of NO\textsubscript{x} concentrations that have not dispersed completely. In fact, inversion conditions are frequent at night thus leading to “accumulation” of NO\textsubscript{x} which dissipate at sunrise. At this stage, it is not possible for the model to capture these conditions unless 2 or 3 consecutive days are modelled thus allowing for a “warm-up” time rather than starting a day at midnight with zero puffs in the modelling domain. Otherwise, the model captures the general trend in NO\textsubscript{x} throughout the day. Estimated concentrations reflecting the contribution of LDGV are less than a factor of two of observations and this is primarily due to the fact that trucks and other commercial vehicle movements as well as other point sources of NO\textsubscript{x} in the City are not taken into account by the model.

Figure 9.9 Evolution of hourly NO\textsubscript{x} concentrations at the Toronto North location (June 21, 2001) (\textit{r}_s=0.22) (Observed = NO\textsubscript{x} concentrations measured at monitoring stations; Predicted = Estimated NO\textsubscript{x} concentrations reflecting the contribution of LDGV)
Figure 9.10 Evolution of hourly NO$_x$ concentrations at the Toronto North location (July 17, 2001) ($r_s=0.80$) (Observed = NO$_x$ concentrations measured at monitoring stations; Predicted = Estimated NO$_x$ concentrations reflecting the contribution of LDGV)

Figure 9.11 Evolution of hourly NO$_x$ concentrations at Toronto Downtown (July 17, 2001) ($r_s=0.73$) (Observed = NO$_x$ concentrations measured at monitoring stations; Predicted = Estimated NO$_x$ concentrations reflecting the contribution of LDGV)
Figure 9.12 Evolution of hourly NO\textsubscript{x} concentrations at the Toronto East location (July 17, 2001) \((r_s=0.49)\)  
(Observed = NO\textsubscript{x} concentrations measured at monitoring stations; Predicted = Estimated NO\textsubscript{x} concentrations reflecting the contribution of LDGV)

Figure 9.13 Evolution of hourly NO\textsubscript{x} concentrations at the Toronto West location (July 17, 2001) \((r_s=0.74)\)  
(Observed = NO\textsubscript{x} concentrations measured at monitoring stations; Predicted = Estimated NO\textsubscript{x} concentrations reflecting the contribution of LDGV)
9.6 Population exposure

Using hourly concentration distributions at the 463 traffic analysis zones (TAZs) making up the City of Toronto, population exposure profiles can be constructed. Recall that TASHA generates a list of activities and trips for individuals throughout the day; for every individual, the durations of trips and activities performed sum to 24 hours. As such, by keeping track of the location of activities and trips and knowing the distribution of NO\textsubscript{x} concentrations (treated as NO\textsubscript{2}) within the urban area, the levels to which individuals are exposed throughout the day, can be accumulated thus generating a daily average NO\textsubscript{2} exposure for every individual. Such an exposure model allows for the estimation of pollutant exposure for groups of people and time periods (e.g. future scenario) for which personal monitoring has not been conducted. In addition, such a model allows for assessing population exposure to specific emission sources, an exercise that is hard to achieve with personal exposure devices. A similar study was recently published by Borrego et al. (2007) whereby predicted concentrations for the City of Lisbon were linked with time-activity patterns for Lisbon residents derived from statistical information for sub-population groups. The highest levels of particulate matter were associated with school and university microenvironments. The authors stressed the need to validate the modelling results and conduct a larger study including modelling of series of days. Note that the approach for estimating exposure in this research and the one described in Borrego et al. (2007) are different from traditional “exposure models” that use measured ambient concentrations to derive indoor concentrations in microenvironments and rely on probability distribution functions (derived from activity pattern surveys) to construct individual time-activity data. A review of exposure models is presented in Jantunen et al. (2007) in the context of the final report for the EXPOLIS study on assessment of human exposure to air pollution in European cities.

9.6.1 Method for estimation of exposure

The overall method developed for estimating 24-hour exposure is as follows:

- **Step 1**: Based on TASHA output, construct for every individual a list of all daily activities containing the following information: location (or TAZ), duration, and time of day for each activity. If an activity starts at 9:30am and finishes at 10:15am; it is split as two activities: a 30min activity occurring between 9am and 10:00am (Hour 9) and a 15min activity occurring between 10:00am and 11:00am (Hour 10). The reason for this breakdown is because concentrations are derived for every TAZ on an hourly basis.
• **Step 2:** Based on hourly NO$_2$ concentrations generated by CALPUFF, construct a matrix of NO$_2$ concentrations for every TAZ and every hour of day.

• **Step 3:** Link **Step 1** and **Step 2** by assigning for every activity an NO$_2$ concentration and weighting this concentration by the duration of the activity. This assumes that concentrations are uniformly distributed within the hour, which is valid considering that the model time step is hourly. This step results in exposure profiles for every individual based on the location and duration of daily activities. Note that at this stage, the total duration of the generated profiles will not add up to 24 hours since time spent travelling is not yet accounted for.

• **Step 4:** Based on TASHA output, construct for every individual a list of all trips containing the following information: Origin, Destination, and time of day for every trip.

• **Step 5:** Based on CALPUFF hourly concentration contours, extract an average concentration for every link on the network and for every hour of the day.

• **Step 6:** This step is the most challenging because it requires the development of average concentrations associated with every Origin-Destination pair and time of day. Essentially this boils down to developing 24 Origin-Destination matrices (each for every hour) with NO$_2$ levels as attributes rather than travel time. This can be done in EMME/2 whereby results from **Step 5** are input as link attributes. Moreover, an additional trip attribute is generated whereby EMME/2 accumulates the NO$_2$ concentrations while trips are being assigned on the network. Note that when trips are assigned on the network, the time spent on every link is known in EMME/2, therefore the NO$_2$ concentrations resulting from accumulating link-based NO$_2$ concentrations while trips are assigned, should be weighted by the time spent on every link. As a result, the NO$_2$ level associated with every Origin-Destination pair would already be weighted for the duration of the trip. This is why in TASHA output; trip duration need not be extracted.

• **Step 7:** Link **Step 4** and **Step 6** by assigning an NO$_2$ level for every trip conducted by every individual in TASHA output.

• **Step 8:** For every individual, sum the NO$_2$ concentrations from activities (**Step 3**) and trips (**Step 7**) in order to obtain a 24-hour average exposure. The exposure level can be linked with person attributes such as age and gender thus providing information on the persons exposed to the highest daily concentrations.

A major assumption of the above-presented method is that the NO$_2$ exposure level is the same as the calculated outdoor NO$_2$ concentration. Clearly, this assumption is not valid from a health perspective. Although related to the quality of outdoor air, indoor air pollutant concentrations are different. They depend on different factors such as building ventilation and whether windows are open or closed. In addition, in-vehicle pollutant concentrations are different from concentrations on the road and can be significantly higher under certain conditions. While it is beyond the scope of this research to assess indoor air quality or in-vehicle driver and passenger exposures, the NO$_2$
estimates can be refined by the incorporation of the results of research on indoor-outdoor air quality correlations and in-vehicle vs. on-street concentrations. Future work should look into refining the NO$_2$ estimates. For the purpose of this research, the NO$_2$ exposure profiles are valid from a policy perspective because there is interest in identifying people who engage in activities located in polluted areas or spend significant time driving on polluted roads. In a 2006 study conducted in Toronto, associations between personal exposures and fixed-site ambient measurements of PM$_{2.5}$, NO$_2$, and CO were studied using personal exposure device data for cardiac compromised individuals (Kim et al., 2006). The author found relatively strong personal-ambient correlations for NO$_2$ suggesting that ambient NO$_2$ levels may be used as surrogates of personal exposure to NO$_2$.

Using output from Section 9.3 (Hourly concentrations at zone centroids) and the method outlined above, an attempt was made at developing exposure profiles for individuals in the TASHA output. A major limitation for the completion of this exercise is the lack of concentrations for TAZs outside the City of Toronto. While TASHA incorporates activities and trips conducted throughout the GTA, hourly concentrations, at this stage, are only available for the City. As a result, exposure can only be derived for Toronto residents who perform all of their activities within the City. Another limitation is the unavailability of trip-based NO$_2$ concentrations due to the limited time and resources for re-running EMME/2. When the EMME/2 data was originally generated for estimation of emissions, the development of exposure profiles was not part of the research agenda.

Despite the above-mentioned limitations, a module was developed to calculate exposure of Toronto residents during their daily activities within the City, not taking into account the time spent travelling. Exposures were calculated based on July 17 predicted ambient concentrations based on average times greater than or equal to 21 hours. This assumes a maximum of 3 hours spent travelling for each individual, which are not accounted for. The total exposure per individual depends on the time-activity pattern and the concentration levels in each visited TAZ; it is the sum of partial exposures in different TAZs and at different times (Equation 11). In each TAZ and hour, a homogeneous NO$_2$ concentration was assumed.
\[
E = \sum_{i} T_i \cdot C_i
\]  
\text{Equation 11}

Where \( E \) = total personal exposure, it is the average concentration for the integration period  
\( T_i \) = time fraction spent in \( i \)-th TAZ  
\( C_i \) = hourly concentration in \( i \)-th TAZ

### 9.6.2 Results

The frequency distribution of individual exposures for the City of Toronto residents based on a 21 hour average exposure on July 17 is presented in Figure 9.14. The distribution failed the Shapiro-Wilk test for lognormality (\( p<0.0001 \)). Assuming that all individuals spend the entire day at home, the distribution of exposures based on the home location was generated and presented in Figure 9.15. Both distributions are similar except that the former (based on time-activity patterns) has less noise than the latter (based on the home location). Figure 9.16 presents both distributions on the same graph, showing how the time-activity distribution “averages-out” the noise in the distribution based on the home location. One interesting difference between both distributions is found by looking at the maxima whereby the highest daily concentration at any location is 74 \( \mu \text{g/m}^3 \) while the highest accumulated concentration by any individual is 81 \( \mu \text{g/m}^3 \). This means that certain individuals accumulate an average daily concentration higher than the highest daily average at any location. This is due to the fact that they may happen to be at the worst time period in each location they visit. While this difference is attributed to only a few individuals within the sample, it provides an example of the effect of moving people in the City.

The similarity in the two distributions raises the question as to whether the daily concentration at the home location can be used as a proxy for the daily individual exposure. In fact, the distribution of daily ambient concentrations at centroids of TAZs is highly correlated with the distribution of population exposure based on the home location. This is illustrated in Figure 9.17 and Figure 9.18 showing the distributions of concentrations at the centroids of the 463 TAZs as well as the distributions of populations based on the home location plotted on a logarithmic x-scale. Both distributions failed the Shapiro-Wilk test for lognormality (\( p<0.0001 \)). In studying the associations between personal exposures measured by personal exposure devices and fixed-site ambient measurement in the City of Toronto, Kim et al. (2006) found relatively good correlations between concentrations at the home location (approximated by the concentration at the home location) and personal exposure devices.
measured at the monitoring location closest to the home location) and personal exposure throughout the entire day. In order to better understand the relation between the daily concentration at the home location and the accumulated concentration based on the time-activity pattern; for each individual in the City of Toronto, both sets of concentrations were tested for correlation. Figure 9.19 presents a scatter plot of concentrations derived from time-activity patterns plotted against daily concentrations at the home location for every individual. Due to the large number of data points, the scatter plot is truncated and includes individuals whose home location has a daily concentration less than or equal to 15 \( \mu g/m^3 \); the correlation between concentrations at the home location and the ones based on time-activity patterns is 0.73 (spearman correlation coefficient) for this portion of individuals. The correlation however is not as important as where these points fall with respect to the \( y = x \) line, indicating that home-based exposure and time-activity exposure yield the same daily concentrations for most individuals. Figure 9.20 and Figure 9.21 illustrate respectively the mean and median of the concentrations generated by accumulating time-activity patterns for individuals plotted as a function of the daily concentration at the home location. It can be seen that individuals living in zones with low daily NO\(_2\) concentrations accumulate over the span of a day an average concentration higher than what they would have accumulated if they stayed at home (data points fall above the \( y = x \) line). In contrast, individuals living in zones characterized by high daily concentrations accumulate in a day an average concentration that is lower than the daily average at the home location (data points fall below the \( y = x \) line). Table 9.3 illustrates the means, standard deviations, minima, and maxima of the distributions of population exposures based on time-activity patterns for selected home-based concentrations.

Based on the limited exposure analysis conducted in the context of this research, it can be seen that while the distribution of concentrations at centroids of TAZs weighted by the number of persons living in each zone yield the same distribution as the one derived from accumulating exposures based on time-activity patterns, the scatter in the data reveals that on an individual basis, both concentrations cannot be considered the same. Clearly, air quality at the home location highly influences the total accumulated exposure on daily basis since most people spend a large portion of the day at home. Yet, it is important to examine the “micro-data” especially for individuals at risk since their time-activity patterns may cause them to accumulate high concentrations despite the fact that they may live in locations characterized by good air quality.
An additional attribute of TASHA that was not taken advantage of in this particular study, is the possibility of attaching socio-economic attributes to daily exposures. The car ownership variable is of special interest as it differentiates the exposures of drivers and non-drivers thus allowing for the computation of equity measures. In addition, exposures can be linked with specific activities such as work, school, or shopping thus providing information on the parts of the day in which individuals are exposed to the highest concentrations.

Figure 9.14 Distribution of individual exposures based on daily time-activity patterns (July 17, 2001)

Figure 9.15 Distribution of individual exposures based on the home location (July 17, 2001)
Figure 9.16 Overlapping distributions of individual exposures based on daily time-activity patterns and on home location (July 17, 2001)

Figure 9.17 Overlapping distributions of concentrations at centroids of TAZs and individual exposures based on home location (January 5, 2001)
Figure 9.18 Overlapping distributions of concentrations at centroids of TAZs and individual exposures based on home location (November 23, 2001)

Figure 9.19 NOx concentration based on time-activity patterns as a function of daily concentration at the home location for individuals living in locations with NOx <=15 µg/m³ (n = 31,477 r_s = 0.73)
Figure 9.20 Median of distribution of exposures based on time-activity patterns as a function of daily concentration at the home location

Figure 9.21 Mean of distribution of exposures based on time-activity patterns as a function of daily concentration at the home location
Table 9.3 Distributions of exposures based on time-activity patterns for selected daily concentrations at the home location

<table>
<thead>
<tr>
<th>24-hr average NOx concentration (µg/m³) at home location</th>
<th>Distribution of NOx concentrations (µg/m³) based on time-activity patterns</th>
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</table>
9.7 Conclusion

This Chapter presents the breadth of results and analyses that can be conducted to assess air quality in the City of Toronto and which form the basis for the development of a set of air quality and exposure indicators of interest to decision-making. The resulting concentrations in the City, under most meteorological conditions and time-based aggregations have revealed a number of “hot-spots” or affected regions. They are mainly located North of the City, along Highway 401 in addition to the interchange of Highway 401 and the Don Valley Parkway (Northeast) as well as the interchange of Highway 401, Highway 427, and Highway 409 (Northwest). South of the City, along the Gardiner expressway, a few “hotspots” are also observed but they are localized: at the interchange of Highway 427 and the Gardiner expressway, between the South Kingsway and Parkside Drive, and when the Gardiner expressway enters downtown Toronto. In fact, all of the “hotspots” seemed to be located around the highways, while the effect of arterial roads did not appear to be significant. This may be due to the dispersion modelling formulation or to the lower level of emissions modelled on arterial roads within the City. Most concentrations are lower than the Ontario ambient air quality standards but close to the WHO standards (which are significantly stricter than the Ontario standards). Accounting for trucks is expected to significantly increase NO\textsubscript{x} emissions and hence cause concentrations to violate the WHO standards and the Ontario standards to a lesser extent. A major finding of this Chapter is the importance of meteorology. In fact, for the same emission rates, the resulting concentrations on different days ranged from very low across the modelling domain to almost alarming levels. This stresses the need to account for varying meteorological conditions. This is typically done by modelling dispersion over an entire year.

A rather innovative attempt at assessing population exposure is presented in this Chapter. Rather than linking average daily concentrations in a TAZ with the average daily number of people in the zone (or number of people residing in the zone), the proposed approach accumulates exposures throughout the day while individuals move from one zone to the other. These results show the importance of accumulating exposures based on time-activity patterns especially for individuals living in low concentration home locations or high concentration home locations as they may accumulate daily levels higher or lower than the daily average concentration at the home location. Additional work should refine the proposed method by linking outdoor
concentrations with indoor air quality as well as improve estimates of in-vehicle population exposure.

