An Integrated Modelling Approach to Estimate Urban Traffic Emissions

by

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Abstract

Vehicular emissions contribute significantly to poor air quality in urban areas. An integrated modelling approach is adopted to estimate microscale urban traffic emissions. The modelling framework consists of a traffic microsimulation model, a microscopic emissions model, and two dispersion models. This framework is applied to a traffic network in downtown Toronto to evaluate summer time morning peak traffic emissions during weekdays for carbon monoxide and nitrogen oxide. The model predicted results are validated against sensor observations with a reasonably good fit. Availability of local estimates of ambient concentration is useful for accurate comparisons of total predicted concentrations with observed concentrations. Both predicted and observed concentrations are significantly smaller than the National Ambient Air Quality Objectives established by Environment Canada. Sensitivity analysis is performed on a set of input parameters and horizontal wind speed is found to be the most influential factor in pollutant dispersion.

Acknowledgments

I find it ironical how acknowledgements are featured at the very beginning of a thesis even though they are the last thing written out once all the ‘real’ writing is complete. Nonetheless, I feel this is probably the most well read section of any thesis!

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Chapter 1

There's so much pollution in the air now that if it weren't for our lungs there'd be no place to put it all.

- Robert Orben, Comedian

1 Introduction

1.1 Background and Motivation

Transportation is a fundamental consequence of economic activity, with urban congestion and air pollution being the unwanted but inevitable by-products. In Canada, over 19.2 million registered vehicles are driven annually for a total of 332 billion kilometres (Statistics Canada, 2009). Traffic generated emissions have been a key area of research for the past several years. Better understanding of how emissions are generated has promoted newer vehicle technologies that continue to seek better vehicle efficiencies and lower emission rates.

Motorized vehicle operation impacts environmental air quality in the form of increased Greenhouse Gas (GHG) emissions and toxic pollutant emissions. The most common air pollutants have been specified by the United States Environmental Protection Agency (US EPA) as 'criteria pollutants'. These include: ozone (O₃), particulate matter (PM), carbon monoxide (CO), nitrogen oxide (NO_x), sulphur oxide (SO_x), and lead (Pb). For a stoichiometric mix, with a perfect air-fuel ratio, complete combustion inside vehicle engine should only result in production of carbon dioxide (CO₂) and water vapour (H₂O). Practically, the optimum air-fuel ratio is never achieved, resulting in incomplete combustion that causes release of pollutants. The general equation for this process is as follows:

Pollutants directly released from the emission source are called primary pollutants. Some primary pollutants are chemically reactive and upon suspension in the air, undergo chemical reactions to form other toxic species called secondary pollutants. Ozone and nitrogen dioxide (NO₂) are two important secondary pollutants associated with traffic emissions; their precursor primary pollutants are volatile organic compounds (VOC's) and nitrogen oxide (NO). Particulate

matter (PM) is another important criteria pollutant that is classified into primary, secondary, and fugitive types; fugitive PM consists of emissions due to road abrasion and wear of tyre or brake lining (Cadle, 1997).

The adverse health impact of criteria pollutants is well documented in literature. CO reduces the oxygen carrying capacity of blood and could be fatal in extreme cases of exposure; NO_x causes severe respiratory problems such as bronchitis; SO_x aggravates lung and heart diseases while PM affects lung function and prolonged exposure can cause premature death. Environmental Protection Agency (2012) provides detailed information on the harmful effects of such pollutants.

Due to improved vehicle technology, use of clean fuel, strict vehicle emission standards, and implementation of environment friendly government policies such as the Clean Air Act Amendments 1990 USA, Clear Air Act 2006 in Canada, and the Canadian Environmental Protection Act 1999, total vehicular emission has generally decreased in North America in the last two decades. Figure 1-1 and 1-2 show the decreasing trend of total CO and NO_x emissions for significantly contributing vehicle categories in Canada (Environment Canada, 2012).

Figure 1-1 Canada NO_x Emission Contribution (in tonnes) 1985-2010 Mobile Sources

Figure 1-2 Canada CO Emission Contribution (in tonnes) 1985-2010 Mobile Sources

In spite of the decrease in total CO and NO_x emissions in Canada due to these mobile sources, the transportation sector continues to be a major source of criteria pollutants. In 2010, all major mobile transportation sources accounted for 41% of total CO emissions and 19% of total NO_x emissions in Canada (Environment Canada, 2012).

Geogenic and biogenic sources are large contributors to net CO emissions (for example, forest fires) and net NO_x emissions (for example, vegetation). However, as a society, we are more concerned about traffic related emissions because of the close proximity of such emissions to a large number of people in urban areas. The recurring peaks in traffic volume correspond to higher emission concentrations in the urban areas, which in turn correspond with large pedestrian volumes on the street. Research studies have determined that high density traffic sites are a key source of higher levels of vehicular emissions (Campbell, et al., 1995) and areas close to busy roads typically have higher emission concentrations (Hoek, et al., 2002). In densely populated downtown areas, the significance of vehicular emissions is accentuated due to presence of large volume of pedestrian and biking traffic on the street level that is directly exposed. Hence, it becomes imperative to investigate street level air quality to quantify population exposure.

Understanding the distribution of traffic pollutants in the urban environment, and evaluating regions of higher pollutant concentration is necessary to characterize the nature of risk to people walking or biking on the street. This research is an attempt to quantify such traffic generated emission concentrations for CO and NO_x on a local road network using an integrated micro-modelling framework.

1.2 Purpose and Scope

The objective of this research is to assess the accuracy of an integrated modelling framework that incorporates a traffic microsimulation model, a microscopic emission generation model, and a pollutant dispersion model, to predict road side pollutant concentrations. The fundamental concept is to microsimulate the movement of vehicles on a given network, estimate emission factors on roadway links using a microscopic emission model, and finally disperse the pollutants generated on roadway links, in the atmosphere within the network, to obtain predicted concentration values.

The framework is applied to a road network in downtown Toronto and predicted concentrations are compared against sensor measured values for CO and NO_x for the morning peak period (7:00 – 9:00 AM) for five selected weekdays, each in June and July 2011. The goal of this work is to develop concentration plots at a micro-scale combining three historically different modelling methods under one common platform; these results could be used to evaluate exposure of pollutants to population at a fine resolution. Such a tool could be potentially used to inform policy decisions regarding street design, neighbourhood scale planning, vehicle technology, and vehicle type distribution. The scope of this research includes the following:

- 1) Application of the proposed framework to obtain predicted concentrations for CO and NO_x for some weekdays in June and July 2011
- 2) Performance evaluation / comparison of two different pollutant dispersion methodologies using sensor observed pollutant concentration values
- 3) Comparison of predicted and observed pollutant concentrations with the National Ambient Air Quality Objectives (NAAQO), Environment Canada

- 4) Sensitivity analyses of significant parameters within the framework that affect pollutant dispersion

1.3 Significance and Potential

Traffic generated pollution has been investigated at the local and regional scale in considerable detail using several different methodologies. Ishaque & Noland (2008) used a traffic microsimulation model and a microscopic emissions model, to estimate emissions for a road network in London. Further, they used a line source Gaussian dispersion model (CAL3QHC) to estimate pollutant concentrations. Hatzopoulou & Miller (2010) estimated average hourly concentration contours on the regional scale in the Greater Toronto Area by simulating pollutant dispersion using activity-based travel demand modelling, incorporating the use of EMME, an average speed based travel demand model. Similarly, Nesamani, et al. (2007) developed an intermediate model for better estimation of average link speeds and then used the MOBILE series model to estimate emissions.

Amirjamshidi, et al. (2012) investigated emissions for the downtown Toronto Waterfront network using a combination of traffic microsimulation model and emissions model; a simplified Gaussian plume dispersion model was applied to estimate roadside emissions that could not simulate the complexity of flow in urban areas. Karim & Matsui (1998) and Karim, et al. (1998) developed and evaluated a mathematical model that predicted pollutant concentrations for CO and NO_x in roadway micro-environments. The line source emission inputs to the dispersion model were based on vehicle speeds and total vehicular flow for eight categories of vehicles.

Ahn & Rakha (2008) showed that macroscopic emission models that are based on average speeds on road links ignore microscopic movement of vehicles and could potentially give incorrect emission rates. Inputting incorrect emission rates into the dispersion model would further increase uncertainty in the final results obtained. Therefore, it is important to microsimulate traffic in a network in order to replicate the movement of vehicles better, and in turn, get better results from the dispersion models.

The integrated approach to combine traffic emissions and dispersion under a single framework has been explored in the past. Hatzopoulou (2008) performed a review of integrated approaches to urban air quality modelling at the local and regional scale. Some examples of integrated local

air quality frameworks include the OSCAR system (Sokhi, et al., 2008), the integrated TREM/VADIS/VISUM system (Borrego, et al., 2003), and the DAPPLE Project (Arnold, et al., 2004). The OSCAR system combines use of traffic flow data, emissions inventory, and dispersion modelling (CAR-FMI, a line source Gaussian model) to assess urban air quality. OSCAR uses a link-based approach where emission factors are estimated using the average link speed. The TREM/VADIS/VISUM system, similar to OSCAR, estimates emissions based on average speed of the vehicles, although it uses a Lagrangian particle model (VADIS) for pollutant dispersion. DAPPLE attempts to combine neighbourhood scale pedestrian and traffic flow to assess population exposure; five minute, hourly, and daily traffic volumes are linked with vehicle type distribution attributes and emission inventories, to perform mesoscopic or microscopic traffic modelling.

The significance of this research lies in, firstly, integrating three different modelling methods, and secondly, incorporating use of traffic microsimulation and microscopic emissions model that are not based on average speed based emission inventories. Subsequently, the emission rates are input into a microscopic Lagrangian particle model and a Gaussian plume model for dispersion.

This research has potential in terms of evaluating population exposure by combining pedestrian microsimulation modelling with the proposed framework. Capturing spatial and temporal variation of street level population exposure to local traffic emissions should lead to interesting policy analysis scenarios. Re-designing urban network configurations for bikeways and pedestrian walkways based on emission exposure profiles, integrating land-use planning to develop pedestrian oriented ‘walking zones’, and evaluation of micro-scale air quality within mobility hubs as proposed by Metrolinx (2008), are all examples of prospective projects that could be analysed using the proposed framework.

1.4 Structure of Thesis

The thesis is organized into nine chapters. The first chapter gives a brief background and introduces the underlying foundation of the proposed work. Chapter 2 presents an overview of the different components of the methodology, describes the study area, and explains the concept of ambient concentrations. Chapters 3, 4 and 5 discuss each component of the modelling framework, namely, the traffic microsimulation model, microscopic emissions model, and the dispersion models. This includes literature review, model characteristics, and methodology.

Chapter 6 describes the final results obtained and performance evaluation of the models. Chapter 7 includes the sensitivity analyses on modelled concentrations. Chapter 8 contains notes on data error, comparison between the two dispersion models used, and comparison of predicted and observed concentrations with the NAAQO standards. Chapter 9 summarizes the research effort and concludes with key remarks on future work.

Chapter 2

2 Overview of Methodology

The proposed research framework consists of three components. They are as follows:

- 1) Traffic microsimulation model, Quadstone PARAMICS (Quadstone Paramics, 2008)
- 2) Microscopic emissions model, Comprehensive Modal Emissions Model (CMEM) (Barth, et al., 1999) (Barth, et al., 2001)
- 3) Dispersion model:
  - a. AERMOD, Environmental Protection Agency (EPA) regulatory model for near field dispersion (Cimorelli, et al., 2004)
  - b. Quick Urban and Industrial Complex (QUIC), Atmospheric Dispersion Modelling System (Los Alamos National Laboratory, 2010)

2.1 Air Quality Modelling Framework

Figure 2-1 shows the overview of the air quality modelling framework adopted.