The main strength in the CALPUFF dispersion modelling is the time-dependency of dispersion whereby the time needed for emissions generated from a source to reach a specific receptor is explicitly modelled. This time-dependency is partially responsible for the shifts in peak concentration periods with respect to peaks in travel and emissions (which are concurrent) whereby zones that are moderately distant (5 Km) from major highways for example are impacted 1 or 2 hours following the peak in travel (depending on the wind speed). Another strength of the dispersion model is the spatial variability in meteorology which is also compounded by the spatial variability in emissions. This causes areas close to the lake for example, to have low concentrations due to the higher wind speeds compared to areas located uptown. Both spatial and temporal variability in concentrations affect the resulting population exposures. An example of this effect is illustrated by the difference in the maxima for exposures accumulated based on time-activity patterns and on home location. Some individuals end-up accumulating a daily exposure higher than the highest daily concentration in any zone because they “happen to be in the worst zones at the worst times in each zone”. This result would not be observed in a model that does not take into account spatial and temporal variability in concentrations and in individual time exposure patterns.

The range of results discussed in this Chapter needs to be examined from a policy perspective in order to determine which approaches are of interest for policy analysis. The next Chapter proposes a set of indicators reflecting the air quality results obtained and highlights the ones that could be of importance to policy-makers.
Chapter 10
Significance of Urban Air Quality Modelling for Policy Analysis

10.1 Introduction
The modelling system, described in Chapters 7, 8, and 9, which combines emission and dispersion modelling for the GTA, is primarily intended for transport policy analysis. The objective of this system is to support the analysis of transport policy scenarios by estimating the “most probable” impact on air quality for every transport scenario. This research estimates four different components of the “air quality impact”: emissions of GHGs, emissions of CACs, distribution of NO₂ concentrations in the urban area and in sensitive locations, and daily NO₂ exposure profiles of individuals. As in any research project, this exercise is associated with various limitations and simplifications that give rise to uncertainty in the model results. The modelling system has also been developed with an intended purpose; therefore, it has boundaries in terms of the types of policies that can be assessed. This Chapter discusses model uncertainty and application and its implications for policy analysis. Despite modelling limitations, valuable information for decision-making can be derived if results and uncertainty are properly communicated to decision-makers. Recall that the aim of the survey (Chapter 2) was to explore the current state of policy appraisal and provide recommendations for modelling and analysis. The main aim of this Chapter is to tie the policy and modelling/analysis work conducted in the context of this research.

10.2 Uncertainty in modelling system and policy implications
In this section, the different sources of uncertainty associated with the air quality modelling application to the GTA are discussed in addition to their effect on policy-decisions. In this context, the main question explored is the following: taking into account that the model will never reflect all the processes that occur in reality, how does understanding of the total uncertainty improve decision-making? And how can we provide recommendations for decision-making in light of model limitations?
10.2.1 Uncertainty in components of the system

Possible sources of error or uncertainty in the current modelling application include: 1) uncertainty in emissions modelling (inputs and model formulation), and 2) uncertainty in dispersion modelling (inputs: emissions and meteorology, choice of modelling formulation, and inherent uncertainty in dispersion modelling). This section discusses the different types and implications of uncertainty.

10.2.1.1 Uncertainty in emission modelling

Various limitations and assumptions made within the context of emission modelling for the GTA have contributed to generating uncertainty in the resulting emissions. A major limitation of this work is the focus on light-duty vehicles only. While the emphasis on light-duty vehicles provides decision-makers with a good understanding of household travel, truck emissions are becoming increasingly recognized as a major source. Overlooking truck emissions also affects dispersion estimates especially given that trucks are responsible for a significant portion of NOx. Another source of uncertainty in emission inputs is the assumption of a uniform distribution of the vehicle fleet across the GTA. This assumption may not be entirely true and there may be a spatial variability in the types of vehicles owned throughout the GTA. This variability would also lead to different VKT per day for different vehicles types. In fact, information on the vehicle fleet was obtained from the Drive Clean program. Alternatively, it can be obtained from Ontario’s Ministry of Transportation vehicle registry. Registration datasets represent all light-duty vehicles that are licensed to operate on the road. The actual operating fleet may be quite different. In a household that owns more than one vehicle, the SUV for example, may be driven less (or more) during the day, than the smaller vehicle. This leads to different emission patterns in the GTA.

In terms of the Mobile6.2 specification, the two main sources of uncertainty include the reliance on the federal test procedure (FTP) for base emission rates and the average speed assumption. Despite the review of the FTP, there is still reason to believe that it only reflects “average” on-road driving conditions and does not adequately reflect aggressive driving or stop-and-go traffic. A discussion on average speed vs. instantaneous emission was conducted in Section 7.3. Clearly, the average speed assumption does not represent “actual” driving conditions. Still, Hickman et al. (1999) found that for most applications, the use of average-speed EFs for typical traffic
situations will capture emissions with sufficient accuracy. The authors found that for single applications i.e. looking at emissions for certain single driving cycles, the uncertainty associated with instantaneous models is high, whereby they predict sometimes wrong trends when evaluating certain measures which affect driving behaviour. By analyzing the results of on-road emission measurements conducted by various laboratories, the authors found large differences which may be attributed to test conditions, equipment, vehicle sampling, or simply differences in vehicle fleets in different countries. These findings indicate that uncertainty exists in both measurement and modelling and care should be taken when assessing whether a more micro approach will indeed achieve more accurate estimates.

10.2.1.2 Uncertainty in dispersion model
Three main types of uncertainty are associated with the current dispersion modelling application, these include: uncertainty in CALPUFF inputs, namely emission estimates and meteorology; uncertainty in model formulation; and inherent uncertainty in dispersion estimates (due to random nature of atmospheric turbulence). Hanna (2007) recognizes a fourth source of error, which is the error in air quality observations/measurements to which model outputs are compared. Observational data are often mistakenly assumed to “reflect reality”, however even with “perfect” instrumentation and sampling, observations are associated with a spatial representation. An air quality measurement conducted at a single point in space (and time) may not reflect the concentration in the surrounding area but merely the concentrations at the specific data collection point. Zanetti (1990) also stresses the issue of measurement errors, which is often forgotten. The author distinguishes errors in measurement from “representativeness” of observations.

Input data
Uncertainty in CALPUFF inputs can be mainly attributed to uncertainty in the emissions and meteorological data. Uncertainty in emissions is discussed in Section 10.2.1.1. A common rule of thumb exists in air dispersion modelling that the uncertainty in boundary layer wind predictions is 1 or 2 m/s (Hanna, 2007). Meteorological inputs into CALMET included MM5 data and local observations in the GTA, both of which are associated with uncertainty (instrumentation and MM5 specification). MM5 data were used due to the lack of sufficient observations and upper air
soundings in the domain. Fox (1984) argues that a well founded and validated meteorological model, such as the MM5 prognostic model, can produce meteorological fields that are more accurate than non-representative data. Prognostic models can filter local perturbations that may be experienced at measurement stations. Meteorological representativeness is important to make sure that conditions likely to produce the highest concentrations are included. Fox (1984) discusses point to point versus climatological (over longer periods of time) representativeness. In the case of the current modelling application, point to point agreement between the CALMET output and observations was considered as less important than agreement over a whole month. This may be a source of error whereby high concentrations predicted for specific days or hours may be correct in terms of the event occurring at some point during the month, but the exact timing may be incorrect. Therefore, the model should be used for determining the frequency of high concentrations occurring over a rather extended period of time (seasonal or yearly) rather than to pinpoint “when” those events are likely to occur. Of course, from a regulatory point of view, this is may not be adequate, however for a transport policy assessment application, this is considered sufficient.

**Model formulation**

A discussion of the CALPUFF model formulation is presented in Section 8.4.2.1. Clearly the puff formulation is more accurate than the Gaussian steady-state formulation. Still, puff evolution is based on Gaussian dispersion which is a simplification of real dispersion processes; the dispersion coefficients are empirical which generates uncertainties in their estimation. In addition, CALPUFF does not explicitly take into account all of the possible chemical transformations like a Lagrangian particle model would. In addition to uncertainty in model physics, a major source of uncertainty lies in the definition of the modelling and receptor grid, and the other simplifications adopted for the current application. Indeed, the grid size adopted in this application is 1.2Km. Although it is common for environmental modellers to use such a grid size, it is possible that certain maxima are not captured if they fall within a grid. Our application treats all NOx as NO2; this simplification overestimates NO2 concentrations and may cause NO2 peaks to occur earlier than they should because of the assumption of “instantaneous” transformation. Future applications should explore a smaller grid-cell size, the treatment of NOx chemistry, and modelling the entire GTA. This will significantly increase computing requirements but is a worthwhile exercise.
**Inherent uncertainty**

Due to the random nature of atmospheric turbulence, dispersion models, even with “perfect” physics formulations, cannot estimate the random part of atmospheric dispersion. As a result, they fall short of estimating the exact same concentrations that are measured by monitoring stations. This lack of accounting for random turbulence effects is commonly referred to as the inherent uncertainty in dispersion modelling. Hanna (2007) describes some of the effects of stochastic turbulence on concentration distributions in a plume of pollutants; the two most important effects include meandering and in-plume variations. Meandering occurs when the size of the turbulent eddy is larger than the width of the plume; the plume is seen to wave back and forth. Stochastic concentration fluctuations inside the plume occur as a result of turbulent eddies smaller than the plume width; this affects the Gaussian assumption of pollutant distribution in-plume. The inherent uncertainty is best explained by environmental modellers using the “ensemble” methodology. Venkatram (1988) defines an ensemble as:

> The ensemble refers to a collection of events governed by a similar set of externally imposed conditions.

Hanna (2007) explains that in meteorological forecasting, the “ensemble” methodology is typically used to estimate uncertainty whereby the best forecast is considered to be the mean or median of a set or “ensemble” of model runs with varying inputs and/or formulations. The spread of the “ensemble” is considered as a measure of uncertainty. Assume the wind velocity can be represented as the sum of average and fluctuating components Zanetti (1990):

$$ V = \bar{u} + u' $$  \hspace{1cm} \text{Equation 12}

Where $\bar{u}$ is the portion of the flow that is resolvable using measurements or meteorological models and $u'$ is the remaining unresolvable component due to the randomness of atmospheric turbulence. We also assume that the concentration measured at a point in time, and associated with the wind expressed in Equation 13 is expressed as:

$$ c = \langle c \rangle + c' $$  \hspace{1cm} \text{Equation 13}

Where $\langle c \rangle$ is the “ensemble” mean. Recall that $u'$ is a stochastic variable, which means that there exists an infinite family of functions $u'$ that satisfy the equation of motion. Each possible
member $u'$ generates a different concentration. The average at a certain point in time of all possible concentrations generated by the different $u'$ gives the “ensemble” mean $\langle c \rangle$. While a monitoring station can provide an estimate of the actual concentration (the sum of the “ensemble” mean and the random component), the dispersion model gives $\langle c \rangle$ (with a certain degree of error associated with other sources of uncertainty). As such, even under ideal conditions, model output will still differ from measured concentrations: this is called the intrinsic or inherent uncertainty. Note that, an air dispersion model provides a single deterministic concentration level at a specific point in time; this value is not a function of the random component but it represents the “ensemble” mean of a set of similar observations with random turbulence. Venkatram (1988) defines the inherent uncertainty as the “deviation between the best possible model prediction and the measured observation”.

**Estimating total uncertainty**

Total model uncertainty includes both the inherent uncertainty and uncertainty in inputs and model formulation. As stated earlier, current dispersion models are deterministic and do not estimate uncertainty within model predictions. As a result, environmental modellers have developed ways to estimate total uncertainty associated with dispersion models. A common rule of thumb is that the uncertainty in prediction of concentrations is about plus or minus a factor of two. There also exist several detailed approaches to estimating uncertainty. A common method is the Monte Carlo approach, which is growing because of increases in computer speed and storage thus allowing for a large number of model runs to be conducted. In the Monte Carlo approach, probability distributions that express the state of knowledge about alternative values for each input should be specified within pre-specified ranges conceivable for each uncertain input. For a review of available methods for estimating uncertainty, refer to Hanna (2007); Borrego et al. (2008); and Venkatram (1983).

Despite the emergence of complex methods for treatment of uncertainty, essentially the most widespread method is to compute statistics between observed and predicted data. Statistical parameters used to evaluate pairs of predicted/observed data include: bias, gross error, variance, correlation coefficient, regression line, normalized fractional bias, and normalized mean square error. A description of the most common statistics used in this context is presented in and Borrego et al. (2008). Sometimes, qualitative observations of time-series plots and isopleths may
be more informative than statistics. According to Zanetti (1990), the acceptance by the scientific community of this comparison between observed and predicted values is most controversial, but is acceptable for practical regulatory applications; he argues:

*It essentially means that it is not a total scientific aberration if apples are compared to oranges. A model forecast of the maximum concentration impact $c_A$ at a location $A$ and time $t_1$ can be compared with the measurement of maximum concentration impact $c_B$ at a location $B$ and time $t_2$, and if the values are close, we are allowed to conclude that, for practical applications, the model can be considered a “good predictor” of the maximum impact. Scientifically speaking, this is not true; if $A$ is distant from $B$ and $t_1$ is much different from $t_2$, the model clearly does not work properly and the similarity between $c_A$ and $c_B$ is only accidental. Scientifically speaking, models should not just predict well, but they should do it for the right reason.*

### 10.2.2 Implications of uncertainty for policy decisions

Based on the discussion conducted in the previous subsection, it is clear that the proposed methodology for assessing the air quality impacts of transport and land-use policy scenarios in the GTA is associated with a wide range of uncertainty. It is beyond the scope of this Chapter to estimate uncertainty and propagate errors from one model to the other. Yet, it is unquestionable that the results of the emission-dispersion-exposure modelling system cannot accurately capture reality and it is expected that measured and modelled air pollutant concentrations will be different. The question that arises is: taking into account the level of uncertainty, do modelling results hold value for policy analysis? If the “single number” output of the model diverges from reality, can the model still capture trends and air quality patterns in the GTA?

Clearly, the air quality model did not provide counter-intuitive results. The highest level of emissions was observed to coincide with peak travel; NO$_2$ concentrations were observed in the vicinity of major highways and were higher in “unfavourable” meteorological conditions. These and other outputs discussed throughout this dissertation, provide evidence that while the “single number” model output may not correspond with the measurement (whether it is travel time, traffic volume, emissions per kilometre, NO$_2$ level, etc.), the modelling system is able to reflect
certain air pollution patterns within the GTA and is sensitive to a range of variables which can be used to construct policy scenarios.

The level of disaggregation in both emission and dispersion modelling may induce some uncertainty yet; it certainly reflects reality better than high level aggregate modelling. Temporal and spatial variation in emissions, dispersion, and individual activities is a key characteristic of this modelling framework making it more comprehensive and realistic than traditional aggregate modelling tools (refer to Sections 7.11 and 9.7). The time-activity patterns of individuals are the main cause for the spatial and temporal variability in traffic, e.g. people travel to work from their home locations to work locations primarily during the morning between 6 and 9am. The spatial and temporal variability in traffic induces a spatial and temporal variability in emissions, e.g. the highest emissions occur in the morning and afternoon primarily on roadways linking employment locations with dwelling locations, vehicle hot soaks occur near the home locations in the afternoon and near work locations in the morning. The spatial and temporal variability in emissions, compounded by the spatial and temporal variability in meteorology, leads to a spatial and temporal variability in air pollutant concentrations, e.g. zones closest to emissions sources incur the highest concentration levels almost concurrently with emission peaks whereas zones located further away are impacted at later times, zones associated with the lowest emissions may incur disproportionately high concentrations due to their location downwind from high emissions. Finally exposure is derived from the same time-activity patterns developed to estimate travel demand. Individuals that generated emissions in the first place are exposed to the resulting concentrations in addition non-drivers who are exposed to pollution that they are not responsible for. The interactions between temporal and spatial disaggregation at the traffic, emission, dispersion, and exposure levels are illustrated in Figure 10.1.
In modelling, and academia in general, uncertainty and probability are not deterrents from using model results and drawing “scientific” conclusions, taking into account the error margin. In fact, even in daily life, a wide range of decisions are conducted based on probabilistic rather than deterministic results. A common example is the output from meteorological models and the daily decisions that are made based on the “weather forecast”. Even in the private sector, products are launched despite less than full certainty of their success in the market. Yet, when it comes to public policy which is subject to public scrutiny and is affected by high political and financial stakes, uncertainty or risk becomes a major impediment to policy decisions. The realities of the public policy environment (inability to test value through market research, poor cost reviews, there is no product recall on a road or streetcar, multiple and sometimes conflicting objectives, mid-course adjustments are difficult to make without losing political or professional face) have led planners and decision-makers to become sceptical towards modelling results due to the associated uncertainty. They are unsure as to how to deal with model outputs and how to
combine them with professional judgement, which remains a crucial element of decision-making.

The general disbelief in models raised by survey participants and discussed in Chapter 3 is essentially linked with model uncertainty and their conviction that the model is “wrong” only because it is associated with uncertainty. There is also a general misconception that measured data reflect reality; planners tend to overlook the fact that data collection and monitoring is also associated with sampling, instrumentation, and analysis errors. They believe that if measured and modelled data do not coincide, then the model is inadequate. In order to improve the relationship between modelling and decision-making, there is a need to 1) educate decision-makers and 2) communicate modelling results differently. In fact, there is a need to educate decision-makers to accept the challenge of decision-making with quantified uncertainty. This means that the presentation of modelling results should move away from the “single number” output in favour of distributions or ranges thus providing decision-makers with an idea of the level of uncertainty associated with the result. This does not mean that every IUM should include error propagation between the different components, however the development of ranges based on knowledge of the model and sensitivity analysis may present decision-makers with a different view of modelling. This would demonstrate that the purpose of the model is not to output a “single number” that tells the decision-maker what to do but rather to provide information on the range of expected outcomes and their associated probabilities. It should be kept in mind that this approach may create conflicts and added debate.

In the environmental field, due to the permitting procedures, models have regulatory applications. This means that they form the basis for decisions; for example a proposed power plant may be relocated or not granted a permit, based on the forecast of the air quality model. This puts a tremendous pressure on air quality modellers to devote significant research in quantifying modelling uncertainties and improving communication between modellers and decision-makers. Due to the lack of a regulatory push in land-use and transport, not enough attention has been devoted to improve policy makers’ belief in models and help them understand the difference between uncertainty and misinformation.
10.3 Policies that can be represented in the current model

Despite the limitations and assumptions listed in this Chapter (Section 10.2.1), this study is innovative in various respects. The link between Mobile6.2C and an activity-based model rather than a conventional trip-based model results in more comprehensive emission estimates for the GTA. The ability of Mobile6.2 to estimate a wide range of emission types (especially exhaust, start, and soaking emissions) on an hourly basis was strengthened by providing the model with local vehicle activity information accounting for the time of day, rather than using the model’s default values. The availability of such input data is highly questionable with the use of conventional trip-based models and peak-hour models that do not account for 24-hour travel. The focus on 24-hour emission profiles rather than peak-period offers a clearer understanding of the daily patterns of pollution generation. Tying link-based emissions with a puff dispersion model is also an innovative approach whereby most dispersion exercises conducted for large urban areas are based on simple Gaussian dispersion and grid-based emissions. The ability to display concentration contours throughout the area and track population on a 24-hour basis enables a better assessment of exposure than with models that assume static population in the urban area.

A list of the types of policies that can be represented in the current system is presented in Table 10.1. In addition, three example policy scenarios for the GTA are presented as an illustration of the capabilities of the modelling system. Note that the scenarios were developed only for illustrative purposes and are not based on current governmental forecasts or visioning exercises. The assessment of policy scenarios is particularly important in order to estimate the impact of a combination of individual measures and capture their interactions. For example, technological improvements in efficiency may result in effective reduction in the per kilometre price of travel and hence lead to an increase in demand. Adding oxygenates to gasoline will increase its volatility and lead to an increase in evaporative emissions.
Table 10.1 Policy measures that can be represented by the modelling system

<table>
<thead>
<tr>
<th>Types of policies</th>
<th>Individual policies</th>
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</thead>
<tbody>
<tr>
<td>Vehicle technology and maintenance</td>
<td>Increasing the fuel efficiency of current vehicles</td>
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<tr>
<td></td>
<td>Gasoline and diesel quality improvement (gasoline Reid Vapour Pressure, oxygenates, diesel sulphur content)</td>
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<tr>
<td></td>
<td>Alternative fuels (natural gas)*</td>
</tr>
<tr>
<td></td>
<td>Inspection and Maintenance programs</td>
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<tr>
<td></td>
<td>Emission Standards</td>
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<tr>
<td></td>
<td>Vehicle retrofit programs (particle traps on buses, catalytic converters )</td>
</tr>
<tr>
<td></td>
<td>Vehicle scrappage and fleet renewal programs</td>
</tr>
<tr>
<td>Transit supply</td>
<td>Reduction in public transport fares, change of fares (zone-based, time-of-day)</td>
</tr>
<tr>
<td></td>
<td>Transit network changes</td>
</tr>
<tr>
<td></td>
<td>Frequency changes</td>
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<tr>
<td>Alternative transportation and car pooling</td>
<td>Bike lanes</td>
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<td></td>
<td>Walk to school programs</td>
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<tr>
<td></td>
<td>Car pooling</td>
</tr>
<tr>
<td>Pricing and taxation</td>
<td>Parking charges</td>
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<td></td>
<td>Road pricing</td>
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<td></td>
<td>Congestion charges</td>
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<td></td>
<td>Emission tax</td>
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<tr>
<td></td>
<td>Fuel tax</td>
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<tr>
<td>Traffic management</td>
<td>Driving bans</td>
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<td></td>
<td>Ride sharing</td>
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<tr>
<td></td>
<td>Parking restrictions</td>
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<tr>
<td></td>
<td>Reduction in road capacity</td>
</tr>
<tr>
<td></td>
<td>Increase in road capacity</td>
</tr>
<tr>
<td>Proposed example scenarios for the Greater Toronto Area</td>
<td>Investments in new roads to accommodate growth</td>
</tr>
<tr>
<td></td>
<td>Telecommuting – work at home for a portion of the population</td>
</tr>
<tr>
<td></td>
<td>Decrease in maximum auto speeds on highways</td>
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<td></td>
<td>Transit signal priority for public transit thus increasing speeds</td>
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<td></td>
<td>Investment in GO service</td>
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<tr>
<td>Social scenario</td>
<td>Implementation of a wide range of new public transport services (light-rail and bus services)</td>
</tr>
<tr>
<td></td>
<td>Light-rail service to the airport</td>
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<tr>
<td></td>
<td>Zone-based fare for public transit in Toronto</td>
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<td></td>
<td>Increase bus frequency</td>
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<td></td>
<td>Congestion pricing in downtown Toronto</td>
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<td></td>
<td>Aggressive road pricing on major highways</td>
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<tr>
<td></td>
<td>No significant changes in vehicle technology</td>
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<td></td>
<td>No new roads</td>
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<tr>
<td>Polluter-pays scenario</td>
<td>Fuel taxes</td>
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<td></td>
<td>Emission taxes based on mileage</td>
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<td></td>
<td>Financial incentives for new vehicle technologies</td>
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<td></td>
<td>Tightening of standards for the Drive Clean I/M program</td>
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<tr>
<td></td>
<td>Introduction of yearly vehicle repair costs to match emission standards</td>
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<tr>
<td></td>
<td>Parking charges in downtown Toronto</td>
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<tr>
<td></td>
<td>Compressed Natural Gas for public transit buses</td>
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</tbody>
</table>

*Mobile6.2 does not assess the effect of methanol, ethanol, and biodiesel
Taking into account the broad range of policies that the current modelling systems can represent, it should be kept in mind that there is also a range of policies that the model is insensitive towards; examples of these include:

- Traffic management policies that affect vehicle drive cycles such as intersection signal timings, geometry of junctions, and types of pedestrian crossings: Impacts on pedestrians cannot be adequately assessed. Indeed, while the current model is useful for modelling the effects of long-range, regional policies; it cannot assess the effects of traffic management and control policies which require the inspection of not only average speeds but also other aspects of vehicle operation such as acceleration and deceleration.

- Vehicle ownership: At this stage, TASHA does not model household vehicle ownership decisions; as such, it is not possible to assess policies that affect the types of vehicles owned by households or the growing market penetration of SUVs.

- Trip generation: At this stage, TASHA does not accommodate for the deletion of trips. As a result, it is not able to model the effect of pricing or other policies on trip generation whereby certain trips may be deleted all-together.

### 10.4 Significance of an air quality indicator

As mentioned in Chapter 6, the development of air quality and exposure indicators was not conducted prior to the modelling but rather, left until after the modelling methodology was designed and modelling results were obtained. Clearly, there is a wide range of results obtained by the emission-dispersion-exposure modelling system: Hourly exhaust emissions, hourly evaporative emissions, hourly NO₂ concentrations (uniform in TAZ or contours), average daily NO₂ concentrations (uniform in TAZ or contours), population per TAZ per hour, population tracking and exposure over a 24-hour period. Clearly, a presentation of all of these outputs to decision-makers is not valuable. Therefore, there is a need to select the outputs that are most illustrative and develop a set of indicators that illustrates the impact of a policy scenario on air quality in the GTA. Note that what is mostly important is the increase or decrease in the value of an indicator in the modelled scenario with respect to the value of the same indicator in the reference case; rather than absolute values of indicators. Based on the modelling work conducted in the context of this research, the proposed air quality and exposure indicators include:
- **Total CO₂ emissions in the GTA (tons):** The spatial variation of CO₂ emissions within the GTA is not relevant; as a whole, the GTA should strive to reduce CO₂ emissions. Clearly, there may be a spatial variation in the responsibility for CO₂ emissions; suburban residents are probably more accountable for traffic-related CO₂ than downtown Toronto residents. Policies that aim at reducing CO₂ emissions may target GTA regions differently; however, at this stage, the current modelling system is only able to estimate CO₂ generated on roadway links. Future research could accumulate CO₂ emissions for trips and hence develop an “accounting framework” for GTA motorists.

- **Total VOC emissions (tons):** VOCs contribute to smog formation by acting as catalysts. While VOC concentrations are not predicted at this stage, the VOC load can be used merely as a proxy for increased probability of smog formation (which depends on various factors including meteorology). Within the current modelling framework, VOCs are emitted both from exhaust and from evaporative conditions. In the summer, VOCs generated during hot soaks, running losses, refuelling, etc. are greater than exhaust VOCs. For this purpose, fuel evaporation needs to be taken into account. Of course, VOC emissions may not weigh as much as NO₂ exposure in the final decision.

- **Percentage of population with 1-hour average NO₂ concentration greater than 200 µg m⁻³:** The percentage of people exposed to NO₂ concentrations per hour is calculated from the hourly NO₂ concentration at the centroid of every TAZ and the number of people in every TAZ extracted from TASHA on an hourly basis. The hourly standard for NO₂ in Ontario is 400 µg m⁻³; however it should be noted that the current modelling framework does not take into account truck emissions of NOₓ which largely contribute to ambient NO₂ levels. As such, a level of 200 µg m⁻³ may indicate that if truck emissions are taken into account, the ambient level would exceed the standards. In fact, the WHO and UK standard for a 1-hour average for NO₂ is 200 µg m⁻³.

- **Percentage of persons with a 24-hour exposure (including driving and activities) higher than 100 µg m⁻³:** This indicator is calculated by tracking exposure for every individual throughout the day. It accounts for the fact that only light-duty vehicle contribution is taken into account. On a 24-hour basis, it is considered acceptable for a specific TAZ to exceed the 100 µg m⁻³ level because it is the individual exposure on a 24-hour basis that is of concern. Certain persons may live in a “polluted” area but work and spend a large portion of their day outside this zone, in a relatively “clean” TAZ; other people who live in a “polluted” area and spend a large amount of time at home, will be reflected in this indicator.
10.5 Conclusion

This Chapter links the policy and modelling components of this research. It summarizes uncertainty associated with the current modelling exercise and ties it to decision-making taking into account understanding of the policy environment. With the increase in complexity of travel patterns and sustainability objectives, policy questions necessitate the use of sophisticated tools which are inevitably associated with a high degree of uncertainty. A successful decision-making process needs to take into account the modelling uncertainty but not allow it to hinder policy decisions. The proposed modelling framework has a range of limitations but is still valuable from a policy perspective. Its sensitivity to a wide range of variables affecting emissions and dispersion increases the policy sensitivity and allows for an evaluation of a broad range of policies at the strategic level. Increased level of detail in the modelling is inherently associated with a wider error margin in light of modelling assumptions and uncertainties in the large amount of input data needed. While a formal comparison between a more “macro” approach to the same problem was not conducted in the context of this research, it is implicit in the current modelling framework that the temporal and spatial disaggregation achieved yield more realistic ambient air quality patterns. People move around in an urban area thus generating emissions and in-turn being exposed to concentrations that are not necessarily proportional to the emissions they are responsible for. The only way of explicitly representing the relation between emissions and exposure is through a modelling framework that represents the temporal and spatial variability of both.

This Chapter enumerates the types of policies that can be modelled and proposes a set of indicators to be used for comparing long-range policy scenarios. The proposed indicators are not meant to reflect trends in measured data but rather to compare future policy-scenarios represented by the model. In fact, it is rather impossible to use the proposed indicators for assessing a current situation since the data needed can only be generated by a model. This distinction is important to note since indicator sets used for comparing strategic policy scenarios are different from indicators meant to reflect trends in existing data.
Chapter 11
Conclusions

11.1 Summary
This research was motivated by the need to assist transport decisions which have recently been faced with numerous challenges, both in the GTA and elsewhere. As one of the fastest growing urban areas in North America, the GTA has indeed become a major economic center and the highest contributor to economic growth in Canada. Yet, this growth has been associated with major drawbacks: suburbanization to accommodate growing populations, increased car ownership and travel demand, deterioration of air quality and public health, and social inequities.

In light of recent worldwide drives for decreasing greenhouse gas emissions, protecting the environment, and improving the quality of life of urban populations; the challenges facing urban policy, and in particular transport policy, have become enormous. This research focuses on the Canadian context, and in particular the GTA, and aims at understanding the current policy environment related to transport decisions as well as proposing ways to overcome some of the aforementioned challenges.

The first part of this research included an exploration and assessment of transport policy appraisal in Canadian agencies. For this purpose, a survey was conducted with planners and policy-makers pertaining to the three levels of government (municipal, provincial, federal) in Canada. The survey targeted three main components of transport policy namely, 1) modelling capabilities within agencies and attitudes towards models and decision-making; 2) current evaluation of external impacts of plans and assessment of transport sustainability; and 3) institutional framework for modelling and decision-making of transport plans and the extent to which transport decisions are integrated among different agencies.

In the first survey component, targeted towards assessing the status of existing long range urban transport models and their role in decision-making, significant differences were found among the three levels of government. In municipalities, especially, various challenges are associated with modelling. First, there is a lack of sufficient resources for implementation or conduct of modelling in order to compare scenarios and evaluate strategic directions. But also, agency
“cultures and politics” were found to play a significant role in limiting the expenditure of funds on large-scale modelling exercises since they are deemed not to be helpful for decision-making. In addition, many planners find modelling exercises frustrating due to the various drawbacks of existing models.

The second survey component attempts to assess the extent to which sustainability objectives drive the planning and policy agenda in Canada and to investigate whether policy appraisal and funding mechanisms actually reflect these objectives. This component also includes a brief visioning exercise whereby participants are asked to envision the long-range future of transportation and other infrastructure in their urban area. Results show that while the sustainability and smart-growth terminology have become widespread and while most long-range plans have incorporated transit expansions, promotion of live/work areas, and intensification of development, they have not been matched by increased funding. This situation has led to frustration among Canadian planners which has translated into a rather gloomy outlook on the future of Canadian cities. Many view their cities as moving towards increased energy consumption, dominance of the private car, social disparity, and environmental damage.

The third survey component explores the issue of institutional integration in the context of transport especially in terms of the role of institutional integration in promoting sustainable transport plans. This component starts with a general hypothesis that there is a lack of integrated policy making across government departments in Canadian urban areas thus leading to ineffective development and implementation of policies that span over different municipalities, disciplines, or government levels. Indeed, the results of this survey component in most Canadian cities, have proved this hypothesis. Institutional structures in Canadian cities seem to be struggling between attempts to centralize decision-making under the umbrella of regional organizations and trends towards fragmentation and decentralization of decisions. There seems to be low institutional integration among the three levels of government and weakened regional visions within most urban areas. Most municipalities complain about the lack of involvement of the federal government in urban issues. They also suffer from clashes between municipal and provincial visions.
The three survey components have helped highlight the needs of policy and hence shaped the scope of this research. Four main conclusions were drawn from this part of the thesis: 1) there is a gap between modelling and decision-making; 2) there is a need to bridge this gap since models are becoming more necessary for decision-making in light of the increasing complexity of travel behaviour and land-use transport interactions; 3) the challenges brought by climate change and sustainable growth have added yet another dimension to transport decisions which have to rely on a range of disciplines; and 4) the need for multidisciplinary assessment of transport decisions is putting pressure on agencies in terms of transcending individual mandates and connecting policy appraisal.