Figure 2-1 Air Quality Modelling Framework Overview

The traffic microsimulation model simulates the movement of vehicles by capturing the spatial and temporal variation of vehicle driving characteristics (speed profile) for each vehicle travelling on the road network. Traffic microsimulation is based on road network input, origin-destination matrix, and driver specific attributes related to driving behaviour. Using a distribution of vehicle types travelling on the network, CMEM estimates emission factors on different roadway links, using disaggregate vehicle operation characteristics obtained from the traffic microsimulation (PARAMICS). The emission rates are estimated analytically by breaking the emission generation process occurring in the vehicle engine into several components. Finally, AERMOD and QUIC simulate the dispersion of emissions in the atmosphere, assuming roadway links to be an emission source. Predicted concentrations are subsequently compared with sensor observed concentrations to evaluate the performance of this framework. Figure 2-2 is an extension of the ‘Basic Air Quality Modelling Framework’ presented in Figure 2-1. It shows primary inputs into each component of the framework. Detailed description of all components is presented in the following chapters.

Figure 2-2 Detailed Air Quality Modelling Framework

2.2 Study Area Specification

The study area selected for application of this framework is the St. George Street and College Street intersection network in downtown Toronto, Canada. It is located on the southern edge of the University of Toronto, St. George Campus. College Street is a four lane road (excluding bicycle lanes) in downtown Toronto, with an average hourly traffic volume of approximately 1,400 vehicles per hour, Southern Ontario Centre for Atmospheric Aerosol Research (SOCAAR, 2011). The other prominent road on the network is the St. George Street which has two lanes; this street changes to Beverley Street south of College. All other roads on the network have low traffic volumes.

The network is approximately 800 m by 600 m with the main intersection located at the centre. The modelled section of College Street lies between two major roads in downtown Toronto – Spadina Avenue on the West and University Avenue on the East. The northern extents of the network lie slightly north of the St. George and Russell Street intersection, while the southern extents lie slightly south of the Beverley and Cecil Street intersection. There is one major intersection within the network - St. George at College Street. Other minor intersections include: College at Huron, College at Ross, College at Henry, College at King's College, Beverley at Cecil, St. George at Galbraith, and St. George at Russell. A map of the study area is shown in Figure 2-3. It also shows the location of the traffic counting sensor (south-west side of intersection) and the pollutant concentration monitoring sensor (north-east side of intersection). This network is selected for the following reasons:

- 1) Presence of heterogeneous building environment with varying building heights
- 2) Heterogeneous vehicle fleet distribution presence on College Street
- 3) Availability of traffic and pollutant concentration data on College Street (SOCAAR, 2011)
- 4) Availability of PARAMICS traffic network for the study area
- 5) Easy access from the University of Toronto Engineering Building for inspection of local network characteristics

Roorda, et al. (2011) used a Gaussian plume equation to show that the lateral concentration of traffic pollutants decreases rapidly as distance increases. The contribution of roadway line source

to pollutant concentration was found to be negligible beyond a lateral distance of ~100 metres from the source. This is an important consideration in setting the size of the study network. The emissions from University Avenue and Spadina Avenue do not significantly impact emission concentrations at the observed concentration sensor location.

Figure 2-3 St. George Street and College Street Intersection Area (Map and Data Library, University of Toronto, 2011) (Lakes Environmental, 2012)

The morning peak period between 7:00 – 9:00 AM is analysed for the following selected weekdays in 2011:

- 1) June 3, 13, 21, 28, 30 – CO analysis
- 2) July 7, 12, 13, 18, 27 – NO_x analysis

CO and NO_x are only analysed for June and July respectively, due to limited observed data availability from the concentration measuring sensor.

2.3 Concentration Terms

Four concentration terms have been extensively used in this research. They are defined as follows:

- 1) Observed or Measured Concentration: The pollutant concentration obtained from the monitoring sensor.
- 2) Modelled Concentration: The pollutant concentration output from the modelling framework.
- 3) Ambient Concentration: The background concentration that is not modelled but estimated using observed values.
- 4) Predicted Concentration: The sum of modelled and ambient or background concentrations.

Ambient concentrations are present due to the persistence of pollutants in the atmosphere. The modelled concentrations are only representative of the traffic emissions occurring within the morning peak period. However, the pollutant monitoring sensor can only capture total concentration in the atmosphere; it cannot distinguish between actively occurring traffic emissions (within the modelling period), and background concentrations that are present in the atmosphere (due to emissions that occurred before the modelling period). Therefore, ambient concentrations need to be estimated, so that accurate comparisons can be made between the ‘predicted’ and sensor observed concentrations. Separating ambient emission concentrations from active traffic emission concentrations, occurring within the modelling period only, is a challenging task. In this research, a night time observed concentration (measured between 3:00 AM – 5:00 AM) is utilized to augment the modelled concentrations, and estimate predicted concentrations (for both CO and NO_x). This night time concentration corresponds with the minimum concentration observed during the entire day, and also occurs when hourly traffic volume on College Street is smallest for any given day. Refer to Chapter 6 for detailed graphs.

The Ontario Ministry of the Environment (MOE) has four sensors located at the east, west, north and south corners of the City of Toronto that measure pollutant concentration (Ontario Ministry of the Environment, 2012). The location of MOE sensors are:

- 1) TD MOE: Toronto Downtown – Bay / Wellesley – 10 m height intake
- 2) TE MOE: Toronto East - Kennedy / Lawrence Ave. East - 4 m height intake
- 3) TN MOE: Toronto North - Hendon (Finch) / Yonge – 5 m height intake
- 4) TW MOE Toronto West – 125 Resources Road (next to Highway 401) – 8 m height intake

Observed concentrations available from the MOE and SOCAAR sensors are compared to test reliability of ambient concentrations estimated using the latter. Data from the MOE west sensor are not used due to its close proximity to Highway 401 where the traffic volume and patterns are expected to be markedly different from the study area. Observed concentrations for CO from the MOE sensors are only available for the downtown (south) sensor in 2010; appropriate comparisons have been made by using SOCAAR data from 2010 in that case. The observed concentration trends for all pollutants are shown in Figure 2-4, 2-5 and 2-6. The monthly average night time concentration pattern for both pollutants is very similar; this confirms the reliability of using SOCAAR sensor night time observed concentrations for ambient concentration estimation.

Figure 2-4 Hourly Average NO Concentration, July 2011, MOE / SOCAAR Sensor

Figure 2-5 Hourly Average NO₂ Concentration, July 2011, MOE / SOCAAR Sensor

Figure 2-6 Hourly Average CO Concentration, June-July 2010, MOE / SOCAAR Sensor

Chapter 3

3 Traffic Microsimulation Modelling: Method

3.1 Introduction to Traffic Microsimulation

Traffic microsimulation is a key component of advanced transportation modelling systems, and finds widespread application in planning and decision making. The microsimulation model used in this analysis is developed using the Quadstone PARAMICS toolkit (Quadstone Paramics, 2008).

3.2 Traffic Modelling Review

A traffic model can be defined as a set of mathematical algorithms based on traffic flow theory that attempts to replicate the behaviour of vehicles on a road network. It can provide valuable information (practically impossible to gather in real life), that can be used by traffic engineers and planners to solve traffic related issues.

The most common classification of traffic models is based on their level of detail, which includes macroscopic, mesoscopic, and microscopic models. Macroscopic models explain traffic flow at a high aggregation level, such that the individual vehicles cannot be distinguished. These models use parameters such as net flow / volume of traffic, density across a section of road, and average speed on road links, to explain the movement of vehicles through the network. Microscopic models, on the other hand, provide considerable disaggregation incorporating driver behaviour and route choice. These models simulate vehicle propagation by incorporating individual interaction between vehicles, and hence are much better at mimicking realistic movement of vehicles on a road link. Mesoscopic models fall between the two categories mentioned above. These models are essentially either microscopic models with some attributes of macroscopic models, or vice-versa.

The first macroscopic model was developed by Lighthill & Whitham (1955) while the first microscopic model, called the car following model, was developed by Pipes (1953). Subsequently, several macroscopic and microscopic traffic models have been developed, building in complexity around the original idea. Other commonly used classifications of traffic

models include process representation (deterministic or stochastic), application (intersection, links, stretches, networks), and operationalisation (analytical or simulation). Such classifications and methodologies adopted by different vehicular traffic flow models have been reviewed by Hoogendoorn & Bovy (2001) in detail.

3.3 Model Selection

A traffic microsimulation model is selected over average speed models (for example, EMME) due to the inherent lack of detail in average speed models to simulate microscopic travel behaviour. Ahn & Rakha (2008) showed that instantaneous speed is an important factor that cannot be ignored while estimating traffic emissions. An average speed model would not be able to provide a sufficient resolution in temporal and spatial variation of driving cycle characteristics, and therefore, is not adopted for this micro-modelling framework.

Several commercial and research oriented traffic microsimulation models are available for application. Papacostas & Prevedouros (2001) classified traffic microsimulation software packages on the basis of their application into three categories. The first category consists of ‘urban street network’ models such as SimTraffic and NETSIM; second, ‘freeways and freeway corridors’ that include models such as INTRAS, FRESIM, and CARSIM; and lastly, fully integrated ‘mixed network’ models such as AIMSUN, CORSIM, INTEGRATION, PARAMICS, SCOT, WATSim, and VISSIM. The third category consists of the most composite traffic microsimulation models that are capable of simulating traffic in complex networks. Extensive work has been done at the University of Toronto, Department of Civil Engineering’s Transportation Research Group using Quadstone PARAMICS on several research studies. A PARAMICS network of the study area was available from Hoy, et al. (2012). Therefore, PARAMICS is selected as the model of choice for microsimulating traffic.

PARAMICS incorporates a car following model which is based on parameters representing the driver’s behaviour, for example, driver aggressiveness, familiarity with the network, mean driver’s reaction time, and headway between the vehicles. For route choice, it uses a generalized cost equation to estimate the shortest path for the input origin-destination (O-D) matrix, and applies an all-or-nothing traffic assignment (for simpler networks) or a dynamic traffic assignment (when multiple path options between one O-D pair are available), to estimate net

traffic flow on different links in the road network. Other inputs into the model include transit routes, lane configuration, and traffic signal timings.

3.4 Network Development and Inputs

The St. George Street and College Street intersection network in PARAMICS was developed by Hoy, et al. (2012) for a study that investigated dispersing microsimulated emissions using a Gaussian model for the morning peak period of a single day. The roadway topology of the network is based on satellite imagery and geometric interpolation. The traffic network is divided into 15 zones that serve as the origin or destination points for all vehicles in the traffic microsimulation.

Figure 3-1 St. George Street and College Street Intersection Network in PARAMICS

All characteristics of the roadway links such as lane widths and speed limits are already incorporated within the network. The network includes a traffic control system which consists of three traffic lights that have been coded with observed traffic signal timings. Operating characteristics of the streetcar service on College Street are also coded in to the network; these characteristics include transit route specification, fixed time schedule (based on morning peak period), and streetcar stop locations. Figure 3-1 shows the study network in PARAMICS used in this research.

The remaining inputs (and the corresponding methods used to develop those inputs) required by PARAMICS in order to perform a model run are as follows:

- 1) Input O-D matrix for traffic flow
  - a. Traffic data collection
  - b. Turning movement percentage and regression modelling
  - c. Monte Carlo simulation
- 2) Vehicle Type Distribution
  - a. Best estimate from literature
  - b. City of Toronto cordon count data
- 3) Other Core Parameters
  - a. Best estimate from literature

The methods adopted to estimate these inputs are discussed in the following sub-sections.

3.4.1 Traffic Data Collection

In order to perform a traffic microsimulation model run, a time varying O-D matrix consisting of different vehicle types is required. To generate O-D matrices, traffic data are obtained from two sources:

- a) Manual traffic count performed on one day at 10 locations throughout the network
- b) Automatic sensor traffic count for the entire study period (modelled weekdays in June-July 2011) at College Street, west of the major intersection (one location only)

The manual traffic count was conducted on June 8, 2011 (Wednesday) from 6:30 - 9:00 AM. Traffic data were manually recorded by a team of 15 traffic counters at 5 minute intervals at 10 different locations within the network using nine different vehicle categories. The details of this survey can be found in Hoy, et al. (2012). The data obtained from this survey contain traffic flow on the network at 5 minute intervals. These data are processed to estimate average turning percentages of vehicles at all intersections within the network. These turning percentages are aggregated to 15 minute intervals for use in this project.