The second part of this research proposes a framework that addresses the four aforementioned policy concerns. The framework is based on the use of ILUTE, an integrated land-use and transport model for the GTA, linked with a set of sustainable transport indicators derived from ILUTE outputs and sustainability impact sub-models outputs thus reflecting a range of transport externalities. This framework is motivated by the need to shift transport appraisals from the traditional cost-benefit frameworks involving measurement of time savings, vehicle operating costs and accidents as well as qualitatively assessing environmental impacts, to a broader approach based on an integrated assessment of transportation impacts on three main levels namely, economic, social, and environmental. Distilling ILUTE results into readily understandable indicators of urban sustainability is proposed as a means of stimulating greater interchange between modellers and policy makers. This research part discusses potential indicators of sustainable transport and proposes to quantify the “environmental pillar” of sustainable transportation.

In order to estimate of a set of environmental indicators, modelling of the main environmental impact of transport in the GTA is needed. This is what the third part of this research has aimed to achieve. Taking into account that the main environmental impact of transport is air quality, this research has developed a modelling framework for 1) estimating emissions from on-road vehicles, 2) dispersing the emissions in order to assess the quality of the ambient air, and 3) linking air quality with population as a means of deriving exposure patterns.
The emission-dispersion-exposure framework starts with the development of link-based exhaust emissions and zone based evaporative emissions for light-duty vehicles in the GTA. For this purpose, the Canadian version of the Mobile6.2 model (Mobile6.2C), developed by the USEPA for estimation of vehicle emission factors, was fitted with travel activity input data derived from TASHA, a “next-generation”, activity-based model of travel demand for the GTA, developed at the University of Toronto. Resulting emissions were plotted in a GIS environment for improved visualization of results. The use of TASHA for the purpose of generating vehicle activity parameters rather than a conventional 4-stage model leads to better emission estimates. The main limitations of this approach include the focus on light-duty vehicle emissions, the lack of information on light-duty vehicle breakdowns by type, and the average speed assumption of Mobile6.2.

Understanding vehicle-induced emissions alone is not sufficient to understanding the problem of air pollution in an urban area. For this purpose, a CALMET/CALPUFF-based air quality model for the City of Toronto was developed, which estimates the contribution of road emissions to local air pollution. The CALMET/CALPUFF modelling framework was selected as the most adequate for the current application. CALMET is a diagnostic meteorological model that provides high resolution data for the modelling domain. It was used along with land-use, terrain, as well as surface and upper-air meteorology to generate an input file to be used by CALPUFF. One of the many strengths associated with the use of CALPUFF is its ability to assign emissions to specific roadway links and treat links as line sources in dispersion, contrary to most existing modelling approaches for large urban areas where emissions are allocated to grid cells. A breadth of results and analyses was conducted to assess air quality in the City of Toronto. In addition, a rather innovative attempt at assessing population exposure was presented; rather than linking average daily concentrations in a zone with the average daily number of people in the zone, the proposed approach accumulates exposures throughout the day while individuals move from one zone to the other. Of course, the air quality modelling exercise was not free of limitations associated with both model formulation and input data.

Following the three parts of this research, the thesis ends by tying the policy and modelling components by proposing a set of environmental indicators that constitute the first set towards linking ILUTE with measures of transport sustainability.
11.2 Research contributions

The most important contribution of the work presented in this dissertation, which is the main element around which this research revolves, is the integrative process whereby models of travel demand, vehicle emissions and dispersion, are integrated in a modelling framework whose main aim is to respond to policy-makers’ needs in terms of environmental appraisal of transport policy. The resulting model system integrates modelling, transportation policy-makers’ visions, and suggests a way of reporting modelling results. It uses a cause-effect chain starting from traffic as the causal factor and ending with population exposure as the final effect. Traditionally, models of travel demand, vehicle emissions, air quality, and population exposure have evolved independently which has led to incompatibilities especially in the case of state-of-the-art models which often require specific and detailed inputs. This is why, for example, most transportation models are linked with simple emission curves and steady-state dispersion functions as a means of quantifying transport-related environmental impacts. This research transcends the traditional methods for coupling models through its focus on integrating recent research in various disciplines in order to gain insight into complex processes. The needs for integrative research have been voiced in various fields of science and engineering especially in environmental science (Rizzoli and Young, 1997; Parker et al., 2002; Moussiopoulos, 2003). Moussiopoulos (2003) defines integration as:

The scientific activity of collecting and synthesizing the scientific elements needed for shaping a direct interface with decision-makers and society

Indeed the integration of different elements requires insight into the various models. Often, different models are not compatible; in particular the output of one element may not be directly useful as input into the next element. An example of such incompatibility is the output of TASHA, the activity-based travel demand model, and the needs of emission modelling. While travel demand modelling focuses on “trips and trip chains”, emission modelling focuses on “vehicles types and vehicle chains” including soak times. This research discusses and proposes solutions to the incompatibilities between individual models. Another by-product of integration is the added dimension or complexity that may arise when different models are linked; this requires insight into the different elements so that simplifications can be made. An example of this “added dimension” is in the linkage between road emissions and atmospheric dispersion.
processes thus requiring judgement calls regarding the treatment of emission sources and receptors. Note that integration not only results in complexity associated with the different models/disciplines but also complexity in terms of addressing the needs of policy-makers. This is why this research focuses on indicators as a means of bridging modelling and decision-making.

The goal of this research is not to end-up with a finished product (from a software perspective), but rather to use the different models, in an integrative manner, as a means of exploring the problem of transport policy appraisal in a new and more holistic way as compared to traditional approaches to model coupling. This approach ensures that advances in transport, emissions, and dispersion modelling are not left in isolation but that each discipline is set within the broader context of the other disciplines. The final product is:

(1) An **interdisciplinary modelling system** combining knowledge from transportation, vehicle emissions, and atmospheric dispersion. It uses state-of-the-art individual models which are transparent and developed as open-source tools, thus enabling them to be “retrofitted” in order to improve compatibility and better cater for the problem at hand.

(2) A device for **communicating modelling results** and knowledge to decision-makers through the use of GIS and performance indicators. The research focuses on understanding the possible gaps between the supply of information by models and the demands of the users and discusses possibilities to bridge those gaps.

(3) A **participatory framework driven by the needs of transport policy**. Communication with policy-makers is a major component of this research. This ensures that visions of policy-makers and lessons learned are clearly understood and reflected by the modelling system. The research also discusses scenario planning and the interactions between modelling and decision-making.
11.3 Recommendations for future research

There are both short-term and long-term additions to the work presented in this thesis that could be envisaged. On the long-term, the inclusion of indicators reflecting the three levels of sustainability as well as a larger range of vehicle types would prove to be valuable additions to the ILUTE modelling framework. On the short-term, various improvements can be made to the current emission-dispersion-exposure system in order to improve its accuracy and forecasting capability. This section discusses both types of recommendations.

11.3.1 Long-term recommendations

While this research has conducted the air quality modelling for transport in the GTA, and proposed a set of environmental indicators based on modelling results, there is a need to develop and quantify both social and economic indicators linked with ILUTE. Otherwise, transport policy assessment in ILUTE will fall into the “reductionist” approach whereby transport scenarios are evaluated solely based on their impacts on air quality. In order to develop social and economic measures, it is proposed to use the same method adopted in the current study: i.e. 1) start with highlighting a broad range of impacts of interest, 2) move to modelling the highlighted impacts and aggregating and/or disaggregating modelling results in various ways, and 3) based on the modelling results, extract the set of indicators. This ensures that the indicator does not shape or constrain the modelling but rather, it is the modelling framework that dictates what is possible and feasible. Of course, this method is not free from biases; some indicators may be of importance to decision-making and yet unfeasible from a modelling point of view; hence, they would fall from the indicator set. However, recall that the aim of this framework is to bridge modelling and decision-making rather than entirely replace decision-making by the model and indicator sets.

This study focuses on light-duty vehicles’ contribution to air quality and overlooks the contribution of trucking to environmental degradation. There is significant evidence that trucks contribute disproportionately to vehicle emissions and hence, they need to be taken into account on the long-term. This effort involves the incorporation of a commercial vehicle movement (CVM) module within ILUTE, and this task is highly challenging. Related to the incorporation of CVM-associated emissions, is the need to look at particulate matter emissions, especially
PM$_{2.5}$ related with diesel emissions and highlighted by the City of Toronto as a problem pollutant in the City: “Mobile Sources alone (Fugitive Road Dust plus Vehicle Tailpipe emissions <PM$_{2.5}$) generate sufficient emissions to create concentrations that exceed AAQC [Ambient Air Quality Criteria] values” (ICF International, 2007).

Beside truck movements, there is also a need to refine the light-duty vehicle fleet types and movements. At this stage, the composition of household vehicles is unknown in addition to daily VKT for the different types of vehicles. A uniform distribution of the vehicle fleet across the region is assumed although it is expected that a spatial variability in the types of vehicles owned by households exists in the GTA. In addition, vehicle operation is assumed to be the same for all vehicle types while it is expected that different vehicle types are driven differently. For example an older third vehicle in a household is not expected to be used the same as the other two vehicles. These limitations can be addressed first by implementing the auto-ownership module in TASHA which captures vehicle transactions and the types of vehicles owned by different households. In addition, refinement to the car allocation module should be done by incorporating some “behavioural” elements to the car allocation process. Small datasets (such as CHASE; the Computerized Household Activity Scheduling Elicitor) which includes household attributes, vehicle attributes, and vehicle usage; can be used for the development of this module.

### 11.3.2 Short-term recommendations

Short-term recommendations are proposed as a way of improving the accuracy of the emission-dispersion-exposure estimates. First, there is a need to incorporate emissions for the entire GTA in CALPUFF rather than just the City of Toronto. This is especially important in order to accumulate 24 hours of exposure to air pollution for individuals. In TASHA, individuals living in the GTA conduct all of their daily activities and travel within the GTA, as such; in order to track exposure during daily activities and travel, there is a need for air pollution data for all zones within the GTA. Another short-term addition involves the implementation of the method proposed in Section 9.5 for assessment of exposure during travel. This method can also be refined by incorporating research findings on in-vehicle-outdoor air pollution correlations.
The current traffic assignment in EMME/2 does not take into account intrazonal trips or trips that occur within TAZs. Since local roads are represented by centroid connectors, intrazonal trips are not assigned to the transportation network. For the purpose of an emission inventory, it is important to include intrazonal trips so that total emissions are not underestimated. Also, since intrazonal trips are short, they maybe include a higher portion of start emissions. Armstrong and Khan (2004) estimated trip lengths for intrazonal trips by importing a digital road network into a GIS software (such as TransCAD) and geocoding intrazonal trip origins and destinations based on Origin-Destination survey results. Trip lengths were then calculated using the shortest path algorithm in GIS, assuming that such trips are not affected by congestion. The resulting intrazonal VKT estimate was 10 percent higher than the one predicted by a conventional factor approach. Venigalla et al. (1999) computed the intrazonal travel time and trip length for each zone as half the travel time and distance from the centroid of the subject zone to its nearest zone centroid. Future work should review existing methods for calculating the contribution of intrazonal trips to the total VKT as well as develop a method for estimating those trips in the context of the GTA.

In terms of refining NO2 concentration estimates, there is a need to incorporate basic NOx chemistry. The current model estimates dispersion of NOx while assuming all NOx concentrations are NO2. This assumes “instantaneous transformation” as well as could lead to an overestimate of NO2 in the near-field. While it is beyond the scope of this research to incorporate all reactions involving formation and destruction of NO2, simple NO2 chemistry that uses background ozone concentrations may prove valuable. Note that it is beyond the scope of this research both on the long-term and short-term to incorporate the mechanisms for ozone formation and the prediction of smog episodes. It is also important to conduct additional model runs thus generating sufficient hourly predictions that can in-turn be compared with observations from air pollution monitoring stations in the GTA, especially in the case where stations are close to roadways.

Moreover, there is a need for finer resolution emissions and air quality modelling to be conducted in downtown Toronto, especially by taking into account urban canyon modelling. Small-scale dispersion runs can be conducted using the California Line Source Model 3 with Queuing and Hot Spot Calculation (CAL3QHC) in selected intersections within downtown
Toronto as a way of assessing the effects of various urban structures in Toronto on local air quality. In addition, a refinement of emission estimates for all links should be made in order to improve on the average-speed assumption of Mobile6.2. This is not to say that microsimulating traffic and emissions in the entire GTA is recommended. However, representative driving patterns can be selected especially on arterial roads and the associated emission factors can be derived from a microscopic emission model. The resulting emission factors can in-turn be weighted by the frequency of these driving patterns in the area for different hours of the day.

In order to improve the policy-sensitivity of emission estimates, there is a need to incorporate transit bus emissions within the modelling framework. This allows for the assessment of policies that target alternative fuels and technologies targeting the bus fleet as well as to capture the effect of transit expansions and frequency increases not only on the potential decrease in auto emissions but also on the increase in bus emissions. The incorporation of bus emissions is inevitably linked with the need to incorporate particulate matter EFs with the Mobile6.2C look-up tables.

Last but not least, perhaps the most pressing and straightforward exercise that is recommended is the use of the developed framework for modelling policy scenarios and testing its sensitivity to different policy inputs.
11.4 Final remarks

Transport policy research is highly challenging, particularly because of its multidisciplinary nature. This research is an illustration of the range of disciplines involved in transport policy appraisal. The “appraisal” component motivates the development of models and tools that can reflect a multitude of impacts of interest to decision-makers, and the “policy” component reminds us that the development of analytical tools needs to address the policy environment and challenges faced by planners and decision-makers. Traditionally, transport policy appraisal was synonymous to cost benefit analysis. Yet recently, the climate change and sustainability agenda, have added numerous dimensions to the problem of urban transport. Proper assessment of a proposed transport policy now necessitates an air quality analysis, an energy analysis, a look at distributional impacts and social equity, as well as a cost-benefit analysis that transcends traditional costs and incorporates the costs of externalities. There is no question that Canadian government agencies are still struggling in the face of this new environment for transport policy.

The complexity of the policy questions can only be dealt with through a multidisciplinary approach. While this approach is indeed challenging from a research point of view, it can be daunting from a policy perspective. Although in need of further improvement, communication of research findings and collaborations across disciplines has been successful in academia, thus helping in the development of cross-disciplinary research. Unfortunately, communication across government departments is nearly non-existent and many orders of magnitude harder to achieve than communication in academia. The new challenges of transport policy require government agencies to transcend individual mandates and form cross-departments work groups and task forces building on their diversity in order to tackle the “new” issues. Yet, current institutional structures and political cultures have not created an environment favourable for cross-disciplinary policy making. While progress is being made, it is slow and overshadowed by the movement away from sustainability. There is a need for more focused efforts both in academia and government as well as communication between both in order to overcome the challenges of climate change and smart-growth in Canada.
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Appendix A
Questionnaire for survey of planners and policy-makers

This survey is part of a research initiative that I am currently involved in with Prof. Eric Miller at the University of Toronto. The research aim is to bridge the gap between modelling and decision-making by linking the results of integrated land-use and transport models with policy evaluation tools. We are proposing to do this by developing and estimating a set of sustainable transport indicators, derived from the output of integrated models, and aggregated within a policy evaluation tool thus providing policy-makers with a set of manageable performance measures that can assist them in decision-making. The aim of this survey is to provide us with an overview of the current evaluation process of transport policy in Canadian agencies and its main challenges, in addition to your own satisfaction with the current situation and how you would view a more “ideal” framework for policy appraisal.

Before we start, can you briefly introduce your background, your role, in addition to the responsibilities of your unit/department?

1- Time frame for planning

- Is your agency mainly involved in long-term (strategic) or short-term planning?
- What is a typical time horizon for strategic planning?
- Can you cite some differences in both policy evaluation and decision-making with respect to long-term and short-term plans?
- How often do you review or alter plans? Can you provide examples?
- In your opinion, are long-term plans more or less credible than short-term plans? What do you think would enhance the credibility of long-term plans?

2- Policy evaluation

- When assessing different policies do you mainly resort to professional judgment or do you supplement professional judgment with formal evaluation tools?
• In the latter case, what types of evaluation tools do you adopt? Do you run your own models? Do you ever employ consultants to run models?

• Different people approach modelling differently; in your case, what role do the results of your models play in decision making? Do you fully trust the results of your models?

• What are the problems/challenges that you are currently facing in policy evaluation (data needs, human resources, availability of tools, time constraints)?

• Can you state your major policy concerns and the types of models or evaluation tools that you think would be able to answer your questions/concerns?

3- Involvement in modelling and policy analysis

• What types of people (background/expertise, level of experience, job description) in your organization are responsible for policy appraisal (including modelling)?

• Can you describe the relationship, in your agency, between modellers (if any) or persons more involved in quantitative policy evaluation and persons who are less involved in modelling and more involved in policy advice?

4- Sustainability planning

• When evaluating different policy alternatives, what types of impacts do you mostly address/consider (environmental, social, economic)?

• How do you understand the concept of “sustainability planning”? What does it mean to you? What aspects do you think it engulfs?

• Does your organization have a working definition of sustainability? If not, do you personally think that your agency should formulate a vision/definition of sustainability?

• Do you explicitly evaluate policies with respect to sustainability objectives? Do you use any types of sustainability indicators or performance measures in policy evaluation?

• Do you think that the availability of sustainability indicators reflecting the results of integrated transportation and land-use models would be beneficial for policy appraisal? Could they lead to better decisions being made?

• Would you be willing to “trust” the results of formal evaluation tools involving the use of sustainable transport indicators in the context of policy assessment? If not, under which conditions do you think models would be more “trustworthy”?
• What types of sustainability indicators do you think are important? Which ones do you think would reflect transport/land-use sustainability?

5- Major changes witnessed in planning and decision-making

• Have you witnessed any major changes in policy evaluation and decision-making in your agency for as long as you have held the current position? If yes, which? How do you think policy evaluation and decision-making will evolve in the next 10-20 years?

6-Future Scenarios

• How do you view the future of transport in your metropolitan area in a business as usual scenario? Out of the three scenarios presented below, which one is the most likely scenario you think transport will evolve towards in the next 25 years? (You surely may envisage combinations of the three scenarios as they draw extreme pictures).

**Economic growth scenario**
This scenario is mainly characterized by an economically stronger Canada with improved trade relations with the US. There is an increased disparity between low and high income groups and increased consumption of energy and natural resources especially by higher income classes. There is an increase in car and truck use for passenger and freight transport, respectively. As a result, an increase in on-road vehicle emissions occurs. Major cities maintain their strong downtown core but increased suburbanization rates are witnessed leading to increased commuting distances. Congestion is dealt with through the use of Intelligent Transportation Systems rather than modal shift to public transport or decreased travel. Motorway tolls are widely implemented. The dispersion of activities and growth in personal mobility ascertain the role of the private car.

**Social equity scenario**
This scenario aims at encouraging immigration in Canada thus leading to population growth. It emphasizes a growth in collective rather than individualistic lifestyles. Employment programs, technical and vocational training provide significant help to the poorer sections of society thus allowing them to have better job opportunities. Accessibility to basic services and to the downtown core is improved but also a significant growth of peripheral regions is witnessed (which may be harmful for the environment). Transit improvements are highly favoured over
road investments; road tolls are very limited. Telecommunications are improved as a means to reduce social exclusion.

**Environmental preservation scenario**
This scenario emphasizes limited population and economic growth to reduce pressure on environmental resources and stresses a reduction in energy and resource consumption. An increase in the tax on consumer goods is introduced to limit the use of non-renewable resources. Research is mainly targeted towards alternative fuels and renewable energy. A radical decrease in environmental pollution is witnessed resulting from tighter environmental standards and higher fuel taxes thus creating higher financial burdens on industries. Urban form is highly targeted towards mixed use development, live/work opportunities. A high penalty on car and truck travel is introduced through emission and ownership taxes; public transport is promoted for passenger travel and rail transport for freight. Telecommunications are improved as a substitute for travel.

7-Institutional integration and involvement in decision-making

- Do you currently evaluate certain policies in conjunction with other government agencies? What kind of policies?
- (If a municipality) Do you coordinate decisions with other neighbouring municipalities?
- Do you organize public meetings and explicitly involve the public in planning decisions? Can you provide examples? What about stakeholder meetings/workshops?
- Who of the following actors/stakeholders in your region have the most influence over the decision-making process and who are the most vocal? Business community, media, non governmental organizations and environmental activists, transit operators, transit riders, community leagues, general public?
- Assuming we agree that integrated policy appraisal is important; which government agencies you think should be involved in coordinated policy appraisal of transport plans? Do you think that agency mandates hinder possible integrated policy evaluation?
Appendix B
Description of Mobile6.2 input data

This appendix describes input data for Mobile6.2 which is subdivided into six broad categories: 1) external conditions, 2) environmental effects on air conditioning, 3) vehicle fleet characteristics, 4) activity data, 5) state programs, and 6) fuel data.

B.1 External conditions and environmental effects on air conditioning

External conditions affecting the level of emissions include calendar year, evaluation month, minimum/maximum temperature during a day, hourly temperature during a day, altitude, and absolute humidity. Environmental effects on air conditioning include cloud cover, peak sun, sunrise/sunset, ambient relative humidity for each hour of the day, and barometric pressure. Note that, while all these inputs affect emissions of Carbon Monoxide (CO), Hydrocarbons (HC), and Nitrogen Oxides (NOx), only the year and month of evaluation affect direct Particulate Matter (PM) emissions, through the impact of fuel characteristics and fleet composition. Altitude, temperature, humidity, and air conditioning usage have no impact on direct PM emissions in Mobile6.2. Input data for external conditions are addressed in USEPA (2004a) and USEPA (2003a). Air conditioning effects are discussed in USEPA (2001a; b).

B.1.1 Calendar year and month of evaluation

Mobile6.2 can model Emission Factors (EFs) for calendar years 1952-2050 inclusive and evaluation months January or July reflecting winter and summer seasons.

B.1.2 Ambient temperature

Temperature is a significant external condition and may be input in two ways, minimum/maximum daily temperatures or hourly data. When minimum and maximum daily temperatures are specified, Mobile6.2 creates a daily temperature profile in which the low temperature is assumed to occur at 6am and the high temperature at 3pm. In the hourly temperature option, a different temperature profile may be defined as compared to the one Mobile6.2 would create. The USEPA recommends the use of minimum and maximum daily
temperatures for analyses of average summer or winter day conditions that will not be used as input into an air quality or dispersion model. The use of hourly temperatures is considered necessary for inventories that will be used for air quality analyses of specific exceedance episodes.

B.1.3 Humidity
Humidity mostly affects NO\textsubscript{x} emissions since water vapour absorbs some of the heat of combustion in the engine, which in turn results in a reduction in NO\textsubscript{x} formation. Moreover, both humidity and temperature are combined by Mobile6.2 to create a heat index which is used to estimate air conditioning usage. As such, high humidity on hot days increases air conditioning usage which indirectly increases HC and CO emissions. In Mobile6.2 humidity may be input either as one average value for the absolute humidity or as 24 values for the relative humidity at each hour of the day. While hourly relative humidity allows a more accurate estimation of air conditioning usage and the quenching effect on NO\textsubscript{x} emissions throughout the day, the absolute humidity command (daily average) requires less data and could be useful for generic modelling of average day ozone or CO conditions. However, hourly relative humidity should be used when modelling a specific exceedance episode. If relative humidity is input, then barometric pressure should also be used. Care should be taken when inputting an absolute humidity value which is inconsistent with the minimum or maximum temperatures used or one which yields a relative humidity greater than 100 percent. For this purpose, the USEPA recommends the absolute humidity input to reflect the lowest humidity value throughout the modelled day.

Concerning the other effects on air conditioning use such as cloud cover, peak sun, and sunrise/sunset, the USEPA recommends the use of default values in most cases, since such values are consistent with conditions for ozone formation. The impact of reasonable changes in the default values is likely to be small. Local data may be necessary in the case where specific ozone exceedance episodes are analyzed.
B.2 Vehicle fleet characteristics

Vehicle fleet characteristics affecting Mobile6.2 emissions include the distribution of vehicle registrations, diesel fractions, annual mileage accumulation rates, natural gas vehicles (NGV) fraction, and alternate EF for NGV. All vehicle fleet characteristics are input as a function of the different vehicle classes. Vehicle fleet characteristics are addressed in USEPA (2004a) and USEPA (2003a). Fleet characterization data in terms of age distributions, average mileage accumulation rates and projected vehicle counts are discussed in USEPA (2001o).

B.2.1 Vehicle registrations

Mobile6.2 covers a 25-year range of vehicle ages, with vehicles 25 years and older grouped together. Age is a significant input and the USEPA recommends the development of local age distributions as opposed to the use of default values. In fact, the age distribution of the fleet affects estimates of the deterioration of vehicle emission control effectiveness as well as determines the fractions of the fleet that meet different emission standards. Typically, local age distributions can be estimated from registration data or from an analysis of inspection and maintenance (I/M) program data.

B.2.2 Annual mileage accumulation rate

The annual mileage accumulation rate reflects the number of miles driven per year; Mobile6.2 divides it by 365 to obtain the mileage driven per day. As such, changing the annual mileage accumulation rate will change the assumed number of miles driven each day. Depending on the type and age of a vehicle, the accumulation rate varies; in fact, older vehicles tend to be driven fewer miles per year than newer ones and trucks tend to be driven more miles per year than cars. Annual mileage accumulation affects the rate at which vehicle emission controls deteriorate as well as the relative emissions contributions of newer and older vehicles. The USEPA recommends the use of default mileage accumulation rates built into Mobile6.2. However, if local mileage accumulation rates are used they normally should not change across calendar years. Mobile6.2 allows the specification of vehicle classes for which new annual mileage accumulation rates are entered while all other classes may be left with the default rates. As a result, local annual mileage accumulation rates may be entered only for the vehicle classes for which local data is available.
B.2.3 Diesel fractions
Within any vehicle class, diesel and gasoline vehicles have distinctly different emission rates; as such, diesel fractions allow the model to separate gasoline and diesel vehicles within a vehicle class. Mobile6.2 includes default diesel sales fractions for 14 composite vehicle classes (excluding urban/transit buses, which are assumed to be all diesel-fuelled, and motorcycles which are assumed to be all gasoline-fuelled). It is possible to enter alternative diesel fractions for any of the 14 classes for which direct information exists. Mobile6.2 projects future diesel fractions as constant beginning in 1996. As such, if no local data are available for years after 1995, the 1996 and later default values in Mobile6.2 should be used for all years after 1996.

B.2.4 Natural gas vehicles (NGV)
Mobile6.2 allows the specification of the fraction of the vehicle fleet by vehicle class that consists of vehicles certified to operate on either compressed or liquefied natural gas. It relies on a set of default emission rates built into the model but allows users to enter alternative emission rates. The use of these commands is primarily limited to analyses of the effects of NGV on a small subset of a typical area-wide fleet. In cases where the fraction of NGV in an area-wide fleet is extremely small, use of these commands may not be necessary. Note that, these commands should only be used for vehicles originally certified as NGV and should not be used for retrofits or dual-fuelled (gasoline and natural gas) vehicles.

B.3 Vehicle activity
Most of the Mobile6.2 default inputs for trip lengths and activity factors were collected through an instrumented vehicle study conducted by the USEPA in Baltimore and Spokane. In this study, data loggers were installed on 168 randomly selected vehicles to monitor vehicle usage. Information from more than 8,500 vehicle-trips was recorded thus yielding a “trip characteristics file”. These vehicle activity characteristics include fractions of Vehicle Miles Travelled (VMT) by vehicle class, VMT by facility, VMT by hour, speed VMT, average speed, starts per day, distribution of vehicle starts during the day, soak distribution, hot soak activity, diurnal soak activity, weekday trip length distribution, and weekend trip length distribution. This section presents an overview of the most significant inputs. Mobile 6.2 default activity values can be found in USEPA (2004a).
B.3.1 VMT fractions by vehicle class
VMT fractions specify the fractions of total VMT that are accumulated by each vehicle class. The fraction of VMT by vehicle class varies from area to area and can have a significant effect on overall emissions. As such, the USEPA encourages the development and use of area-specific estimates of VMT by vehicle class. Note that, in many cases, the local available information is not detailed enough to include all vehicle classes. For this purpose, the USEPA has recommended a method for disaggregation of local information by using the Mobile6.2 average distribution values to split the VMT for the aggregate class into the needed subgroup VMT estimates (USEPA, 2003a). The VMT by vehicle class in Mobile6.2 is a calculated value and varies from calendar year to another due to uneven growth in the vehicle sales by vehicle class. For this purpose, the default VMT distribution used in the calculation must be taken from the calendar year that coincides with the calendar year of the local data used.

B.3.2 VMT fractions by facility type
The fraction of VMT by roadway or facility type varies from area to area and can have a significant effect on overall emissions from highway mobile sources. For this purpose, the USEPA recommends the use of local hourly VMT data by roadway and vehicle type. Mobile6.2 adopts four roadway categories namely, freeway, arterial/collector, local roadway, and freeway ramp. In many cases, hourly data may not be available and only daily or peak/off peak VMT distributions may be available to be distributed to the individual hours of the day. For this purpose, the USEPA has recommended a method for disaggregating local information to hourly data (USEPA, 2004a). Note that Mobile6.2 does not require that values for all vehicle classes be entered, so that only the vehicle classes that need to be changed must be entered (USEPA, 2003a; USEPA, 2001v).

B.3.3 VMT fractions by hour
Although the fraction of VMT by hour of the day varies from area to area, the USEPA classifies this variation as having a negligible effect on overall daily emissions from highway mobile sources and suggests the use of default values (USEPA, 2003a).
B.3.4 VMT fractions by average speed
The Mobile6.2 definition of speed includes all operation of vehicles including intersections and other obstacles to travel, which may result in stopping and idling. As a result, average speeds, as used in Mobile6.2, will tend to be less than nominal speed limits for individual roadway links. The distribution of VMT by average speed has a significant effect on overall daily emissions from highway mobile sources; as such, the USEPA encourages the development and use of local estimates of VMT by average speed. Mobile6.2 uses average speed distributions to represent the driving on all of the roadway links within the area to be modelled for each hour of the day. The average speed distributions have 14 values which represent the fraction of all VMT which occurs at 2.5 miles per hour, and 5 to 65 mph in 5 mph increments. Once the average speed is determined for each roadway segment in the area to be modelled, the VMT for each segment can be assigned to one of the average speed bins. Once the VMT for all of the roadway network segments has been placed in bins, the VMT in each bin would be divided by the total VMT for that driving cycle set (the sum of all of the bins) to give the fraction of VMT in that bin; the sum of the fractions must be one (USEPA, 2003a; USEPA, 2001u).

B.3.5 Average speed
This command is used to enter a single average speed, instead of an average speed distribution. If emissions are to be estimated for an individual roadway link or a set of individual roadway links, then a single average speed estimate (in any hour of the day) for each particular link or roadway segment must be used for each model run, instead of an average speed distribution. In this case, Mobile6.2 assumes a default speed distribution for each average speed input and cannot be used to model the observed speed distribution of individual roadway links. The USEPA recommends the use of this command when modelling individual roadway links for specific time periods less than a day. Four roadway scenarios are available to be associated with the average speed namely, non-ramp, freeway, arterial, and area-wide. Note that the average speeds used for individual roadways must be consistent with default values used to generate average speed distributions. If the average speeds and VMT estimates are consistent, then summing the emission results from individual roadway segments, or running a single Mobile6.2 run using VMT distributions by average speed will result in the same overall emission estimate. Concerning idling emission rates (in grams per hour); Mobile6.2 assumes they are the same as for driving at 2.5 mph. Idling emission rates are best calculated using this command for the arterial/collector driving cycle set.
with the average speed set to 2.5 miles per hour. Note that only the running exhaust emission results (not including engine start emissions) are used to calculate idle emission rates (USEPA, 2003a).

B.3.6 Starts per day and per hour
Engine start emissions, especially those occurring after a cold start, account for a significant fraction of the emissions over a vehicle trip. Only light-duty vehicles, light-duty trucks and motorcycles account for engine starts separately. The emission rates for heavy-duty vehicles and buses include engine starts but the user cannot adjust the number of engine starts and the soak time distributions. Start distributions are addressed in USEPA (2003a). Engine start emissions are addressed in USEPA (2001w; x).

B.3.7 Soak distribution
Although the distribution of soak times before an engine start vary from area to area, it is expected that this variation has a negligible effect on overall daily emissions from mobile sources. Default values for the distribution of the soak times before an engine start may be adopted instead of local values. Soak length activity factors for start emissions are addressed in USEPA (2002c).

B.3.8 Hot soak activity
Hot soak emissions refer to HC losses from fuel vapours in the intake manifold and fuel system, driven off the vehicle by the heat of the engine immediately after shut down. If the vehicle is restarted, the full hot soak effect is interrupted, resulting in fewer hot soak emissions. Diesel and NGV are assumed to have negligible hot soak evaporative emissions and as such only gasoline-fuelled vehicles are affected by the hot soak activity. In Mobile6.2, hot soak duration (after the key off) is defined to range from a minimum of one second (instantaneous) to a maximum of one hour. The one-hour limit has been chosen in Mobile6.2 for consistency with the FTP definition of a hot soak. A minimum trip length of four minutes was chosen to qualify the subsequent soak as a valid hot soak. In Mobile6.2, the same distribution of hot soak times is used for all vehicle classes. Although the distribution of hot soak times after an engine shut down, vary from area to
area, it is expected that this variation has a negligible effect on overall daily emissions from mobile sources (USEPA, 2003a; USEPA, 2001f; h; l).