Carrying out detailed traffic counts for all weekdays modelled in the study is practically infeasible; therefore, traffic sensor data obtained from SOCAAR (2011) are used to generate

estimates for vehicular flow on College Street at a fine resolution. The smart eye Traffic Data Sensor (TDS) is installed on a building close to the intersection at approximately 15 metres height, and captures traffic on all four lanes of College Street, west of the major intersection. The sensor uses video image processing techniques and classifies vehicles into two categories - passenger cars and trucks, providing counts at 5 minute intervals (Smart Systems, 2008). Observed traffic data are aggregated at 15 minute intervals and organised for the modelled weekdays in June and July 2011 between 7:00 - 9:00 AM.

Analysis of traffic data obtained from the TDS indicates that traffic on College Street distinctly differs between weekdays and weekends, as shown in Figure 3-2. Data from the manual traffic count are used to synthesize traffic flow values on the network for the entire study period. Since the manual traffic count was performed on a weekday, it is considered imprudent to apply those results on weekends, due to a big difference between morning peak period traffic flows for weekdays and weekends. Therefore, weekend concentrations are not modelled in this study.

Figure 3-2 Average Hourly Sensor Observed Traffic on College Street for June and July 2011

3.4.2 Origin-Destination (O-D) Matrix

3.4.2.1 Turning movement percentage

Turning movement percentages are available in 5 minute intervals between 7:00 – 9:00 AM for all intersections within the network from the manual survey count. These percentages are averaged to 15 minute intervals. Minor adjustments are made to balance the total percentages at

some intersections where the sum is not 100% upon aggregation. Different sets of turning percentage matrices are developed as follows:

- 1) Cars / Light Vehicles: The turning percentages are assumed to vary at 15 minute intervals, but are constant for the different days that are modelled.
- 2) Medium / Heavy Vehicles: The turning percentages are assumed to be constant for the entire morning peak period and also constant for the different days that are modelled.

Figure 3-3 shows a flowchart explaining the procedure followed in input O-D matrix estimation.

Figure 3-3 Process Flowchart: O-D Matrix Estimation

3.4.2.2 Regression modelling

The TDS only provides traffic counts on College Street; the remaining traffic flows are calculated by developing regression models. These models correlate manually counted traffic flows on College Street with traffic on other streets. To estimate traffic on other streets as a percentage of the traffic on College Street, the constant term in regression models is kept zero. A total of 15 regression models are developed; 9 for cars / light vehicles and 6 for medium / heavy vehicles. The regression models are assumed to be constant for the morning peak period of all modelled days.

Figure 3-4 shows a typical regression model for Southbound car / light vehicle traffic on St. George Street correlated with total car / light vehicle traffic on College Street for 7:00 - 9:00 AM.

Figure 3-4 Passenger Car Model relating College St. Traffic with Southbound St. George St. Traffic; SB: Southbound; CL: Cars / light vehicles

Table 3-1 lists the regression models developed to estimate synthetic traffic volumes at different locations within the network. The models generally show good correlation and high R^2 values. Medium / heavy vehicle volumes on King`s College (Southbound) and Galbraith (Westbound) are assumed to be zero since they are very small roads, and a negligible number of vehicles were counted on them during the manual traffic survey.

Next, these models are applied to generate synthetic traffic counts on the network. It is imperative to note that only the locations required to identify a traffic flow pattern on the network are modelled using regression analysis. The remaining values are estimated based on 'balancing' traffic at different intersections within the network using turning percentages obtained from the manual traffic counts. The balancing process involves keeping the net flow of vehicles through an intersection consistent.

Table 3-1 Regression Models for Light and Heavy vehicles based on manual traffic count data

Regression Models	Car / Light Vehicles	Medium / Heavy Vehicles
St. George NB	$0.18 * V_C ; R^2 = 0.88$	$0.21 * V_T ; R^2 = 0.84$
St. George SB	$0.33 * V_C ; R^2 = 0.93$	$0.17 * V_T ; R^2 = 0.64$
Beverley NB	$0.16 * V_C ; R^2 = 0.87$	$0.21 * V_T ; R^2 = 0.89$
Beverley SB	$0.24 * V_C ; R^2 = 0.89$	$0.17 * V_T ; R^2 = 0.84$
Huron SB	$0.06 * V_C ; R^2 = 0.69$	$0.08 * V_T ; R^2 = 0.53$
College WB*	$1.09 * V_{CW} ; R^2 = 0.99$	$0.52 * V_{TW} ; R^2 = 0.66$
King's College SB	$0.03 * V_C ; R^2 = 0.59$	0
Galbraith WB	$0.12 * V_C ; R^2 = 0.83$	0
Russell EB	$0.08 * V_C ; R^2 = 0.86$	$0.06 * V_T ; R^2 = 0.16$

V_C : Total eastbound and westbound car traffic on College Street; V_T : Total eastbound and westbound truck traffic on College Street; V_{CW} : Total westbound car traffic on College Street, V_{TW} : Total westbound truck traffic on College Street. (All observed traffic on College Street measured west of the major intersection); EB: Eastbound, WB: Westbound, SB: Southbound, NB: Northbound. * East of the intersection

3.4.2.3 Monte-Carlo Simulation

A Monte-Carlo simulation method developed by Hoy, et al. (2012) is adopted to generate the O-D matrix. Using the traffic flow matrix and turning movement percentages, an O-D cumulative percentage matrix is created that contains the cumulative probability of a vehicle travelling between a given O-D pair. Subsequently, a Monte-Carlo simulation is applied to randomly distribute vehicles based on these probabilities. Using a Monte-Carlo simulation effectively randomizes the constant turning movements used for traffic flow development.

Eight O-D matrices are created at 15 minute intervals for 'cars / light vehicles' and 'medium / heavy vehicles' for every weekday modelled in the study period. Table 3-2 shows a sample O-D matrix generated for cars and light vehicles between 8:15 – 8:30 AM on July 7, 2011.

Table 3-2 Sample O-D matrix generated at 15 minute interval, July 7, 2011 8:15 – 8:30 AM

O/D	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Total
1	0	3	0	5	0	0	0	56	1	0	27	1	0	0	3	96
2	1	0	0	0	0	0	0	21	0	0	5	0	0	0	0	27
3	0	0	0	0	18	0	0	0	0	0	0	0	0	0	0	18
4	0	0	3	0	11	0	0	15	0	12	170	10	0	0	0	221
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	2
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	20	1	0	6	0	0	7	0	0	1	21	1	0	0	3	60
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	20	5	6	101	3	0	0	0	0	9	0	9	0	0	2	155
12	1	0	1	8	0	0	0	0	0	1	0	0	0	0	0	11
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
15	33	8	0	0	0	0	0	1	0	0	0	0	0	0	0	42
Total	76	17	10	120	32	0	7	93	1	23	225	21	0	0	8	633

A divisor of 1.71 is used in PARAMICS to factor down the O-D matrix counts because the TDS overestimates traffic. Morning peak period data from the manual traffic count are compared with TDS data for the same day (June 8, 2011) to estimate this divisor value.

3.4.3 Other Inputs

PARAMICS is a stochastic model where randomness in the model results is generated using a random seed number. It is necessary to analyse the effect of different random seed inputs in the traffic microsimulation, on the output emission rates obtained from CMEM, the emissions model. Another important consideration is the vehicle type distribution which is necessary to accurately model emissions using a traffic microsimulation model. Both the vehicle type distribution and PARAMICS random seed analysis is described in subsequent chapters once the microscopic emissions model has been introduced.

Other core parameters that affect the microsimulation results are the mean headway between vehicles and the mean driver's reaction time (Chu, et al., 2004). The mean headway is defined as the average time gap between two vehicles on the network. The mean driver's reaction time is the average time taken by the driver to respond to any 'event' on the network. Both these parameters are indicative of the driver behaviour and can vary temporally and geographically.

Jansuwan & Narupiti (2005) suggest that the mean headway ranges from 0.3-1.9 seconds, while Johansson & Rumar (1971) state that the mean driver's reaction time ranges from 0.3-2.0 seconds. Other acceptable ranges include 0.6-2.2 seconds for mean headway and 0.3-1.9 seconds for mean driver's reaction time, given by Park & Qi (2004). A default value of 1.0 second which satisfies all the above ranges is selected for both these parameters.

Chapter 4

4 Emissions Modelling: Method

4.1 Emission Modelling Review

Traffic emission models estimate emission factors on roadway links of a traffic network, based on attributes such as vehicular fleet composition, volume of traffic flow, vehicle operating characteristics (speed profile), and geographic terrain of the study network. Aggregate emission factor models generally calculate the average speed on each link, and use a specific vehicle type distribution, to estimate emission rates on roadway links. Emission rates for specific vehicle type, age, and speed are usually based on a sample of driving cycles that have been pre-tested in the laboratory. Other factors that may be included are driving load, air conditioner operation, and vehicle operation state. Total emission for any pollutant is then estimated by multiplying the emission rate with vehicle trip characteristics such as distance travelled, time taken, and trip count. Microscopic emission models correlate emission output and fuel consumption with independent instantaneous variables that describe vehicle operation at a fine scale. It is well established in the literature that emission models that account for variations in instantaneous vehicular speed provide more accurate results than models that cannot do so (Ahn & Rakha, 2008) (Moulvi, 2010).

Average speed models such as MOBILE (Environmental Protection Agency, 2012), and EMFAC (California Environmental Protection Agency, 2010), cannot operate at a microscale. Newer emission models such as Comprehensive Modal Emission Model (CMEM) (Barth, et al., 1999) (Barth, et al., 2001), VT Micro (Rakha, et al., 2004), and Motor Vehicle Simulator (MOVES) (Environmental Protection Agency, 2012) are microscopic in nature, and can provide second-by-second / disaggregate emission rates for a given roadway link based on vehicle driving cycles. Driving cycle of a vehicle can be defined as a disaggregate characterisation of the speed-time profile of a vehicle, that explains detailed vehicular motion based on idling, acceleration, deceleration, and cruising activity of the vehicle. COPERT 4 is another emissions model that has been widely employed in Europe for evaluating technological and legislative decisions (EMISIA, 2011). MOVES has replaced the MOBILE6 as the new regulatory emission

model for the US EPA, indicating an increasing interest in microsimulation of emissions from vehicles.

Bai et al. (2009) compared MOVES-HVI demo (an earlier version of MOVES with macroscopic modelling abilities) with EMFAC for carbon dioxide and methane emissions in Los Angeles, California, and concluded that MOVES represented a ‘major modelling improvement’ in terms of comprehensive emissions estimation; they also stressed the need for good quality local data to develop a good modelling system. Rakha, et al. (2003) compared the MOBILE 5a / 6 series models with VT-MICRO / CMEM version 2.0, using data from Oak Ridge National Laboratory and EPA for light duty gasoline vehicles. They concluded that MOBILE5a performed poorly, MOBILE6 generally had good consistency with VT-Micro results, while CMEM showed certain abnormalities in estimating NO_x at high engine loads, and CO at low speed and high acceleration levels. Recently, Vallamsundar & Lin (2011) compared the performance of MOVES and MOBILE for NO_x and CO₂ in Cook County, Illinois, and concluded that MOVES could significantly affect emission estimates at regional and project level; the paper also stressed the importance of obtaining accurate local data for making best use of the MOVES methodology. Moulvi (2010) investigated the impact of driver behaviour on exhaust emissions and demonstrated unreliability of estimates obtained using average speed calculations. The paper emphasized CMEM accuracy and showed that it is more sensitive to changes than MOVES for CO₂ emissions.