B.3.9 Diurnal soak activity

Diurnal emissions refer to HC losses from fuel vapours driven off the vehicle from the increasing temperature of the fuel in the tank and other locations on the vehicle while the engine is shut down and during times of day when the ambient temperature is rising. The ability of the vehicle emission control components to adsorb these vapours depends on how long the vehicle has been subjected to diurnal emission generation. If the vehicle is restarted, the full diurnal effect is interrupted, resulting in fewer diurnal emissions. In Mobile6.2, diesel and NGV are assumed to have negligible diurnal evaporative emissions and as such only gasoline-fuelled vehicles are affected by the diurnal soak activity. In Mobile6.2, three types of diurnals can occur:

- Multi-day diurnal: Occurs if a vehicle is operated, and then “soaks” (is parked) for two or more days, and experiences two or more cycles of sufficiently large thermal gradients during the multi-day soak period to raise fuel tank temperatures past a threshold value.
- Full or one-day diurnal: Begins prior to the beginning of the temperature rise (6am), and can last for up to 24 hours.
- Interrupted diurnal: similar to the previous ones, except that the soak periods range from a minimum of one hour up to 24 hours, and they start later in the day (i.e. the vehicle is operated during the morning so that the early morning heat build, beginning at 6am, is interrupted).

Diurnals, which range from 25 to 48 hours, are a combination of a one-day diurnal and an interrupted diurnal or multi-day depending on when they start. Diurnal activity estimates are based on whether a multi-day, full-day, or interrupted diurnal has occurred at each time interval. In fact, at every hourly interval, a vehicle may or may not be experiencing a diurnal. A consistent distribution of diurnal soak activity will have the total fraction of vehicles soaking in a given hour less than one. The diurnal activity should show a reduction in soaking vehicles as they are started and begin to operate in subsequent hours of the day. Although the distribution of diurnal soak time varies from area to area, it is expected that this variation has a negligible effect on overall daily emissions from mobile sources (USEPA, 2003a; and USEPA, 2001c; d; e; g; n).
B.3.10 Vehicle trip length duration

Mobile6.2 distinguishes weekends from weekdays in terms of activity and emissions, and a user input is required to tell the model which one is to be reported; the default is weekday. Based on the instrumented vehicle study, the default trip rate for cars in Mobile6.2 is 7.28 trips per day and 5.41 trips per weekend. In Mobile6.2, trip length duration distributions were estimated first by categorizing each of the 8,500 vehicle trips into a particular weekday-weekend and hourly group. A vehicle trip was classified as a weekday trip if it started on Monday through Friday; and a weekend trip if it started on Saturday or Sunday. A vehicle trip was classified into a particular hourly group if any part of the trip duration was in a given hourly group. A given vehicle trip could potentially be classified into one, two, or even three different hourly groups depending on the duration of the trip, and how many group interval boundaries it crossed. For example, if a vehicle trip is from 8:20am to 8:40am, it is classified as a twenty-minute trip in hourly group 8 (8-9am). If the trip is from 7:51 to 8:15, its contribution has to be split between two hourly groups (7 and 8). Thus, a nine-minute trip is assigned to the 7th group (7-8am), and a fifteen-minute trip is assigned to the 8th group (8-9am). Subsequently, each trip is classified into one of six trip duration categories based on the trip duration in minutes (<=10 min, 11-20 min, 21-30 min, 31-40 min, 41-50 min, >50 min). Trip lengths duration distributions are addressed in USEPA (2003a). Default values for the VMT distribution by trip length and hourly group are presented in (USEPA, 2001m).

B.4 Vehicle fuel characteristics

Fuel characteristics are addressed in USEPA (2004a) and USEPA (2003a). Fuel sulphur effects are addressed in USEPA (2001p); fuel oxygenation effects are addressed in USEPA (2001q); EFs for NGV are addressed in USEPA (2001r); and the emission effects of reformulated gasoline (RFG) are addressed in USEPA (2001s).

B.4.1 Gasoline Reid Vapour Pressure (RVP)

The volatility of gasoline in Mobile6.2 is indicated by the Reid Vapour Pressure (RVP) of the dispensed fuel. The RVP value should not include the effects of potentially added oxygenates since they are determined in another command. Note that RVP values supplied in Mobile6.2 runs
for the month of July (or when the season is summer) in areas which opted into the RFG program (beginning in the 1995 calendar year), will be overridden by Mobile6.2.

B.4.2 Reformulated gasoline (RFG)

RFG is a US federal fuel emission performance specification program; Mobile6.2 models a single representative set of fuel properties that represent all RFG formulations. In the case of an RFG program to be modelled, the only inputs to be specified include the season (winter or summer) and the RFG region (North or South) thus allowing Mobile6.2 to select the appropriate fuel formulation. The US Clean Air Act defines the RFG summer as May 1 through September 15 and winter as the rest of the year. RFG only affects emissions in calendar years 1995 and later. In the summer season, user supplied values for gasoline sulphur content, gasoline RVP, and gasoline oxygen content are overridden by Mobile6.2 default RFG values. Since season is an important parameter for RFG; although Mobile6.2 will choose the appropriate season based on the user supplied value for month, it is recommended to specify the season as well as month when modelling RFG.

B.4.3 Gasoline oxygen content

According to the USEPA, areas that are known to have significant market penetration of ether blends and/or alcohol blends, should characterize the relative market shares and oxygen content of these fuel blends and account for them in their mobile source emission inventory. If, together, oxygenated blends account for less than 2 percent of total gasoline sales within an inventory area, and if there is no mandatory or locally endorsed voluntary program for ether blends, then oxygenated fuels need not be explicitly modelled. Note that when RFG is indicated, Mobile6.2 will automatically account for oxygenated gasoline as part of the RFG gasoline formulation.

Typically either ethers or alcohols are added to gasoline in order to add oxygen to the engine during combustion. This would moderate rich air to fuel ratios thus reducing exhaust emissions. However, adding alcohol to gasoline increases its volatility, which may increase evaporative HC losses. Note that the USEPA allows waivers for gasoline volatility limits in some areas, which allow the addition of alcohol to gasoline. It is therefore important to know whether volatility
limits are in place and whether waivers have been allowed in order to properly model oxygenated gasoline. The default value for gasoline oxygen content in Mobile6.2 is zero.

B.4.4 Gasoline sulphur content
Sulphur is a naturally occurring contaminant in petroleum used to refine gasoline. Sulphur is associated with a reduction in the performance of the catalytic converters. Mobile6.2 explicitly accounts for the effects of the sulphur content of gasoline on the emission estimates for gasoline fuelled highway mobile sources.

B.4.5 Diesel sulphur content
The sulphur content of diesel fuel has a significant effect on emissions of PM from diesel vehicles. In fact, most sulphur in fuels is emitted as sulphur dioxide and eventually converted to sulphates in the atmosphere. A small amount of fuel sulphur is emitted directly as sulphates (generally hydrated sulphuric acid). Sulphates are a significant precursor for the formation of secondary particulates, particularly PM$_{2.5}$. Input of proper diesel fuel sulphur levels is essential to accurate PM calculations.

B.5 State programs
Mobile 6.2 can model two main types of programs namely, Inspection and Maintenance (I/M) and anti-tampering programs. Due to the lack of anti-tampering programs in the GTA, this section only addresses I/M programs since the former will not be modelled. Mobile6.2 includes program options such as On-board diagnostics (OBD), exhaust, and evaporative I/M checks. It has the ability to model up to seven separate I/M programs simultaneously, which simplifies the modelling of programs in which different model years are subject to different requirements. In fact, I/M programs that have both exhaust and evaporative inspection components are modelled as two separate, simultaneous programs. Mobile6.2 can model eleven different types of exhaust I/M programs and four different types of evaporative I/M programs. I/M programs and their effects on vehicle emissions are addressed in USEPA (2004a); USEPA (2003a; b); USEPA (2002 b; d); USEPA (2001t); and USEPA (1998).
Appendix C
Evolution of start hydrocarbon emissions throughout the day in the GTA

5.00 – 5.59 am

6.00 – 6.59 am

7.00 – 7.59 am
Appendix D
Effect of surface station observation weight on wind field

The next two figures A1 and A2 illustrate the effect of the surface station weights in CALMET on the resulting wind field. Figure D1 shows how large weights affect wind vectors beyond the vicinity of the station thus wiping-out Step1 wind fields. In Figure D2 wind vectors are more sensible, winds speeds are lower over land and higher over water.

Figure D1 Large weights assigned to surface station data
Figure D2 Low weight assigned to surface station data
Appendix E
CALMET input file

CALMET.INP      2.1             Hour Start and End Times with Seconds
MM5 for entire domain
Obs from 6 surface stations in GTA

-------------------------------- Run title (3 lines) --------------------------------
CALMET MODEL CONTROL FILE
--------------------------------

INPUT GROUP: 0 -- Input and Output File Names

Subgroup (a)
-------------
Default Name  Type          File Name
------------  ----          ---------
GEO.DAT       input    ! GEODAT=C:\CALPRO6P\GTATEST\GEO.DAT !
SURF.DAT      input    ! SRFDAT=C:\CALPRO6P\GTATEST\SURF6S-1.DAT !
CLOUD.DAT     input    * CLDDAT=             *
PRECIP.DAT    input    * PRCDAT=             *
WT.DAT        input    * WTDAT=             *
CALMET.LST    output   ! METLST=CALOBPW1.LST     !
CALMET.DAT    output   ! METDAT=CALOBPW1.DAT    !
PACOUT.DAT    output   * PACDAT=             *

All file names will be converted to lower case if LCFILES = T
Otherwise, if LCFILES = F, file names will be converted to UPPER CASE
T = lower case       ! LCFILES = F    
F = UPPER CASE

NUMBER OF UPPER AIR & OVERWATER STATIONS:

Number of upper air stations (NUSTA) No default      ! NUSTA = 0  !
Number of overwater met stations (NOWSTA) No default ! NOWSTA = 0  !

NUMBER OF PROGNOSTIC and IGF-CALMET FILES:

Number of MM4/MM5/3D.DAT files (NM3D) No default ! NM3D = 1 !
Number of IGF-CALMET.DAT files (NIGF) No default ! NIGF = 0 !

!END!

Subgroup (b)
-------------
Upper air files (one per station)
-----
Default Name  Type          File Name
------------  ----          ---------
UP1.DAT      input     1  * UPDAT=UP_X.DAT * *END*

Subgroup (c)
-------------
Overwater station files (one per station)
-----
Default Name  Type          File Name
------------  ----          ---------
SEA1.DAT     input     1  * SEADAT=SEA_449.DAT * *END*
Subgroup (d)
----------------------------------
MM4/MM5/3D.DAT files (consecutive or overlapping)
----------------------------------
Default Name Type File Name
------------ ----  ---------
MM51.DAT input 1 ! M3DDAT=C:\CALPRO6P\GTATEST\3D_1.DAT! !END!

----------------------------------
Subgroup (e)
----------------------------------
IGF-CALMET.DAT files (consecutive or overlapping)
----------------------------------
Default Name Type File Name
------------ ----  ---------
IGFn.DAT input 1 * IGFDAT=CALMET0.DAT * *END*

----------------------------------
Subgroup (f)
----------------
Other file names
----------------
Default Name Type File Name
------------ ---- ---------
DIAG.DAT input * DIADAT= *
PROG.DAT input * PRGDAT= *
TEST.PRT output * TSTPRT= *
TEST.OUT output * TSTOUT= *
TEST.KIN output * TSTKIN= *
TEST.FRD output * TSTFRD= *
TEST.SLP output * TSTSLP= *
DCST.GRD output * DCSTGD= *

NOTES: (1) File/path names can be up to 70 characters in length
        (2) Subgroups (a) and (f) must have ONE 'END' (surrounded by
delimiters) at the end of the group
        (3) Subgroups (b) through (e) are included ONLY if the corresponding
number of files (NUSTA, NOWSTA, NM3D, NIGF) is not 0, and each must have
an 'END' (surround by delimiters) at the end of EACH LINE

!END!

INPUT GROUP: 1 -- General run control parameters
-----------------------------------
Starting date: Year (IBYR) -- No default ! IBYR = 2001 !
               Month (IBMO) -- No default ! IBMO = 1 !
               Day (IBDY) -- No default ! IBDY = 0 !
Starting time: Hour (IBHR) -- No default ! IBHR = 0 !
               Second (IBSEC) -- No default ! IBSEC = 0 !
Ending date: Year (IEYR) -- No default ! IEYR = 2001 !
              Month (IEMO) -- No default ! IEMO = 6 !
              Day (IEDY) -- No default ! IEDY = 30 !
Ending time: Hour (IEHR) -- No default ! IEHR = 23 !
             Second (IESEC) -- No default ! IESEC = 0 !
UTC time zone (ABTZ) -- No default ! ABTZ= UTC-0500 !
(character*8)
PST = UTC-0800, MST = UTC-0700 , GMT = UTC-0000
CST = UTC-0600, EST = UTC-0500

Length of modeling time-step (seconds)
Must divide evenly into 3600 (1 hour)
(NSECDT) Default:3600 ! NSECDT = 3600 !
Units: seconds

Run type (IRTYPE) -- Default: 1 ! IRTYPE= 1 !
0 = Computes wind fields only
1 = Computes wind fields and micrometeorological variables
   (u*, w*, L, zi, etc.)
(IRTYPE must be 1 to run CALPUFF or CALGRID)

Compute special data fields required
by CALGRID (i.e., 3-D fields of W wind
components and temperature)
in additional to regular Default: T ! LCALGRD = T !
fields ? (LCALGRD)
(LCALGRD must be T to run CALGRID)

Flag to stop run after
SETUP phase (ITEST) Default: 2 ! ITEST = 2 !
(Used to allow checking
of the model inputs, files, etc.)
ITEST = 1 - STOPS program after SETUP phase
ITEST = 2 - Continues with execution of
      COMPUTATIONAL phase after SETUP

Test options specified to see if
they conform to regulatory
values? (MREG) No Default ! MREG = 0 !
0 = NO checks are made
1 = Technical options must conform to USEPA guidance
   IMIXH -1 Maul-Carson convective mixing height
   over land; OCD mixing height overwater
   ICOARE 0 OCD deltaT method for overwater fluxes
   THRESHL 0.0 Threshold buoyancy flux over land needed
   to sustain convective mixing height growth
   ISURFT > 0 Pick one representative station, OR
   -2 in NOOBS mode (ITPROG=2) average all
   surface prognostic temperatures to get
   a single representative surface temp.
   IUPT > 0 Pick one representative station, OR
   -2 in NOOBS mode (ITPROG>0) average all surface
   prognostic temperatures to get a single
   representative surface temp.

!END!

--- INPUT GROUP: 2 -- Map Projection and Grid control parameters ---

Projection for all (X,Y):
-----------------------------------------------

Map projection (PMAP) Default: UTM ! PMAP = UTM !
UTM : Universal Transverse Mercator
TTM : Tangential Transverse Mercator
LCC : Lambert Conformal Conic
PS : Polar Stereographic
EM : Equatorial Mercator
LAZA : Lambert Azimuthal Equal Area

False Easting and Northing (km) at the projection origin
(Used only if PMAP= TTM, LCC, or LAZA)
(FEAST) Default=0.0  ! FEAST = 0.000 !
(FNORTH) Default=0.0  ! FNORTH = 0.000 !

UTM zone (1 to 60)
(Used only if PMAP=UTM)
(IUTMZN) No Default ! IUTMZN = 17 !

Hemisphere for UTM projection?
(Used only if PMAP=UTM)
(UTMHEM) Default: N ! UTMHEM = N !
N : Northern hemisphere projection
S : Southern hemisphere projection

Latitude and Longitude (decimal degrees) of projection origin
(Used only if PMAP = TTM, LCC, PS, EM, or LAZA)
(RLAT0) No Default ! RLAT0 = 0N !
(RLON0) No Default ! RLON0 = 0E !

TTM : RLON0 identifies central (true N/S) meridian of projection
RLAT0 selected for convenience
LCC : RLON0 identifies central (true N/S) meridian of projection
RLAT0 selected for convenience
PS : RLON0 identifies central (grid N/S) meridian of projection
RLAT0 selected for convenience
EM : RLON0 identifies central meridian of projection
RLAT0 is REPLACED by 0.0N (Equator)
LAZA: RLON0 identifies longitude of tangent-point of mapping plane
RLAT0 identifies latitude of tangent-point of mapping plane

Matching parallel(s) of latitude (decimal degrees) for projection
(Used only if PMAP = LCC or PS)
(XLAT1) No Default ! XLAT1 = 0N !
(XLAT2) No Default ! XLAT2 = 0N !