Microscopic emission models can truly exploit the benefit of using a traffic microsimulation model in order to estimate a more accurate emission rate on roadway links. Evidently, average speed models are rejected for analysis of emissions in this study.

4.2 Model Selection

Several studies have investigated traffic emissions using microscopic traffic modelling. Chen & Yu (2007), Nam, et al. (2003), Noland & Quddus (2006), and Stathopoulos & Noland (2003) used a combination of VISSIM and CMEM to evaluate emissions. The combination of PARAMICS and CMEM has also been employed in the past by Brownstone, et al. (2008) and Amirjamshidi, et al. (2012) to evaluate policy scenarios from a traffic emissions perspective. More recently, Xie, et al. (2012) used the combination of PARAMICS and MOVES to analyse impact of alternative fuel use on overall fuel reduction in Greenville, South Carolina. Both

MOVES and CMEM represent state-of-the-art emission modelling approaches and are considered for this study. MOVES contains vehicle type distribution data for the United States, however, local Canadian fleet attributes are currently not incorporated. CMEM contains a plug-in that can be integrated with PARAMICS and executed simultaneously along with the traffic microsimulation runs. The combination of PARAMICS and CMEM thus provides a robust and structured method to apply microsimulation to estimate emission rates on the roadway network; hence CMEM is selected for application in this project.

4.2.1 Comprehensive Modal Emissions Model (CMEM)

CMEM was developed at the University of California, Riverside. It employs a power-demand modelling approach based on mathematical representation of emission production in the vehicle engine. All emission generating physical processes associated with the vehicle operation are broken down into different stages with several different parameters characterising the nature of these processes. These parameters can be roughly classified into engine attributes (vehicle specification / engine characteristics) and vehicle operating variables (state of the vehicle and its components during operation). Vehicular operation is in turn affected by the geometric layout and grade of the roadway. CMEM can provide CO₂, CO, NO_x, HC (hydrocarbons) and fuel use estimates for each roadway link on the network. The current CMEM version 3.0 developed in 2005 does not include Particulate Matter (PM) emission estimation, and in spite of their import in urban air pollution, PM emissions are not evaluated in this research. CMEM currently comprises 28 light duty vehicles and 3 heavy duty vehicles. Further details on the model can be obtained from Barth, et al. (1999), Barth, et al. (2001) and Scora & Barth (2006).

4.3 Vehicle Type Distribution

The vehicle type distribution is based on data obtained from Amirjamshidi, et al. (2012) who used the Canadian Vehicle Survey from Statistics Canada (2009), to predict a best estimate of the vehicle composition in Toronto. Malcolm, et al. (2003) concluded that in addition to use of average driving speeds for estimating traffic emissions, the average regional vehicle type distribution could also add to inaccuracies in emission estimates. Therefore, it is important to take the spatial variability of the vehicle type distribution into account.

The vehicle type distribution obtained from Amirjamshidi, et al. (2012) is augmented with City of Toronto cordon count data (Data Management Group, 2004). Count data obtained for College Street west of Spadina Avenue for the time period between 7:00 - 9:00 AM are used. This location is closest to the study area where cordon count data are available. The data provide a distribution of vehicles into passenger cars (auto), light, medium and heavy duty trucks. Based on this data, a best estimate of the vehicle type distribution is developed as shown in Table 4-1. In reality, the vehicle type distribution varies by time of day and also between different modelling days. Since it is practically impossible to capture this variation, the distribution is assumed to be constant for the study period. The total traffic volume on the network is distributed into two O-D matrices (based on vehicle type) that are input into PARAMICS. One matrix consists of cars and light vehicles, while the other consists of medium and heavy vehicles. The CMEM vehicle types are then assigned to the two matrices based on the vehicle type distribution. The PARAMICS and CMEM model combination is run for the morning peak period between 7:00 - 9:00 AM for all selected weekdays in June and July 2011. Eight O-D matrices are input at 15 minute intervals for the 2 hour simulation period. The CMEM emission rate outputs are averaged at 15 minute intervals. Figure 4-1 shows a general process flowchart presenting the integration of PARAMICS and CMEM.

Figure 4-1 Process flowchart: Integration of PARAMICS and CMEM

4.4 Emission Output Processing

CMEM generates two output files - a vehicle activity summary and an emissions summary. The activity summary contains a list of average velocities and accelerations for all links on the network. It also provides link lengths and total distance travelled by vehicles on that particular link. The emissions summary file contains cumulative emissions generated for CO₂, CO, HC, NO_x and fuel usage for each 15 minute period in the 2 hour simulation period. The CMEM output

data are processed for developing inputs to the dispersion models. This is covered in the following chapter once the dispersion modelling methodologies have been introduced.

Table 4-1 Vehicle Type Dist. (Amirjamshidi, et al., 2012) (Data Management Group, 2004)

MEDIUM AND HEAVY VEHICLES MATRIX

CMEM Category	Description	Proportion
25	Truck, Gasoline powered, LDT (>8500GVW)	10.02%
40	Truck, Diesel powered, LDT (>8500GVW)	66.45%
5	HDD 1994-1997, 4 stroke engine, Electric, FI, Normal emitting	4.80%
6	HDD 1998, 4 stroke engine, Electric, FI, Normal emitting	1.11%
7	HDD 1999-2002, 4 stroke engine, Electric, FI, Normal emitting	17.62%

CAR AND LIGHT VEHICLES MATRIX

CMEM Category	Description	Proportion
8	Tier 1, >50K mi, Low P/W ratio	9.97%
9	Tier 1, >50K mi, High P/W ratio	37.53%
19	Runs Lean	0.50%
20	Runs Rich	0.50%
21	Misfire	0.80%
22	Bad Catalyst	0.50%
16	1988-1993,>3750 LVW	0.56%
17	Tier 1 LDT2/3 (3751-5750 LVW or Alt LVW)	1.84%
4	3 way catalyst, FI, >50K mi, Low P/W ratio	2.69%
5	3 way catalyst, FI, >50K mi, High P/W ratio	10.67%
10	Tier 1, <50K mi, Low P/W ratio	6.83%
11	Tier 1, <50K mi, High P/W ratio	27.31%
26	Ultra Low Emissions Vehicle	0.29%

Chapter 5

5 Pollutant Dispersion Modelling: Method

5.1 Dispersion Modelling and Meteorology

Dispersion models simulate the movement of pollutants in air by replicating physical atmospheric phenomenon, with an objective to estimate emission concentrations in a given region. Dispersion of anthropogenic air pollution occurs in the planetary boundary layer (PBL), which forms the lowest part of the troposphere that is in direct contact with the earth's surface. It is imperative to understand atmospheric characteristics in order to comprehend dispersion models and their application.

Moussiopoulos, et al. (2003) characterised nine levels of atmospheric system scales and described how pollutant modelling is primarily based on scale segmentation, as opposed to integration of several scales for a single modelling method. Tiwary & Colls (2010) classified dispersion models on the scale of their application as macroscale (1000 kilometres/days), mesoscale (10-100 kilometres/hours), and microscale (<1 kilometre/minutes) models; Zannetti (1990) classified the different transport scales of air pollution as near-field (<1km), short-range (<10km), intermediate transport (10-100km), long-range (>100km), and global effects. Different factors affect dispersion depending on the scale of the dispersion modelling process. Macroscale dispersion is affected by general circulation of winds, upper level flows, jet streams, and other general synoptic weather systems (for example, air masses, fronts, cyclones, anticyclones, polar lows); mesoscale dispersion is affected by thermally induced circulations, sea and land breezes, monsoon circulation, urban heat island effect, and mountain/valley effects; microscale systems are affected by characteristics of the internal boundary layer and obstacle wakes (Arya, 1999). Wind flow, which is an important dispersion factor, can be mechanically generated or turbulence associated; the latter being dependent on atmospheric stability. Horizontal winds are primarily responsible for advection or transport of pollutants, while turbulence helps in dispersion or dilution of the pollutants.

The PBL can be divided into the surface layer (which includes the surface roughness layer) and the outer layer. The turbulent (sensible heat / latent heat of evaporation or condensation) and

radiative exchange of energy between the earth's surface plays an important role in the thermal stratification of the lowest layer of the PBL, which is the surface layer. The net radiation received during the day is positive, and therefore, heat is radiated outwards from the earth's surface, developing a temperature profile decreasing with height such that the highest temperature occurs closest to the surface. During night-time, the net radiation is negative so that the earth's surface absorbs heat from the lowest layers of the atmosphere. This reverses the temperature profile such that temperature increases with height, and the lowest temperature occurs closest to the surface. Thus, usually day time is a case of active mixing, while night time is a quiet period with suppressed vertical movement in the atmosphere.

The dry adiabatic lapse rate is defined as the rate of decrease in temperature with altitude for a parcel of dry air rising under adiabatic conditions. This rate is ~ 1 degree decrease per kilometre increase in height. When the actual rate of decrease of temperature is greater than this value, then the surface layer is generally unstable; if it is smaller than this value, then the surface layer is generally stable. Three widely used methods to classify atmospheric stability are empirical relationships developed by Pasquill (1974), the Richardson numbers (Businger, 1966) (Pandolfo, 1966), and the Monin-Obukhov (M-O) length parameter (Monin & Obukhov, 1954). These parameters in turn derive values from other atmospheric variables such as the surface heat flux, temperature, pressure, and specific humidity.

A diurnal cycle of meteorology, as described above, results in a daily inversion during night time which results in a stable surface layer where dispersion is restricted and higher concentrations of pollutants are likely. Such a layer is called the Stable Boundary Layer (SBL) where mechanical turbulence dominates. In the morning, as the earth's surface starts radiating heat back into the atmosphere, the stable surface erodes, and an unstable layer is formed, which eventually replaces the stable layer formed during the night. This layer is called the Convective Boundary Layer (CBL), where convective turbulence plays a dominating role in dispersion. During the evening, net radiation of heat again becomes negative, thereby generating a stable surface layer and thus the cycle continues. The depth to which any surface layer exerts influence on dispersion in the PBL is known as the mixing height, which is an important parameter in characterising the state of atmosphere for dispersion modelling.

Dispersion models can be classified on the basis of several different characteristics. Zannetti (1990) classified dispersion models as Gaussian, Eulerian and Lagrangian models. Khare & Sharma (2002) classified models on the basis of their size, time horizon, and pollutants. They further described three modelling approaches, namely, deterministic mathematical, statistical, and physical modelling. A large number of dispersion models developed in the past have focused on deterministic mathematical modelling which consists of analytical models (Gaussian plume / Puff formulations) and numerical models (Lagrangian and Eulerian approaches). These models usually incorporate several empirical relationships that have been developed using physical modelling. Holmes & Morawska (2006) classified dispersion models into Box models, Gaussian models, Lagrangian / Eulerian models, Computational Fluid Dynamics (CFD) models, and models that include Aerosol Dynamics; depending on the features of application, they also performed a detailed review of several software packages that are employed in the field.

Physical modelling involves developing 3-dimensional scaled down models of a life sized study area, and evaluating wind flow patterns in order to develop empirical relationships that are coded into analytical and numerical dispersion models. Statistical approaches apply regression and principal component analyses to develop statistical models that can generate concentration patterns based on certain input parameters.

All mathematical dispersion models can essentially be classified into Eulerian or Lagrangian models. Eulerian models investigate and observe processes at fixed points in space with the frame of reference either stationary or moving. The Lagrangian approach is to track the movement of pollutant particles in a 3-dimensional grid, subject to stochastic movement of every individual particle. Generally, such models require the specification of a mean wind component and a turbulent wind component that may be estimated using randomly generated numbers. CFD models analyse dispersion in terms of fluid flow by using the Navier-Stokes equation which describes the motion of pollutants as fluids. Box models are simplistic dispersion models that are based on the principle of conservation of mass within a box; the concentrations are calculated assuming that the pollutants are homogeneously distributed inside the box. Gaussian models are popular dispersion models that use the Gaussian plume distribution equation, either in a simple form, or with a complex formulation (such as the Gaussian puff model) to disperse pollutants, and estimate concentrations at fixed receptor locations throughout the network. Gaussian based models are essentially Eulerian in their approach.

5.1.1 Dispersion Modelling Review and Model Selection

Most commonly used models for near field pollutant analyses in North America include AERMOD, CAL3QHCR, and CALINE 3/4 which are all Gaussian models. A comparative review of EPA preferred dispersion models has been performed by Jungers, et al. (2006). The CALINE models were developed by Caltrans (California Department of Transportation) and have been extensively used in California to analyse traffic emissions. CAL3QHCR is based on the same line source formulation employed in CALINE3, with additional equations for queuing and estimating concentrations at roadway intersections better. CALINE3 can only handle 20 links and 20 sources at a time while CAL3QHCR can only handle 120 roadway links. Both these models are known to perform poorly in low wind conditions, and cannot explicitly model the presence of buildings around the intersection. HIWAY2 is another line source Gaussian model that has been used by EPA in the past to evaluate highway emissions. However, it cannot simulate complex terrain and obstacles similar to CALINE.

HYROAD is an EPA model with ‘Alternative’ status that integrates three modules (micro-scale traffic simulation, emission, and pollutant dispersion) for estimating CO emissions up to 500 metres from traffic intersections (Carr, et al., 2002). Two commonly used dispersion models in Europe include the Atmospheric Dispersion Modelling System (ADMS) Series developed by Cambridge Environmental Research Consultants (CERC, 2010), and the Operational Street Pollution Model (OSPM) developed in Denmark (Berkowicz, et al., 1997). The former is a ‘new generation’ Gaussian plume model while the latter combines the Gaussian formulation with the Box modelling approach to estimate concentrations in street canyons. The ADMS-3 is also listed as an ‘Alternative’ under the EPA’s list of dispersion models. A review of most commonly used operational models applied for dispersion on traffic intersections can be found in Tiwary, et al. (2011).

EPA’s main regulatory models are AERMOD and CALPUFF. AERMOD is a steady state Gaussian plume dispersion model which is currently the EPA regulatory model for near field dispersion (Environmental Protection Agency, 2012). It has significant modelling capacity for stationary sources; for mobile source emissions, the unwieldy nature of using AERMOD has been recognized by Jungers, et al. (2006). CALPUFF is the EPA regulatory model for far field dispersion. It is a non-steady state model that is time sensitive to concentrations as opposed to

AERMOD which is a steady state model. The application of CALPUFF for near field analysis is prone to error (Brode & Anderson, 2008) and it is not considered for application in this study.

Several studies have used Gaussian models to evaluate traffic emissions in the past. Batterman, et al. (2010) analysed near road concentrations using a reduced form emission / dispersion model based on MOBILE6.2 and CALINE4 for CO and PM_{2.5} predictions, and obtained reasonable agreement with observed emissions for a freeway and a traffic intersection. Marmur & Mamane (2003) evaluated the performance of HIWAY2 and CALINE4 for NO_x concentrations on a highway, and found that both models had similar predictions for at-grade road sections. Vaitiekunas & Banaityte (2007) used AERMOD to assess traffic related emissions on a mesoscale; the emission rates input into the dispersion model were based on aggregate average values for fleet distribution and traffic flow. Zou, et al. (2009) analysed population exposure to SO₂ using AERMOD for a combination of vehicular and industrial sources in Dallas. Kesarkar, et al. (2007) integrated AERMOD with a weather forecasting model to estimate PM₁₀ emissions for a 25 square kilometre area in Pune, India; these PM₁₀ emissions came from a wide variety of sources including vehicular exhaust, industrial operations et cetera, that were estimated using certain emission inventories. Singh, et al. (2006) evaluated the performance of AERMOD and CALINE for fine PM emissions; generally, AERMOD seemed to estimate higher emission concentrations compared to CALINE. Chen, et al. (2009) compared the performance of CALINE4, CAL3QHC and AERMOD and concluded that even though AERMOD could better simulate atmospheric processes, CALINE4 and CAL3QHC might be better when detailed meteorological data-sets (as required in AERMOD) are not available.

Lagrangian models are becoming more popular for dispersion analysis as advancement in computing technologies has reduced computational times considerably. The Quick Urban and Industrial Complex (QUIC) dispersion model is a fast response Lagrangian particle dispersion model that has been developed by Los Alamos National Laboratory (2010) to compute concentrations of pollutants in a short span of time. QUIC has been used for analysis of ultrafine particles in urban / semi-urban areas by Zwack, et al. (2011) and Bowker, et al. (2007); Fernando, et al. (2010) analysed PM₁₀ emissions in urban areas using QUIC. However, in spite of tremendous potential to simulate micro-scale dispersion of traffic related gaseous pollutants in urban areas, no current studies that apply QUIC for such analyses are known to the author. Other

Lagrangian models such as GRAL have been employed in the past, for example, in Oettl, et al. (2001), to analyse roadway concentrations.

Some of the most commonly applied dispersion models were introduced in this section. The reader should refer to Holmes & Morawska (2006) for a detailed review and an all encompassing classification of various dispersion software packages available throughout the world. A brief summary of models evaluated for this research is shown in Table 5-1. (California DoT, 1989) (Environmental Protection Agency, 1995) (Berkowicz, et al., 1997) (Environmental Protection Agency, 2004) (Los Alamos National Laboratory, 2010).

Table 5-1 Brief Review of Dispersion Models Evaluated

DISPERSION MODEL	Gaussian Plume Models (CALINE4, CAL3QHCR)	Gaussian Plume Models AERMOD/AERMET	Gaussian Plume and Box - OSPM	Lagrangian Dispersion Modelling QUIC
Description	Steady State Gaussian Plume	Steady state Gaussian Plume. AERMET meteorological pre-processor ; AERMAP – terrain and receptor data; AERMOD – Conc. Est.	Street canyon model; Gaussian Plume (Direct distribution) + Box Model (Re-circulating and background conc.)	Rockle Wind Model – Mean Wind Field (QUIC-URB), Langevin Walk Equations for Turbulence (QUIC PLUME)
Scale	Local	Local, Regional	Local	Local/Regional
Pollutants	CALINE4 - NO ₂ CO TSP; CAL3QHCR - CO PM NO _x	Gases / Particles	NO _x , NO ₂ , O ₃ , CO, PM	Gases / Particles
Source Type	Line	Point, Area, Volume	Line	Point, Line, Area, Volume
Output Freq.	1h	1h	1h	Seconds-Hours
Building Effects	No	Yes (Limited)	Yes (Simple)	Yes (Complex)

Air quality impacts due to vehicular emissions have been investigated at the local, regional, and global scales extensively. However, very few studies have attempted to apply an integrated micro-modelling framework as proposed in this research, to microsimulate traffic, use microscopic emissions modelling to estimate emission rates on roadway links, and use a microsimulating dispersion model to estimate pollutant concentrations at a local level. The intent of this research is to maintain a consistent level of detail throughout the framework, such that

none of the methodologies (traffic microsimulation, emission, and dispersion) are extensively compromised.

AERMOD and QUIC are selected for dispersion analysis in this research with two main objectives. The first is to apply a Lagrangian microscale dispersion model (QUIC), to estimate traffic emissions, and secondly, to compare results with the best available near field Gaussian dispersion model (AERMOD). AERMOD is considered an aggregate model here, since, like most other Gaussian dispersion models, it can only provide hourly resolution of concentrations, hence, would serve to average out the effect of traffic microsimulation at 15 minute intervals. AERMOD View, a software package that provides a Graphic User Interface developed by Lakes Environmental (2012) is used to perform all AERMOD related analysis. The following sections describe the dispersion models adopted in further detail and discuss the input data preparation method.

5.2 AERMOD

AERMOD is a steady state Gaussian plume model that uses a meteorological pre-processor called AERMET to characterise the atmospheric conditions in the PBL, and a terrain pre-processor called AERMAP to characterize terrain elevation and prepare source / receptor heights for pollutant dispersion. Gaussian models assume that pollutants originating from a plume travel in the downstream wind direction simultaneously dispersing in the vertical and horizontal directions following a Gaussian or a Normal Distribution. This distribution depends on the horizontal wind speed / direction (responsible for transport of pollutants) and turbulence (responsible for dilution in the atmosphere).

AERMET calculates several PBL parameters (for the CBL and SBL) such as friction velocity (u_*), Monin-Obukhov (M-O) length (an atmospheric stability parameter, L), convective velocity scale (an indicator of convective turbulence in the CBL, w_*), temperature scale (θ_*), mixing height (the maximum height in which dispersion occurs, z_i), and surface heat flux (an indicator of incoming / outgoing radiation from the earth's surface, H). The inputs into AERMET are albedo (a radiation reflection coefficient), surface roughness, wind speed, wind direction, temperature, and cloud cover.

AERMOD subsequently applies the AERMET estimated parameters to generate vertical profiles for wind speed (u), wind direction, turbulent fluctuations in the vertical and lateral directions (σ_v , σ_w), and potential temperature gradient ($d\theta/dz$), using measured data and similarity relationships. AERMAP requires formatted Digital Elevation Model (DEM) terrain data and the receptor grid location in order to process the elevation data. It provides AERMOD with source / receptor heights and terrain elevation data. AERMOD also incorporates some effects of surrounding buildings on wind flow by calculating building downwash using the Building Profile Input Program (BPIP); in effect, this restricts the ascent of pollutants in building wake regions. Finally, based on the outputs of AERMAP and BPIP, using vertical profiles for atmospheric parameters, AERMOD estimates concentrations at receptor locations for the specified emission sources using the Gaussian distribution formulation. Specifically, AERMOD uses a Gaussian distribution in vertical and horizontal directions in the SBL. In the CBL, it uses a Gaussian distribution in horizontal and a bi-Gaussian probability density function in the vertical direction. A sample equation used to estimate concentrations in a stable boundary layer (SBL) is:

$$C_s(x_r, y_r, z) = \frac{Q}{\sqrt{2\pi}u\sigma_{zs}} F_y \sum_{m=-\infty}^{\infty} \left[\exp\left(-\frac{(z - h_{es} - 2mz_{ieff})^2}{2\sigma_{zs}^2}\right) + \exp\left(-\frac{(z + h_{es} + 2mz_{ieff})^2}{2\sigma_{zs}^2}\right) \right]$$

$$F_y = \frac{1}{\sqrt{2\pi}\sigma_y} \exp\left(-\frac{y^2}{2\sigma_y^2}\right)$$

Where,

C_s : Concentration

Q : Source strength

z : Receptor height

y : Lateral distance

F_y : Lateral distribution function

z_{ieff} : Effective mechanical mixing layer depth

σ_{zs} : Vertical dispersion coefficient

σ_y : Lateral dispersion coefficient

u : Wind speed

h_{es} : Plume height (which includes source height + buoyant plume rise)

The complete model formulation including algorithms, equations and full set of assumptions can be reviewed in Cimorelli, et al. (2004) and Environmental Protection Agency (2004). Figure 5-1 shows a process flowchart indicating the flow of data in AERMOD.

Figure 5-1 Process Flowchart: AERMOD Methodology

5.3 Quick Urban and Industrial Complex (QUIC)

QUIC is a fast response Lagrangian particle dispersion model that simulates the movement of pollutant particles by tracking their motion through a 3-dimensional gridded space (comprising several grid cells), under the effect of wind. QUIC version 5.8 is used for modelling purpose. It comprises two key modules - QUIC-URB and QUIC-PLUME.