LCC : Projection cone slices through Earth's surface at XLAT1 and XLAT2
PS : Projection plane slices through Earth at XLAT1
(XLAT2 is not used)

Note: Latitudes and longitudes should be positive, and include a
letter N, S, E, or W indicating north or south latitude, and
east or west longitude. For example,
35.9 N Latitude = 35.9N
118.7 E Longitude = 118.7E

Datum-region
-----------

The Datum-Region for the coordinates is identified by a character
string. Many mapping products currently available use the model of the
Earth known as the World Geodetic System 1984 (WGS-84). Other local
models may be in use, and their selection in CALMET will make its output
consistent with local mapping products. The list of Datum-Regions with
official transformation parameters is provided by the National Imagery and
Mapping Agency (NIMA).

NIMA Datum - Regions(Examples)
--------------------------------------------------------------------------------
WGS-84    WGS-84 Reference Ellipsoid and Geoid, Global coverage (WGS84)
NAS-C     NORTH AMERICAN 1927 Clarke 1866 Spheroid, MEAN FOR CONUS (NAD27)
NAR-C     NORTH AMERICAN 1983 GRS 80 Spheroid, MEAN FOR CONUS (NAD83)
NWS-84    NWS 6370KM Radius, Sphere
ESR-S     ESRI REFERENCE 6371KM Radius, Sphere

Datum-region for output coordinates
(DATUM) Default: WGS-84 ! DATUM = NAR-B !

Horizontal grid definition:
-----------------------------------
Rectangular grid defined for projection PMAP,
with X the Easting and Y the Northing coordinate

No. X grid cells (NX) No default ! NX = 210 !
No. Y grid cells (NY) No default ! NY = 210 !

Grid spacing (DGRIDKM) No default ! DGRIDKM = 1.2 !
Units: km

Reference grid coordinate of
SOUTHWEST corner of grid cell (1,1)
Vertical grid definition:

No. of vertical layers (NZ) No default  ! NZ = 10  !

Cell face heights in arbitrary vertical grid (ZFACE(NZ+1)) No defaults
Units: m
! ZFACE = 0.,20.,40.,80.,160.,320.,700.,1300.,1700.,2300.,3000. !

INPUT GROUP: 3 -- Output Options

DISK OUTPUT OPTION

Save met. fields in an unformatted output file ? (LSAVE) Default: T  ! LSAVE = T !
(F = Do not save, T = Save)

Type of unformatted output file:
(IFORMO) Default: 1  ! IFORMO = 1 !
1 = CALPUFF/CALGRID type file (CALMET.DAT)
2 = MESOPUFF-II type file (PACOUT.DAT)

LINE PRINTER OUTPUT OPTIONS:

Print met. fields ? (LPRINT) Default: F  ! LPRINT = T !
(F = Do not print, T = Print)

Print interval (IPRINF) in hours Default: 1  ! IPRINF = 24 !
(Meteorological fields are printed every 24 hours)

Specify which layers of U, V wind component to print (IUVOUT(NZ)) -- NOTE: NZ values must be entered
(0=Do not print, 1=Print)
(used only if LPRINT=T)
Defaults: NZ*0
! IUVOUT = 0 , 0 , 0 , 0 , 0 , 0 , 0 , 0 , 0 , 0 !
ITOUT = 0, 0, 0, 0, 0, 0, 0, 0, 0, 0 !

Specify which meteorological fields to print
(used only if LPRINT=T) Defaults: 0 (all variables)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Print ?</th>
</tr>
</thead>
<tbody>
<tr>
<td>STABILITY</td>
<td>0</td>
</tr>
<tr>
<td>USTAR</td>
<td>0</td>
</tr>
<tr>
<td>MONIN</td>
<td>0</td>
</tr>
<tr>
<td>MIXHT</td>
<td>0</td>
</tr>
<tr>
<td>WSTAR</td>
<td>0</td>
</tr>
<tr>
<td>PRECIP</td>
<td>0</td>
</tr>
<tr>
<td>SENSHEAT</td>
<td>0</td>
</tr>
<tr>
<td>CONVZI</td>
<td>0</td>
</tr>
</tbody>
</table>

Testing and debug print options for micrometeorological module

Print input meteorological data and internal variables (LDB) Default: F ! LDB = F !
(F = Do not print, T = print)
(NOTE: this option produces large amounts of output)

First time step for which debug data are printed (NN1) Default: 1 ! NN1 = 1 !

Last time step for which debug data are printed (NN2) Default: 1 ! NN2 = 2 !

Print distance to land internal variables (LDBCST) Default: F ! LDBCST = F !
(Output in .GRD file DCST.GRD, defined in input group 0)

Testing and debug print options for wind field module
(all of the following print options control output to wind field module's output files: TEST.PRT, TEST.OUT, TEST.KIN, TEST.FRD, and TEST.SLP)

Control variable for writing the test/debug wind fields to disk files (IOUTD)
(0=Do not write, 1=write) Default: 0 ! IOUTD = 0 !

Number of levels, starting at the surface, to print (NZPRN2) Default: 1 ! NZPRN2 = 1 !

Print the INTERPOLATED wind components ? (IPR0) (0=no, 1=yes) Default: 0 ! IPR0 = 0 !

Print the TERRAIN ADJUSTED surface wind components ? (IPR1) (0=no, 1=yes) Default: 0 ! IPR1 = 0 !

Print the SMOOTHED wind components and the INITIAL DIVERGENCE fields ? (IPR2) (0=no, 1=yes) Default: 0 ! IPR2 = 0 !

Print the FINAL wind speed and direction fields ? (IPR3) (0=no, 1=yes) Default: 0 ! IPR3 = 0 !

Print the FINAL DIVERGENCE fields ? (IPR4) (0=no, 1=yes) Default: 0 ! IPR4 = 0 !

Print the winds after KINEMATIC effects are added ? (IPR5) (0=no, 1=yes) Default: 0 ! IPR5 = 0 !
Print the winds after the FROUDE NUMBER
adjustment is made?
(IPR6) (0=no, 1=yes) Default: 0 ! IPR6 = 0 !

Print the winds after SLOPE FLOWS
are added?
(IPR7) (0=no, 1=yes) Default: 0 ! IPR7 = 0 !

Print the FINAL wind field components?
(IPR8) (0=no, 1=yes) Default: 0 ! IPR8 = 0 !

!END!

-------------------------------------------------------------------------------
INPUT GROUP: 4 -- Meteorological data options

NO OBSERVATION MODE (NOOBS) Default: 0 ! NOOBS = 1 !
0 = Use surface, overwater, and upper air stations
1 = Use surface and overwater stations (no upper air observations)
   Use MM4/MM5/3D.DAT for upper air data
2 = No surface, overwater, or upper air observations
   Use MM4/MM5/3D.DAT for surface, overwater, and upper air data

NUMBER OF SURFACE & PRECIP. METEOROLOGICAL STATIONS

Number of surface stations (NSSTA) No default ! NSSTA = 6 !
Number of precipitation stations
(NPSTA=-1: flag for use of MM5/3D.DAT precip data)
(NPSTA) No default ! NPSTA = 0 !

CLOUD DATA OPTIONS
Gridded cloud fields:
(ICLOUD) Default: 0 ! ICLOUD = 3 !
ICLOUD = 0 - Gridded clouds not used
ICLOUD = 1 - Gridded CLOUD.DAT generated as OUTPUT
ICLOUD = 2 - Gridded CLOUD.DAT read as INPUT
ICLOUD = 3 - Gridded cloud cover from Prognostic Rel. Humidity
   at 850mb (Teixera)
ICLOUD = 4 - Gridded cloud cover from Prognostic Rel. Humidity
   at all levels (MM5toGrads algorithm)

FILE FORMATS
Surface meteorological data file format
(IFORMS) Default: 2 ! IFORMS = 2 !
(1 = unformatted (e.g., SMERGE output))
(2 = formatted (free-formatted user input))

Precipitation data file format
(IFORMP) Default: 2 ! IFORMP = 2 !
(1 = unformatted (e.g., PMERGE output))
(2 = formatted (free-formatted user input))

Cloud data file format
(IFORMC) Default: 2 ! IFORMC = 2 !
(1 = unformatted - CALMET unformatted output)
(2 = formatted - free-formatted CALMET output or user input)

!END!

-------------------------------------------------------------------------------
INPUT GROUP: 5 -- Wind Field Options and Parameters

WIND FIELD MODEL OPTIONS
Model selection variable (IWFCOD) Default: 1 ! IWFCOD = 1 !
0 = Objective analysis only
1 = Diagnostic wind module

Compute Froude number adjustment effects? (IFRADJ)  Default: 1 ! IFRADJ = 1 !
(0 = NO, 1 = YES)

Compute kinematic effects? (IKINE)  Default: 0 ! IKINE = 1 !
(0 = NO, 1 = YES)

Use O'Brien procedure for adjustment of the vertical velocity? (IOBR)  Default: 0 ! IOBR = 0 !
(0 = NO, 1 = YES)

Compute slope flow effects? (ISLOPE)  Default: 1 ! ISLOPE = 1 !
(0 = NO, 1 = YES)

Extrapolate surface wind observations to upper layers? (IEXTRP)  Default: -4 ! IEXTRP = -1 !
(1 = no extrapolation is done, 2 = power law extrapolation used, 3 = user input multiplicative factors for layers 2 - NZ used (see FEXTRP array), 4 = similarity theory used, -1, -2, -3, -4 = same as above except layer 1 data at upper air stations are ignored

Extrapolate surface winds even if calm? (ICALM)  Default: 0 ! ICALM = 0 !
(0 = NO, 1 = YES)

Layer-dependent biases modifying the weights of surface and upper air stations (BIAS(NZ))
-1<=BIAS=1
Negative BIAS reduces the weight of upper air stations by 10%; BIAS=-1, reduces their weight by 100% Positive BIAS reduces the weight of surface stations by 20%; BIAS=1 reduces their weight by 100% Zero BIAS leaves weights unchanged (1/R**2 interpolation)
Default: NZ*0

Minimum distance from nearest upper air station to surface station for which extrapolation of surface winds at surface station will be allowed (RMIN2: Set to -1 for IEXTRP = 4 or other situations where all surface stations should be extrapolated)
Default: 4. ! RMIN2 = 4.0 !

Use gridded prognostic wind field model output fields as input to the diagnostic wind field model (IPROG)  Default: 0 ! IPROG = 14 !
(0 = NO, [IWFCOD = 0 or 1]
1 = Yes, use CSUMM prog. winds as Step 1 field, [IWFCOD = 0]
2 = Yes, use CSUMM prog. winds as initial guess field [IWFCOD = 1]
3 = Yes, use winds from MM4.DAT file as Step 1 field [IWFCOD = 0]
4 = Yes, use winds from MM4.DAT file as initial guess field [IWFCOD = 1]
5 = Yes, use winds from MM4.DAT file as observations [IWFCOD = 1]
13 = Yes, use winds from MM5/3D.DAT file as Step 1 field [IWFCOD = 0]
14 = Yes, use winds from MM5/3D.DAT file as initial guess field [IWFCOD = 1]
15 = Yes, use winds from MM5/3D.DAT file as observations [IWFCOD = 1]

Timestep (hours) of the prognostic model input data (ISTEPPG)  Default: 1 ! ISTEPPG = 1 !

Use coarse CALMET fields as initial guess fields (IGFMET) (overwrites IGF based on prognostic wind fields if any)
Default: 0 ! IGFMET = 0 !

RADIUS OF INFLUENCE PARAMETERS

Use varying radius of influence  Default: F ! LVARY = T!
(if no stations are found within RMAX1, RMAX2, or RMAX3, then the closest station will be used)

Maximum radius of influence over land in the surface layer (RMAX1)  No default  ! RMAX1 = 999.
Units: km

Maximum radius of influence over land aloft (RMAX2)  No default  ! RMAX2 = 999.
Units: km

Maximum radius of influence over water (RMAX3)  No default  ! RMAX3 = 999.
Units: km

OTHER WIND FIELD INPUT PARAMETERS

Minimum radius of influence used in the wind field interpolation (RMIN)  Default: 0.1  ! RMIN = 0.05
Units: km

Radius of influence of terrain features (TERRAD)  No default  ! TERRAD = 20.
Units: km

Relative weighting of the first guess field and observations in the SURFACE layer (R1)  No default  ! R1 = 2.
Units: km
(R1 is the distance from an observational station at which the observation and first guess field are equally weighted)

Relative weighting of the first guess field and observations in the layers ALOFT (R2)  No default  ! R2 = 2.
Units: km
(R2 is applied in the upper layers in the same manner as R1 is used in the surface layer).

Relative weighting parameter of the prognostic wind field data (RPROG)  No default  ! RPROG = 0.
Units: km
(Used only if IPROG = 1)

Maximum acceptable divergence in the divergence minimization procedure (DIVLIM)  Default: 5.E-6  ! DIVLIM = 5.0E-06

Maximum number of iterations in the divergence min. procedure (NITER)  Default: 50  ! NITER = 50

Number of passes in the smoothing procedure (NSMTH(NZ))
NOTE: NZ values must be entered
Default: 2, (mxnz-1)*4 ! NSMTH = 2, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4

Maximum number of stations used in each layer for the interpolation of data to a grid point (NINTR2(NZ))
NOTE: NZ values must be entered

Critical Froude number (CRITFN)  Default: 1.0  ! CRITFN = 1.

Empirical factor controlling the influence of kinematic effects (ALPHA)  Default: 0.1  ! ALPHA = 0.1

Multiplicative scaling factor for extrapolation of surface observations to upper layers (FEXTR2(NZ))  Default: NZ*0.0
! FEXTR2 = 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0.
(Used only if IEXTRP = 3 or -3)
BARRIER INFORMATION

Number of barriers to interpolation of the wind fields (NBAR)  Default: 0  ! NBAR = 0 !

Level (1 to NZ) up to which barriers apply (KBAR)  Default: NZ  ! KBAR = 10 !

THE FOLLOWING 4 VARIABLES ARE INCLUDED ONLY IF NBAR > 0

NOTE: NBAR values must be entered for each variable
Units: km

X coordinate of BEGINNING of each barrier (XBBAR(NBAR))  ! XBBAR = 0. !
Y coordinate of BEGINNING of each barrier (YBBAR(NBAR))  ! YBBAR = 0. !

X coordinate of ENDING of each barrier (XEBAR(NBAR))  ! XEBAR = 0. !
Y coordinate of ENDING of each barrier (YEBAR(NBAR))  ! YEBAR = 0. !

DIAGNOSTIC MODULE DATA INPUT OPTIONS

Surface temperature (IDIOPT1)  Default: 0  ! IDIOPT1 = 0 !
0 = Compute internally from hourly surface observations or prognostic fields
1 = Read preprocessed values from a data file (DIAG.DAT)

Surface met. station to use for the surface temperature (ISURFT)  Default: -1  ! ISURFT = -1 !
(Must be a value from 1 to NSSTA, or -1 to use 2-D spatially varying surface temperatures, or -2 to use a domain-average prognostic surface temperatures (only with ITPROG=2))
(Used only if IDIOPT1 = 0)

Temperature lapse rate used in the computation of terrain-induced circulations (IDIOPT2)  Default: 0  ! IDIOPT2 = 0 !
0 = Compute internally from (at least) twice-daily upper air observations or prognostic fields
1 = Read hourly preprocessed values from a data file (DIAG.DAT)

Upper air station to use for the domain-scale lapse rate (IUPWT)  Default: -1  ! IUPWT = -1 !
(Must be a value from 1 to NUSTA, or -1 to use 2-D spatially varying lapse rate, or -2 to use a domain-average prognostic lapse rate (only with ITPROG>0))
(Used only if IDIOPT2 = 0)

Depth through which the domain-scale lapse rate is computed (ZUPT)  Default: 200.  ! ZUPT = 200. !
(Used only if IDIOPT2 = 0)  Units: meters

Initial Guess Field Winds (IDIOPT3)  Default: 0  ! IDIOPT3 = 0 !
0 = Compute internally from observations or prognostic wind fields
1 = Read hourly preprocessed domain-average wind values from a data file (DIAG.DAT)

Upper air station to use for the initial guess winds (IUPWND)  Default: -1  ! IUPWND = -1 !
(Must be a value from -1 to NUSTA, with
indicating 3-D initial guess fields, and IUPWND=1 domain-scaled (i.e. constant) IGF)
(Used only if IDIOPT3 = 0 and noobs=0)

Bottom and top of layer through which the domain-scale winds are computed
(ZUPWND(1), ZUPWND(2))
(Used only if IDIOPT3 = 0, NOOBS>0 and IUPWND>0) Units: meters

Observed surface wind components for wind field module (IDIOPT4) Default: 0
0 = Read WS, WD from a surface data file (SURF.DAT)
1 = Read hourly preprocessed U, V from a data file (DIAG.DAT)

Observed upper air wind components for wind field module (IDIOPT5) Default: 0
0 = Read WS, WD from an upper air data file (UP1.DAT, UP2.DAT, etc.)
1 = Read hourly preprocessed U, V from a data file (DIAG.DAT)

LAKE BREEZE INFORMATION

Use Lake Breeze Module (LLBREZE)
Default: F

Number of lake breeze regions (NBOX)
X Grid line 1 defining the region of interest ! XG1 = 0. !
X Grid line 2 defining the region of interest ! XG2 = 0. !
Y Grid line 1 defining the region of interest ! YG1 = 0. !
Y Grid line 2 defining the region of interest ! YG2 = 0. !

X Point defining the coastline (Straight line)
(XBCST) (KM) Default: none ! XBCST = 0. !

Y Point defining the coastline (Straight line)
(YBCST) (KM) Default: none ! YBCST = 0. !

X Point defining the coastline (Straight line)
(XECST) (KM) Default: none ! XECST = 0. !

Y Point defining the coastline (Straight line)
(YECST) (KM) Default: none ! YECST = 0. !

Number of stations in the region (Surface stations + upper air stations)
Station ID's in the region (METBXID(NLB))
(Surface stations first, then upper air stations)
! METBXID = 0 !
Convective mixing ht. equation (CONSTE) Default: 0.15 ! CONSTE = 0.15 !
Stable mixing ht. equation (CONSTN) Default: 2400. ! CONSTN = 2400. !
Overwater mixing ht. equation (CONSTW) Default: 0.16 ! CONSTW = 0.16 !
Absolute value of Coriolis parameter (FCORIOL) Default: 1.0E-4 ! FCORIOL = 1.0E-04!

SPATIAL AVERAGING OF MIXING HEIGHTS
Conduct spatial averaging (IAVEZI) (0=no, 1=yes) Default: 1 ! IAVEZI = 1 !
Max. search radius in averaging process (MNMDAV) Default: 1 ! MNMDAV = 3 !
Units: Grid cells
Half-angle of upwind looking cone for averaging (HAFANG) Default: 30. ! HAFANG = 30. !
Units: deg.
Layer of winds used in upwind averaging (ILEVZI) Default: 1 ! ILEVZI = 1 !
(must be between 1 and NZ)

CONVECTIVE MIXING HEIGHT OPTIONS:
Method to compute the convective mixing height (IMIHXH) Default: 1 ! IMIHXH = 1 !
1: Maul-Carson for land and water cells
-1: Maul-Carson for land cells only - OCD mixing height overwater
2: Batchvarova and Gryning for land and water cells
-2: Batchvarova and Gryning for land cells only - OCD mixing height overwater
Threshold buoyancy flux required to sustain convective mixing height growth overland (THRESHL) Default: 0.0 ! THRESHL = 0. !
(expressed as a heat flux units: W/m3 per meter of boundary layer)
Threshold buoyancy flux required to sustain convective mixing height growth overwater (THRESHW) Default: 0.05 ! THRESHW = 0.05 !
(expressed as a heat flux units: W/m3 per meter of boundary layer)

Option for overwater lapse rates used in convective mixing height growth
(ITWPROG) Default: 0 ! ITWPROG = 2 !
0 : use SEA.DAT lapse rates and deltaT (or assume neutral conditions if missing)
1 : use prognostic lapse rates (only if IPROG>2) and SEA.DAT deltaT (or neutral if missing)
2 : use prognostic lapse rates and prognostic delta T (only if iprog>12 and 3D.DAT version# 2.0 or higher)
Land Use category ocean in 3D.DAT datasets (ILUOC3D) Default: 16 ! ILUOC3D = 16 !
Note: if 3D.DAT from MM5 version 3.0, iluoc3d = 16
if MM4.DAT, typically iluoc3d = 7

OTHER MIXING HEIGHT VARIABLES
Minimum potential temperature lapse rate in the stable layer above the current convective mixing ht. Default: 0.001 ! DPTMIN = 0.001 !
(DPTMIN) Units: deg. K/m
Depth of layer above current conv.
mixing height through which lapse rate is computed (DZZI)

Minimum overland mixing height (ZIMIN)

Maximum overland mixing height (ZIMAX)

Minimum overwater mixing height (ZIMINW) -- (Not used if observed overwater mixing hts. are used)

Maximum overwater mixing height (ZIMAXW) -- (Not used if observed overwater mixing hts. are used)

OVERWATER SURFACE FLUXES METHOD and PARAMETERS

ICOARE

0: original deltaT method (OCD)

10: COARE with no wave parameterization (jwave=0, Charnock)

11: COARE with wave option jwave=1 (Oost et al.) and default wave properties

-11: COARE with wave option jwave=1 (Oost et al.) and observed wave properties (must be in SEA.DAT files)

12: COARE with wave option 2 (Taylor and Yelland) and default wave properties

-12: COARE with wave option 2 (Taylor and Yelland) and observed wave properties (must be in SEA.DAT files)

Note: When ICOARE=0, similarity wind profile stability PSI functions based on Van Ulden and Holtslag (1985) are substituted for later formulations used with the COARE module, and temperatures used for surface layer parameters are obtained from either the nearest surface station temperature or prognostic model 2D temperatures (if ITPROG=2).

Coastal/Shallow water length scale (DSHELF)

(for modified z0 in shallow water)

( COARE fluxes only)

Default: 0. ! DSHELF = 1. !
units: km

COARE warm layer computation (IWARM)

1: on - 0: off (must be off if SST measured with IR radiometer)

Default: 0

COARE cool skin layer computation (ICOOL)

1: on - 0: off (must be off if SST measured with IR radiometer)

Default: 0

RELATIVE HUMIDITY PARAMETERS

3D relative humidity from observations or from prognostic data? (IRHPROG)

Default: 0 ! IRHPROG = 0 !

0 = Use RH from SURF.DAT file
only if NOOBS = 0,1

1 = Use prognostic RH
only if NOOBS = 0,1,2

TEMPERATURE PARAMETERS

3D temperature from observations or from prognostic data? (ITPROG)

Default: 0 ! ITPROG = 1 !

0 = Use Surface and upper air stations
only if NOOBS = 0

1 = Use Surface stations (no upper air observations)
Use MM5/3D.DAT for upper air data
only if NOOBS = 0,1

2 = No surface or upper air observations
Use MM5/3D.DAT for surface and upper air data
only if NOOBS = 0,1,2
Interpolation type
(1 = 1/R ; 2 = 1/R**2)       Default: 1       ! IRAD = 1 !

Radius of influence for temperature
interpolation (TRADKM)         Default: 500.   ! TRADKM = 500. !
Units: km

Maximum Number of stations to include
in temperature interpolation (NUMTS)  Default: 5   ! NUMTS = 5 !

Conduct spatial averaging of tempera-
tures (IAVET)  (0=no, 1=yes)       Default: 1       ! IAVET = 1 !
(will use mixing ht MNMDAV,HAFANG
so make sure they are correct)

Default temperature gradient
below the mixing height over
water (TGDEFB)                  Default: -0.0098   ! TGDEFB = -0.0098 !
Units: K/m

Default temperature gradient
above the mixing height over
water (TGDEFA)                  Default: -0.0045   ! TGDEFA = -0.0045 !
Units: K/m

Beginning (JWAT1) and ending (JWAT2)
land use categories for temperature
interpolation over water -- Make
bigger than largest land use to disable

PRECIP INTERPOLATION PARAMETERS

Method of interpolation (NFLAGP)      Default: 2       ! NFLAGP = 2 !
(1=1/R,2=1/R**2,3=EXP/R**2)

Radius of Influence (SIGMAP)         Default: 100.0  ! SIGMAP = 100. !
Units: km
(0.0 => use half dist. btwn
nearest stns w & w/out
precip when NFLAGP = 3)

Minimum Precip. Rate Cutoff (CUTP)    Default: 0.01   ! CUTP = 0.01 !
(values < CUTP = 0.0 mm/hr)
Units: mm/hr

!END!

---------------------------------------------

INPUT GROUP: 7 -- Surface meteorological station parameters

---

SURFACE STATION VARIABLES
(One record per station -- 6 records in all)

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>ID</td>
</tr>
<tr>
<td>X coord. (km)</td>
<td>Y coord. (km)</td>
</tr>
</tbody>
</table>

| ! SS1 = 'WWB' | 71437 | 597.330 | 4794.830 | -5 | 10 |
| ! SS2 = 'YKZ' | 71639 | 630.990 | 4857.610 | -5 | 10 |
| ! SS3 = 'YHM' | 71263 | 586.970 | 4780.250 | -5 | 10 |
| ! SS4 = 'YTZ' | 71265 | 629.070 | 4832.020 | -5 | 10 |
| ! SS5 = 'YYZ' | 71624 | 610.420 | 4837.240 | -5 | 10 |
| ! SS6 = 'WWZ' | 71432 | 644.490 | 4790.110 | -5 | 10 |

1 Four character string for station name
(MUST START IN COLUMN 9)

2 Six digit integer for station ID

!END!
INPUT GROUP: 8 -- Upper air meteorological station parameters

UPPER AIR STATION VARIABLES
(One record per station -- 0 records in all)

1     2
Name    ID      X coord.   Y coord.  Time zone
(km)       (km)
-----------------------------------------------

1
Four character string for station name
(MUST START IN COLUMN 9)

2
Five digit integer for station ID

!END!

INPUT GROUP: 9 -- Precipitation station parameters

PRECIPITATION STATION VARIABLES
(One record per station -- 0 records in all)
(NOT INCLUDED IF NPSTA = 0)

1          2
Name   Station    X coord.  Y coord.
Code       (km)      (km)
------------------------------------

1
Four character string for station name
(MUST START IN COLUMN 9)

2
Six digit station code composed of state
code (first 2 digits) and station ID (last
4 digits)

!END!
Appendix F Comparison of measured and modelled wind fields

<table>
<thead>
<tr>
<th></th>
<th>CALMET OUTPUT (Hamilton Airport)</th>
<th>OBSERVATIONS (Hamilton Airport)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JAN</td>
<td><img src="image1" alt="Wind Map JAN" /></td>
<td><img src="image2" alt="Wind Map JAN" /></td>
</tr>
<tr>
<td></td>
<td><img src="image3" alt="Wind Map JAN" /></td>
<td><img src="image4" alt="Wind Map JAN" /></td>
</tr>
<tr>
<td>FEB</td>
<td><img src="image5" alt="Wind Map FEB" /></td>
<td><img src="image6" alt="Wind Map FEB" /></td>
</tr>
<tr>
<td></td>
<td><img src="image7" alt="Wind Map FEB" /></td>
<td><img src="image8" alt="Wind Map FEB" /></td>
</tr>
<tr>
<td>MAR</td>
<td><img src="image9" alt="Wind Map MAR" /></td>
<td><img src="image10" alt="Wind Map MAR" /></td>
</tr>
<tr>
<td></td>
<td><img src="image11" alt="Wind Map MAR" /></td>
<td><img src="image12" alt="Wind Map MAR" /></td>
</tr>
</tbody>
</table>
### CALMET OUTPUT (Hamilton Airport)

<table>
<thead>
<tr>
<th>Month</th>
<th>Wind Rose</th>
<th>Wind Direction</th>
<th>Wind Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>OCT</td>
<td><img src="image1" alt="Wind Rose October" /></td>
<td>W</td>
<td>10 m/s</td>
</tr>
<tr>
<td>NOV</td>
<td><img src="image2" alt="Wind Rose November" /></td>
<td>NW</td>
<td>8 m/s</td>
</tr>
<tr>
<td>DEC</td>
<td><img src="image3" alt="Wind Rose December" /></td>
<td>NE</td>
<td>6 m/s</td>
</tr>
</tbody>
</table>

### OBSERVATIONS (Hamilton Airport)

<table>
<thead>
<tr>
<th>Month</th>
<th>Wind Rose</th>
<th>Wind Direction</th>
<th>Wind Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>OCT</td>
<td><img src="image4" alt="Wind Rose October" /></td>
<td>NE</td>
<td>10 m/s</td>
</tr>
<tr>
<td>NOV</td>
<td><img src="image5" alt="Wind Rose November" /></td>
<td>E</td>
<td>8 m/s</td>
</tr>
<tr>
<td>DEC</td>
<td><img src="image6" alt="Wind Rose December" /></td>
<td>SE</td>
<td>6 m/s</td>
</tr>
</tbody>
</table>

*Note: Wind roses show the distribution of winds for each month.*
<table>
<thead>
<tr>
<th></th>
<th>CALMET OUTPUT (Pearson Airport)</th>
<th>OBSERVATIONS (Pearson Airport)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JAN</td>
<td><img src="image" alt="Diagram for January" /></td>
<td><img src="image" alt="Diagram for January" /></td>
</tr>
<tr>
<td>FEB</td>
<td><img src="image" alt="Diagram for February" /></td>
<td><img src="image" alt="Diagram for February" /></td>
</tr>
<tr>
<td>MAR</td>
<td><img src="image" alt="Diagram for March" /></td>
<td><img src="image" alt="Diagram for March" /></td>
</tr>
<tr>
<td></td>
<td>CALMET OUTPUT (Pearson Airport)</td>
<td>OBSERVATIONS (Pearson Airport)</td>
</tr>
<tr>
<td>-------</td>
<td>---------------------------------</td>
<td>--------------------------------</td>
</tr>
<tr>
<td>APR</td>
<td><img src="image1" alt="April Chart" /></td>
<td><img src="image2" alt="April Chart" /></td>
</tr>
<tr>
<td>MAY</td>
<td><img src="image3" alt="May Chart" /></td>
<td><img src="image4" alt="May Chart" /></td>
</tr>
<tr>
<td>JUN</td>
<td><img src="image5" alt="June Chart" /></td>
<td><img src="image6" alt="June Chart" /></td>
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</tbody>
</table>
CALMET OUTPUT (Pearson Airport) | OBSERVATIONS (Pearson Airport)

**JUL**

**AUG**

**SEP**
<table>
<thead>
<tr>
<th></th>
<th>CALMET OUTPUT (Pearson Airport)</th>
<th>OBSERVATIONS (Pearson Airport)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OCT</td>
<td>![Calmet Diagram for OCT]</td>
<td>![Observations Diagram for OCT]</td>
</tr>
<tr>
<td>NOV</td>
<td>![Calmet Diagram for NOV]</td>
<td>![Observations Diagram for NOV]</td>
</tr>
<tr>
<td>DEC</td>
<td>![Calmet Diagram for DEC]</td>
<td>![Observations Diagram for DEC]</td>
</tr>
<tr>
<td></td>
<td>CALMET OUTPUT (Island Airport)</td>
<td>OBSERVATIONS (Island Airport)</td>
</tr>
<tr>
<td>-------</td>
<td>-------------------------------</td>
<td>------------------------------</td>
</tr>
<tr>
<td>JUL</td>
<td><img src="image" alt="JUL CALMET Output" /></td>
<td><img src="image" alt="JUL Observations" /></td>
</tr>
<tr>
<td>AUG</td>
<td><img src="image" alt="AUG CALMET Output" /></td>
<td><img src="image" alt="AUG Observations" /></td>
</tr>
<tr>
<td>SEP</td>
<td><img src="image" alt="SEP CALMET Output" /></td>
<td><img src="image" alt="SEP Observations" /></td>
</tr>
<tr>
<td></td>
<td>CALMET OUTPUT (Island Airport)</td>
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</tr>
<tr>
<td>------</td>
<td>--------------------------------</td>
<td>------------------------------</td>
</tr>
<tr>
<td>OCT</td>
<td><img src="image1.png" alt="Diagram" /></td>
<td><img src="image2.png" alt="Diagram" /></td>
</tr>
<tr>
<td>NOV</td>
<td><img src="image3.png" alt="Diagram" /></td>
<td><img src="image4.png" alt="Diagram" /></td>
</tr>
<tr>
<td>DEC</td>
<td><img src="image5.png" alt="Diagram" /></td>
<td><img src="image6.png" alt="Diagram" /></td>
</tr>
</tbody>
</table>
Appendix G

Effect of City of Toronto emissions on surrounding regions (June 21, 2001)
Appendix H City of Toronto concentration contours (June 21, 2001)
Appendix I
Hourly NO₂ concentrations at zone centroids (June 21 vs July 17, 2001)
Appendix J
Daily NO$_2$ concentrations at zone centroids (12 selected days)
Appendix K
Hour corresponding to the maximum daily concentration (12 selected days)