QUIC-URB is a 3-dimensional wind generator that uses the Rockle (1990) formulation to simulate mean wind flow in a complex building environment. It combines building flow parameterizations and a consistent mass flow equation to obtain a time averaged wind flow for the entire network. The inputs into QUIC-URB include wind speed, wind direction, and building

environment of the study area. The building environment can be developed using the City Builder Tool. QUIC-PLUME describes the positions of particles using the following equation:

$$x = x_p + U\Delta t + \frac{(u'_p + u')\Delta t}{2}$$

$$u' = u'_p + du$$

Where,

x: x-coordinate of particle

p: Subscript for previous position

U: Mean wind speed

u': Fluctuating component of instantaneous wind

Δt : Time step to update particle positions and grid velocities

du: Small turbulent component of velocity

Similar equations can be formulated for y / z coordinates and the corresponding velocities. 'du' is estimated using a random walk model that uses surface layer parameterization of atmospheric parameters, and the random number generator, RAN2. QUIC also incorporates turbulence associated with walls and rooftops. Other inputs into QUIC-PLUME include the inverse M-O length, temperature, surface pressure, vertical temperature profile, and relative humidity, to characterize the atmospheric conditions in PBL. Inputting a strong negative value of the inverse M-O length (indicative of unstable atmosphere) enhances turbulence within QUIC. Using the instantaneous wind comprising mean wind flow and turbulence, the model traces movement of individual particles released in the modelling domain. Based on the atmospheric input parameters, wind flow, and input emission rates, concentration contours are estimated in pre-specified 'collecting boxes' in the domain. Concentration is calculated by counting the number of particles present in a given grid cell for a specific averaging time period. The equation to estimate concentrations is:

$$\chi_{i,j,k} = \sum \frac{Q\Delta t_c}{n_{tot} dx_b dy_b dz_b t_{ave}}$$

Where,

$\chi_{i,j,k}$: Concentration

Q: Source strength

dx_b, dy_b, dz_b : Sampling box size in x, y and z direction

n_{tot} : Total particles released during simulation

t_{ave} : Sampling time

Δt_c : Time between particle collection for concentration estimation

Further details on the QUIC model can be found in Williams, et al. (2004) and Pardyjak & Brown (2007). Figure 5-2 shows the QUIC methodology.

Figure 5-2 Process Flowchart: QUIC Methodology

5.4 Dispersion Modelling Inputs: Data Processing

The following section discusses the data inputs prepared to perform model runs using AERMOD and QUIC dispersion models.

5.4.1 AERMOD Inputs

5.4.1.1 Emission Sources

For traffic pollutants, roadway links are assumed to be line emission sources. Generally, roadway emission sources are modelled as a series of volume or area sources where the road is distributed into reasonably spaced volumes or areas. However, in this study, roadway links are modelled as

a series of point sources since building downwash effects can only be estimated for point sources in AERMOD. CMEM provides emission rates for 146 links on the study network at 15 minute intervals for each day modelled. These link sources are distributed into 200 point sources on the network with an average spacing of ~15 metres. Separate point sources are created for northbound, southbound, eastbound, and westbound lanes for all roads on the network. The level of disaggregation of roadway links into point sources is limited by the building downwash computing time of the BPIP model.

CMEM outputs provide cumulative emission in grams for each link at 15 minute intervals for the 2 hour modelling period on any given day. Source emission rates are calculated by first calculating the emission rate for each 15 minute period and then aggregating these values to an hourly average (since AERMOD can only receive hourly aggregated inputs). Finally, these hourly aggregated emission rates are distributed amongst the point sources. All point sources are located at a height of 1 metre, based on the standard height for paved and unpaved road sources as recommended by Ontario Ministry of the Environment (2009). Figure 5-3 shows the point emission sources modelled on the St. George and College Street intersection.

Figure 5-3 Series of point sources, AERMOD View

5.4.1.2 Meteorological Data

AERMOD has intensive meteorological data requirements. It requires upper air and surface air data sets for several atmospheric parameters in order to characterise the PBL before performing dispersion. No accurate weather station data was available for the study area. Meteorological

data comprising surface and upper air data for the desired study period (June-July 2011) and location (St. George and College Street intersection, Geographic Coordinates: 43.67 N, 79.4 W; Baseline elevation: 107 m) is purchased from Lakes Environmental (2012). This data provides a good source of local meteorological data for the study area; hourly surface meteorological data are available in the SAMSON data format and upper air meteorological data are available in NCDC TD-6201 format (WebMET, 2012).

These data are generated using MM5 prognostic wind model (PSU NCAR, 2008) that can predict mesoscale and regional scale circulation in the atmosphere; data are obtained for a hypothetical weather station located at the St. George and College intersection. Availability of site specific meteorological data is vital in modelling the atmosphere correctly, and in turn, obtaining accurate estimates of pollutant concentrations using the dispersion models. Details regarding the use of MM5 model in generating meteorological data can be found in Lakes Environmental (2010). The height of the anemometer for the surface data is 14 metres. AERMET requires classification of the modelling domain into different ‘sectors’ depending on land use. A single sector is specified encompassing the entire domain with ‘urban’ land use type. This is used to estimate the radiation reflection characteristics and surface roughness within the domain. AERMET outputs two files that contain processed meteorological data ready for input into AERMOD. Figure 5-4 shows the wind rose generated for the morning peak period in June and July 2011.

Figure 5-4 Wind Rose for Weekdays, 7:00-9:00 AM in June (left) and July (right), 2011

5.4.1.3 Land DEM and Building Data, Receptors

The Shuttle Radio Topography Mission (SRTM) 60-second Canadian Digital Land Elevation data available from web GIS (2012) are used to obtain study area elevation. Building data are obtained from Map and Data Library, University of Toronto (2011). It consists of a GIS map containing building dimensions and layout of the study area. The domain extents are based on the roadway network developed in PARAMICS. Figure 5-5 shows the building geometry of the study area imported into AERMOD View. The ground elevation of the study network is fairly constant and is not expected to be an important factor in modelling concentrations.

Figure 5-5 St. George Street and College Street Intersection, AERMOD View

10,000 pollutant concentration receptors are specified in a 100×100 grid matrix (each cell is $7.3 \text{ m} \times 6.07 \text{ m}$) over the study network to capture the spatial distribution of concentration for the entire network. Additionally, four (4) discrete receptors are specified at the observed sensor area located on the southern wall of the Wallberg Building, close to the intersection and approximately 20 feet from College Street. The concentrations obtained at the discrete receptor located at Universal Transverse Mercator (UTM) coordinates (629379.4, 4835244.49) are used for making comparisons to the measured values. Concentrations are estimated at two heights (3 metres and 1 metre), to observe vertical concentration variation close to the surface. Figure 5-6 shows the receptor network in AERMOD View.

Figure 5-6 Receptors, AERMOD View

5.4.2 QUIC Inputs

5.4.2.1 Emission Sources

QUIC can model source geometry as spherical shell, rectangular area / volume, moving point, line and cylinder. The roadway links from CMEM are aggregated into 17 line emission sources (12 – major, 5 – minor). These emission sources are aggregated based on their proximity to the St. George and College Street intersection such that model complexity and runtime are reduced, without diluting emissions over a very large source length. For minor source contributors, the roadway links in both directions are merged and represented by a single line source as shown in Figure 5-7. The latter assumption does not affect modelled concentrations at the observed sensor location significantly due to extremely low emission rates for these unified links. The temporal variability of line sources is modelled by replicating the 12 major line sources at 15 minute intervals; the minor line sources are aggregated for the 2 hour modelling period. Each emission source is a finite duration continuous release only ‘operating’ or releasing pollutant particles for the 15 minute period it corresponds to. Thus, a total of 101 sources are specified in the domain, with 12×8 line sources (for eight 15 minute periods in the two hour simulation) for major contributors and 5 line sources for minor contributors. Both CO and NO_x are assumed to be un-reactive, non-decaying ideal gases during dispersion.

Figure 5-7 Line emission sources, QUIC

5.4.2.2 Meteorological and Other Data

All meteorological data inputs for QUIC are obtained from AERMET outputs. Wind profile obtained for a single station within the study area is used to generate mean wind flow in QUIC-URB. The station is located on the Southwest corner of the intersection; coordinates of the station in the QUIC City Builder framework are (X=353.6 m, Y=222.7 m). A logarithmic vertical wind profile is adopted for mean wind computation. The inputs required by QUIC-URB are inverse M-O length, wind speed, wind direction, reference height for wind measurement, and surface roughness. A surface roughness of 1 metre is used based on Engineering Sciences Data Unit (1972). QUIC-PLUME also requires the inverse M-O length to characterise atmospheric stability.

The domain size is 760 m $\times$ 540 m $\times$ 150 m. This space is divided into 2,565,000 cells, each of size 4 m $\times$ 3 m $\times$ 2 m for computation of particle movement. Other inputs include convective boundary layer height, surface and ambient temperature (assumed to be equal), ambient relative humidity, and ambient pressure. The total number of particles released during the simulation is 145,440. Each particle is associated with a dose of the pollutant. Total concentration in any given grid cell is computed by counting the number of particles present in that cell for a specific averaging time period. A simulation time step of 5 seconds is used as recommended in the QUIC manual (Los Alamos National Laboratory, 2010).

5.4.2.3 Land DEM, Building Data and Receptors

The topography of the study network is assumed to be flat. Building data, obtained from Map and Data Library, University of Toronto (2011) is used to manually generate 3-dimensional building environment using the City Builder tool. The modelling domain developed is shown in Figure 5-8. The extent of the domain is based on the roadway network developed in PARAMICS. QUIC does not require specification of a receptor location before dispersion. Upon completion of the dispersion process, all concentrations are measured at the grid box with QUIC City Builder coordinates (X=406 m, Y=247.5 m) as shown by the vertical line segment in Figure 5-8.

Figure 5-8 St. George Street and College Street Intersection, QUIC City Builder

5.5 Sensitivity of Traffic Microsimulation Random Seed

As discussed previously, PARAMICS requires a random number input that generates stochasticity in the model. For each day modelled in the study period, several realisations (of the random seed) are ideally required to obtain a distribution of emission rate outputs from CMEM that vary spatially and temporally. Processing a large number of realisations for PARAMICS is practically infeasible. Due to time constraints on model runs, a sensitivity analysis is performed to estimate the coefficient of variation (ratio of standard deviation and sample mean, CV) for emission rates input into AERMOD and QUIC due to change in the PARAMICS random number seed. June 20, 2011 is randomly selected to perform this analysis. A separate evaluation for July 2011 (for NO_x) is not considered, since the traffic patterns observed on College Street for both months are identical (Figure 3-2). Five replications are generated and the CV's for input emission rates for AERMOD and QUIC are analysed. Large coefficients are observed for

extremely low emission rates. QUIC emission rate input variations are generally smaller than AERMOD. Due to difference in source geometry, CV values are different for QUIC and AERMOD, although they have been generated using the same CMEM emission rate outputs. Figure 5-9, 5-10, 5-11, and 5-12 show the coefficient of variation graphs obtained from the sensitivity analysis. Five PARAMICS / CMEM runs are performed for each modelling day; for significant emission rates, the confidence interval and error on mean input emission rate are estimated for use in the validation process. The values computed are as follows:

- 1) QUIC CO Inputs: 95% Confidence interval with 6.5% error
- 2) QUIC NO_x Inputs: 95% Confidence interval with 10% error
- 3) AERMOD CO Inputs: 75% Confidence interval with 22.5% error
- 4) AERMOD NO_x Inputs: 95% Confidence interval with 14% error

Figure 5-9 AERMOD CO Inputs CV

Figure 5-10 AERMOD NO_x Inputs CV

Figure 5-11 QUIC CO Inputs CV

Figure 5-12 QUIC NO_x Inputs CV

Chapter 6

6 Model Results and Analysis

This chapter presents results obtained from the modelling framework. CO and NO_x concentrations, predicted using the modelling framework, are compared with sensor measured concentrations and the validity of framework is established.

6.1 Pollutant Dispersion Analysis

6.1.1 Observed Pollutant Data

The observed pollutant data are obtained from the Southern Ontario Centre for Aerosol Atmospheric Research Laboratory (SOCAAR, 2011). Air samples are collected from the Wallberg Building located on the north-east corner of St. George and College Street intersection. The height of collection is ~3 metres. Figure 6-1 shows the location of the sampling site.

CO concentration is analysed using the Teledyne Gas Filter Correlation CO Analyzer Model 300E (Teledyne Instruments). It can measure a minimum of 0.04 parts per million (ppm), with an error of ~15% for a range of 0-5 ppm. NO_x concentration is analysed using the Thermo Scientific Trace Level NO_x Analyzer, Model 42i-TL (Thermo Scientific). It can measure a minimum of 50 parts per trillion (ppt), with an error of ~15% at a range of 0-500 parts per billion (ppb) (SOCAAR, 2012). CO and NO/NO₂ concentration data, available at 1 minute intervals for June and July 2011 respectively, are used for analysis. Observed concentrations are averaged to hourly values for comparison with AERMOD predicted concentrations, and to 15 minute intervals for comparison with QUIC predicted concentrations.

It can be seen in Figure 6-2 and 6-3 that both CO and NO_x show increase in concentrations during the morning peak traffic period between 7:00 - 9:00 AM. It is also observed that the evening peak traffic period does not generate a similar increase; this may be because the evening peak period is spread over a longer time period compared to the morning peak. The next sub section briefly describes some characteristics of the pollutants modelled.

Figure 6-1 Sampling Site Location: Southern wall of Wallberg Building facing College Street.

Figure 6-2 Average Hourly CO Concentration, Weekdays, June 2011

Figure 6-3 Average Hourly NO/NO₂ Concentration, Weekdays, July 2011

6.1.1.1 Pollutant Characteristics

Nitrogen oxide is composed of seven different compounds, the most common ones being N₂O (nitrous oxide), NO (nitric oxide), and NO₂ (nitrogen dioxide). N₂O is greenhouse gas while NO/NO₂ is important from an emissions perspective, due to the associated health risks. Most atmospheric NO₂ is released in the form of NO from the tailpipes of vehicles. This NO rapidly oxidizes to form NO₂ in approximately two hours (Environmental Protection Agency, 1999). Subsequently, NO₂ undergoes several chemical reactions to form O₃ and reaches a 'photo-stationary state' where repetitive cyclical chemical reactions occur in the presence of sunlight. However, in the presence of volatile organic compounds (VOC's), these chemical reactions result in net accumulation of tropospheric ozone (Arya, 1999). The equations are as follows:

Yao, et al. (2005) estimated that the direct contribution of NO₂ emissions to atmospheric NO₂ concentration is small, indicating that NO is a main component of NO_x emissions, that eventually oxidizes to form NO₂. This observation is corroborated by the sensor measured NO/NO₂ concentration graph. During the peak traffic period between 7:00 - 9:00 AM, approximately 40% of all measured NO_x consists of NO, compared to 5:00 AM in the morning, when only 13% of all measured NO_x consists of NO. This is shown in Figure 6-4.

In comparison, CO is not associated with similar complex chemical transformations; although CO oxidizes to CO₂ in the presence of the hydroxyl radical in the atmosphere. CO₂ even though important from a greenhouse gas perspective, does not have any significant adverse health effects associated with it.

Figure 6-4 NO Concentration as a Percentage of Total NO_x Concentration, Weekdays, July 2011

The following sections present the analysis of AERMOD and QUIC predicted concentrations. Wind speed is a significant dispersion parameter as shown in Chapter 7, Sensitivity Analyses. Therefore, residual concentration (the difference between predicted and observed concentration) is plotted with wind speed to notice any patterns, in each comparison.

6.1.2 AERMOD Results

Hourly averaged concentration contours are generated for the study period. Figures 6-5, 6-6, 6-7, and 6-8 show the hourly averaged spatial distribution of CO and NO_x for a typical weekday in June and July 2011 respectively for 1 metre and 3 metres heights. Note the difference in scales of the legend for the different height contours.

Figure 6-5 Avg. CO Conc., St. George and College Street, June 3, 8:00 – 9:00 AM, 1m height

Figure 6-6 Avg. CO Conc., St. George and College Street, June 3, 8:00 – 9:00 AM, 3m height

Figure 6-7 Avg. NO_x Conc., St. George and College Street, July 13, 7:00 – 8:00 AM, 1m height

Figure 6-8 Avg. NO_x Conc., St. George and College Street, July 13, 7:00 – 8:00 AM, 3m height

Higher concentrations are observed along College Street which has higher traffic volumes than all other roadways on the network. Extremely high concentrations are observed very close to the point sources on the roadway network. This needs to be considered when evaluating the overall performance of the model. It is observed that the pollutant concentrations decrease rapidly as one moves away laterally from the roadways; concentrations also decrease considerably as height increases. AERMOD does not consider the presence of buildings explicitly during the dispersion process. Even though the effect of building downwash has been incorporated, recirculation of pollutants in the street canyon is not captured by AERMOD completely. Since AERMOD is a steady state model, concentrations are not time sensitive; therefore, concentrations in each hour are independent of the values estimated in the previous hour.

6.1.2.1 CO - AERMOD Predicted Vs Sensor Observed

For each modelled weekday in June 2011, AERMOD computes two average hourly CO concentration values at the receptor location. These two values correspond to the average concentration between 7:00 - 8:00 AM and 8:00 - 9:00 AM. Street level concentrations are a combination of the concentration due to traffic flow and background (or ambient) concentrations (Hatzopoulou, 2012). Atmospheric residence times of CO can span up to a few months (Weinstock, 1969). Therefore, emission estimates from the morning traffic period cannot fully account for the sensor observed concentrations. To account for the accumulation of background concentration from the previous hours / days / months, ambient values are added to the modelled values to obtain the final predicted concentrations. The ambient values for CO are calculated based on analysis of the daily observed CO concentrations and observed traffic volume on College Street. As shown in Figure 3-2, the least average hourly traffic observed on College Street is between 3:00 – 5:00 AM. Further, Figure 6-2 and 2-6 show that for the corresponding time period, observed CO concentration also reaches a minimum. Therefore, the average observed CO concentration between 3:00 – 5:00 AM, on any given day in the study period, is assumed to be representative of the ambient CO concentration for that particular day. This ambient concentration is used to make a proper comparison between final predicted and total measured concentrations.

Modelled and observed CO data points are plotted together as shown in Figure 6-9. 100% of the predicted values are within a factor of two of the observed values. The ‘factor of two’

comparison is a widely used measure to explain the significance of predicted concentrations (Arya, 1999). The error on observed concentrations is ~15%. This error is also applied to the ambient component of the predicted values since ambient observed concentrations also have ~15% error. The ‘factor of two’ envelope is shown in Figure 6-10. Residual concentrations are plotted against wind speed as shown in Figure 6-11 to observe if the residual values have any correlation with the wind speed. Typically, at low wind speeds, higher residual concentrations should be observed, compared to high wind speed cases. For the five days modelled, the residual concentrations increase with wind speed. This suggests that wind direction is possibly influencing the modelled concentrations. A further testing of wind speed and direction is performed in Chapter 7.

Figure 6-9 Observed Vs AERMOD Predicted Hourly Average CO Concentration

Figure 6-10 AERMOD CO: Predicted Vs Observed Concentration

Figure 6-11 AERMOD Residual CO Concentration Vs Wind Speed

6.1.2.2 NO_x – AERMOD Predicted Vs Observed

Similar to CO, for every modelled weekday in July 2011, AERMOD computes two hourly average NO_x concentrations at the receptor location between 7:00 - 9:00 AM. NO_x can persist in the atmosphere for at least several days (Environmental Protection Agency, 1999) and therefore, estimating ambient concentrations is essential to improve compatibility of comparison with total measured concentrations. Figure 6-3, 2-4 and 2-5 show that the minimum concentrations for NO_x occur around 3:00 – 5:00 AM, which correspond with the lowest traffic levels on College Street (Figure 3-2). Therefore, the average NO_x concentration between 3:00 – 5:00 AM, for any given day, is assumed to be representative of the ambient concentration present for that particular day. The highly reactive NO comprises only ~13% of NO_x during the night; therefore, this is a fair assumption for estimating total ambient NO_x. All observed NO_x (comprising NO and NO₂) and modelled NO_x data points are plotted as shown in Figure 6-12. Observed concentrations have ~15% error which is also applied to the ambient component of predicted observations since the latter consists of observed night time NO_x concentrations. 60% of the predicted concentrations are within a ‘factor of two’ of the observed concentrations as shown in Figure 6-13. Model performance for NO_x is worse compared to CO as shown by the ‘factor of two’ envelope. The model under-predicts concentrations throughout; modelled NO_x concentrations do not explain the difference between observed NO_x concentration in the AM peak and the ambient NO_x concentration. NO₂ contribution from traffic sources to total atmospheric NO₂ concentrations is

small as shown by Yao, et al. (2005); since atmospheric NO_2 is a major component of NO_x in the atmosphere (about 60% for the morning peak period based on observed sensor data), this could explain some of the difference between modelled and observed concentrations.

Figure 6-12 Observed Vs AERMOD Predicted Hourly Average NO_x Concentration

Figure 6-13 AERMOD NO_x : Predicted Vs Observed Concentration

Figure 6-14 AERMOD Residual NO_x Concentration Vs Wind Speed

Figure 6-14 shows the plots of residual concentration with wind speeds. AERMOD constantly under-predicts for NO_x concentrations for all wind speeds, indicating that the model may have a bias that is not being captured.

6.1.3 QUIC Results

QUIC generates average concentrations at 15 minute intervals in the modelling domain, for selected weekdays in June 2011 (for CO) and selected weekdays in July 2011 (for NO_x). Eight data points are generated for each modelling day, corresponding with the eight '15 minute intervals' for the 2 hour simulation period between 7:00 – 9:00 AM. The concentrations are analysed at heights of 3 metres and 1 metre. All comparisons with observed concentrations are made for the 3 metre height. Figures 6-15, 6-16, 6-17, and 6-18 show the spatial distribution of CO and NO_x for a typical weekday in June and July 2011 respectively. The spatial distribution of pollutants shows that highest emissions are concentrated along the roadway line sources. The concentrations decrease rapidly as the lateral distance from the roadway source increases. It is also observed that concentrations decrease with height.

Figure 6-15 Avg. CO Conc., St. George and College Street, June 3, 7:00 - 7:15 AM, 1m height

Figure 6-16 Avg. CO Conc., St. George and College Street, June 3, 7:00 - 7:15 AM, 3m height

Figure 6-17 Avg. NO_x Conc., St. George and College Street, July 13, 8:45 - 9:00 AM, 1m height

Figure 6-18 Avg. NO_x Conc., St. George and College Street, July 13, 8:45 - 9:00 AM, 3m height

QUIC explicitly takes building geometry and associated wind effects into account. QUIC is a non-steady state model, where concentrations in the previous 15 minute interval affect the concentrations in the following time interval. As opposed to AERMOD, QUIC is a stochastic model since it computes the turbulent component of velocity using a random number generator. Even though the change in concentration due to different random seed inputs is generally very small, notable variations could occur in the tail of a plume due to higher variability (Los Alamos National Laboratory, 2010). The combined effect of several emission sources that are active for any given 15 minute period in the study, on modelled concentrations at the sensor location, could be substantial for different random number sets. Therefore, 30 model runs are performed, using different random number realisations, to estimate a distribution of modelled concentrations for both pollutants at the receptor location. June 3 and July 13 are randomly chosen for CO and NO_x analysis, respectively. 16 distributions are generated (8 15 minute time periods for CO, 8 15 minute time periods for NO_x). Each distribution consists of 30 modelled concentrations at the receptor location. Since modelled concentrations are generated at 15 minute intervals, for the 2 hour simulation period, 8 distributions are evaluated for each pollutant. The Kolmogorov-

Smirnov test is used to check every distribution for a normal shape. At 98% confidence, all 16 distributions pass the test for a normal distribution. Figure 6-19 shows sample normal distribution curves for modelled CO and NO_x concentrations for one 15 minute interval. The mean and the standard deviation of each distribution are then calculated to obtain an average coefficient of variation for each pollutant. This coefficient of variation is 0.26 for the CO sample and 0.35 for the NO_x sample.

Figure 6-19 Sample Normal Distribution for QUIC Modelled Concentration at the Observed Sensor location for June 3, 2011 (7:15 - 7:30 AM, CO) and July 13, 2011 (8:30 - 8:45 AM, NO_x)

Even though QUIC is a fast response model, due to the complexity of the modelling domain, number of sources and simulation time period, the model runs are time consuming and resource intensive. For a complete analysis of the selected weekdays in June and July 2011, the total run time using a Microsoft Windows PC with 4GB RAM and 2.2 GHz processor is approximately 20 hours. It is practically infeasible to generate distributions of concentration values for each modelled day based on the analysis described above, since it would take approximately 600 hours of run time alone. Therefore, a margin of error due to random variation is computed on the modelled results, using the average coefficient of variations calculated above. For a single model run:

- 1) QUIC CO Analysis: With 75% confidence, the modelled concentration for a single replication is within $\pm 30\%$ of the expected value of the modelled concentration
- 2) QUIC NO_x Analysis: With 70% confidence, the modelled concentration for a single replication is within $\pm 37\%$ of the expected value of the modelled concentration

In calculating these intervals and error values, it is assumed that the coefficient of variation remains constant for all modelling days that belong to the same month. This assumption is justifiable since input atmospheric conditions for the morning peak period do not vary significantly within a month; note that a sample of eight different 15 minute interval traffic conditions has been tested with two wind speeds / directions (hourly averages) for each pollutant to estimate the average coefficient of variation.

Margin of error on QUIC modelled concentration presented in the following subsections are based on variability due to stochasticity within QUIC only. These bars do not include error in CMEM generated outputs due to random seed variation in PARAMICS. The confidence interval and margin of error calculated above also applies to modelled results developed in the sensitivity analyses described in Chapter 7.

6.1.3.1 CO – QUIC Predicted Vs Observed

For every weekday modelled in June 2011, QUIC estimates CO concentrations for eight 15 minute intervals spread over the 7:00 – 9:00 AM simulation period. Ambient CO concentrations are added to modelled values to estimate final predicted concentrations for comparison with the sensor observations. Based on this analysis, each modelled and observed CO data point is plotted together as shown in Figure 6-20. 20% of the predicted values are within a ‘factor of two’ of the observed values as shown in Figure 6-21.

Figure 6-20 Observed Vs QUIC Predicted, 15 minute averaged CO Concentration

Figure 6-21 QUIC CO: Predicted Vs Observed Concentration   Figure 6-22 QUIC Residual CO Concentration Vs Wind Speed

The predicted CO concentrations are generally higher than the observed values indicating that QUIC is consistently over predicting. The plot of residual concentration against wind speed, as shown in Figure 6-22, highlights the fact that as wind speed increases, the residual concentration value decreases. One of the possible reasons for QUIC over predicting CO concentrations could be error in the vehicle type distribution.

6.1.3.2 NO_x – QUIC Predicted Vs Observed

For the 5 weekdays modelled in July 2011, NO_x concentration estimates are generated by QUIC for eight 15 minute intervals spread over 7:00 – 9:00 AM simulation period. Background concentrations for NO_x are estimated using the same methodology applied for AERMOD. All modelled and observed NO_x concentrations are plotted in Figure 6-23. The predicted and sensor observed concentration follow similar patterns and the differences are generally within the range of measurement / simulation error. 97% of predicted values are within a ‘factor of two’ of the observed values as shown in Figure 6-24. The QUIC model performance for NO_x is better than for CO. Figure 6-25 shows that as the wind speed increases the residual concentration decreases, suggesting that the model predicts higher concentrations at low wind speeds and vice-versa.

Figure 6-23 Observed Vs QUIC Predicted, 15 minute averaged, NO_x Concentration

Figure 6-24 QUIC NO_x: Predicted Vs
Observed Concentration

Figure 6-25 QUIC Residual NO_x
Concentration Vs Wind Speed

6.2 Performance Evaluation

6.2.1 Introduction

To make a consistent comparison between AERMOD and QUIC results, QUIC generated 15 minute average concentrations are aggregated to hourly values as plotted in Figure 6-26 (CO) and Figure 6-27 (NO_x). Two important observations are:

- 1) For CO, none of the QUIC predicted hourly averaged concentration values are within the 'factor of two' envelope, compared to AERMOD which has all its hourly averaged values within this factor.
- 2) For NO_x, all of the QUIC predicted hourly averaged values are within the 'factor of two' envelope compared to only 60% of AERMOD predicted hourly averaged values.

This indicates the modelling framework performs better for CO using AERMOD and for NO_x using QUIC. However, these mean values are being tested for only one location in the modelling domain. A visual analysis of the spatial distribution of pollutants (refer to Appendix B, Figure B3, B4, and B5 for sample graphs), shows that AERMOD occasionally estimates unrealistically

high concentration for both CO and NO_x on the roadway. These high concentration regions are located very close to the point sources modelled in AERMOD. Increasing the number of point sources could help spread the concentration better; however, model run time would increase considerably in that case. In comparison, the spatial distribution of pollutant concentrations modelled using QUIC looks more realistic. Specifically, QUIC results do not exhibit peaks / troughs of extremely high or low concentrations as observed for AERMOD results. Due to limited observed data, a comparison between the ‘modelling framework’ predicted concentrations and observed concentrations is not performed.

Figure 6-26 Hourly Average CO Concentrations, AERMOD Vs QUIC Vs Observed

Figure 6-27 Hourly Average NO_x Concentrations, AERMOD Vs QUIC Vs Observed

QUIC can model intra hour variability in concentrations. For example, in the case of NO_x, the coefficient of variation (CV) of predicted and observed concentrations calculated within the 2 hour modelling period is expressed as a percentage for the five days modelled as shown in Figure 6-28; a high CV value demonstrates the significance of modelling pollutants at finer averaging time periods, to capture high variability in concentrations. This graph suggests that concentrations can vary substantially within the hour; therefore, it would be useful to model pollutants at smaller averaging periods to capture the true variability in concentrations; the graph shows that on an average, QUIC can model the variation well (18%) compared to observed concentration (19%).

Figure 6-28 Coefficient of Variation of Hourly Concentration for QUIC Modelled and Sensor Observed Values, NO_x, Five Weekdays, July 2011

It is not possible to perform a similar analysis using AERMOD, since the minimum concentration output time resolution is 1 hour. An intra hour variation in concentration could be useful to analyse areas where higher pollutant concentrations are observed, and air pollution standards are frequently exceeded; QUIC would be more useful than AERMOD for that purpose.

6.2.2 Performance Evaluation

Performance measures can generally be divided into statistical measures of difference, and correlation measures comparing modelled and observed data points (Arya, 1999). Several statistical parameters have been proposed to evaluate predicted and observed concentrations since the 1980 AMS Workshop on Dispersion Model Performance (Fox, 1981). Weil, et al. (1992) conducted a detailed review of methods used to evaluate air-quality models. The most commonly suggested evaluation parameters are the bias (d) between predicted and observed concentrations, the gross error (GE, bias of the absolute difference between the predicted and observed concentrations), and variance of the difference (Arya, 1999). The bias and gross error are defined as:

$$d = (m - o)_n$$

$$GE = \text{Mod } |(m - o)_n|$$

Where, m : n th reading of modelled concentration

o : n th reading of observed concentration

Other measures that are widely used include the fractional bias (FB) (Irwin & Smith, 1984) and the fractional scatter (FS) (Cox & Tikvart, 1985). FB and FS specify the ability of the model to reproduce the average, and the breadth of the observed concentrations, respectively. They are defined as follows:

$$FB = 2 \frac{M-O}{M+O} \qquad FS = 2 \frac{S_m-S_o}{S_m+S_o}$$

Where,

M: Mean modelled concentration

O: Mean observed concentration

S_m: Standard deviation of modelled concentration

S_o: Standard deviation of observed concentration

For the calculation of FB and FS, typically, only the highest 25 concentrations are evaluated in an unpaired state of time and location. This means that the highest predicted and observed concentrations are evaluated regardless of their time of occurrence or location of measurement. Such a comparison is scientifically flawed and has been criticised by Zannetti (1990). A more stringent measure is a paired comparison where the time and location of predicted and observed concentrations are fixed. The latter is adopted in for both FB and FS estimation. Additionally, instead of only measuring the top 25 concentrations, all data records are evaluated to provide a stricter test for the modelling framework performance. FB and FS values range from +2 (indicating high over-prediction) to -2 (indicating high under-prediction). It is important to note that in case of AERMOD only 10 concentration values are predicted for each pollutant, therefore, only those values have been used for estimation of these statistical parameters.

Zannetti (1990) proposed several methods for evaluating dispersion models including the Pearson correlation coefficient (R), the regression line passing through the origin, and frequency distribution analyses of the residual values, among others. The Pearson correlation coefficient is an indicator of the strength of the linear relationship between the predicted and the observed concentration value. Ideally this value should equal 1 for perfect replication of observed concentrations by the model. The regression line captures the fit of the observed data to the predicted value; the slope of the line generally indicates whether the model is over-predicting or under-predicting. Additional measures include the normalized mean square error (NMSE)

(Hanna & Heinold, 1985) and the ‘factor of two’ comparison (F2) (introduced earlier in this chapter). The NMSE is defined as follows:

$$NMSE = \frac{\overline{(m - o)^2}}{M \cdot O}$$

Where,

M: Mean modelled concentration

O: Mean observed concentration

m: Modelled concentration for one reading

o: Observed concentration for one reading (the bar on numerator indicates values are averaged over all data records)

Table 6-1 provides a summary of all the statistical performance evaluation parameters analysed for comparison between AERMOD and QUIC. Hourly results for QUIC are generated by aggregating the 15 minute averaged results for better comparison with AERMOD. ‘d’ and ‘GE’ represent the average value for the complete data record; these values are in ppm for CO and mg/m³ for NO_x. The Pearson correlation coefficient (R_p) measures the correlation between observed and predicted concentrations.

The performance of both dispersion models varies for both pollutants. QUIC performs better for NO_x, while AERMOD performs better for CO. However, AERMOD has a negative correlation for CO concentrations indicating that as observed concentrations increase, AERMOD predicted concentrations decrease; QUIC, on the other hand, has a positive correlation. This indicates that even though the ‘factor of two’ performance of AERMOD is better than QUIC, it is not able to accurately replicate the observed trends of CO concentrations. For CO, QUIC has a high positive FB and FS value indicating over-prediction; whereas AERMOD has a negative value for FB and FS indicating under-prediction; the NMSE is large for QUIC and quite small for AERMOD. QUIC has a higher correlation with predicted values for NO_x than AERMOD; the smaller FB and FS values confirm that QUIC performs better than AERMOD for NO_x.

Table 6-1 Statistical Performance Evaluation of AERMOD and QUIC

Statistical Parameter	AERMOD CO Hourly	AERMOD NO _x Hourly	QUIC CO 15-min	QUIC NO _x 15-min	QUIC CO Hourly	QUIC NO _x Hourly
D (ppm or mg/m ³)	-0.004	-0.025	0.460	-0.00006	0.460	-0.00006
GE (ppm or mg/m ³)	0.053	0.025	0.460	0.014	0.460	0.011
Var.	0.004	0.0001	0.066	0.0003	0.029	0.0002
R _p	-0.204	0.353	0.122	0.392	0.432	0.674
F2	100%	60%	20%	97.5%	0%	100%
FB	-0.017	-0.671	1.000	-0.001	1.000	-0.001
FS	-0.211	-0.880	1.333	0.365	1.213	0.499
NMSE	0.071	0.587	1.736	0.139	1.497	0.068

6.3 Comments

The proposed micro-modelling framework is validated for both AERMOD and QUIC at their respective scale of averaging concentrations for both pollutants with some reservations. Following are key remarks on this validation process:

- 1) AERMOD performs better than QUIC for CO, although, it has negative correlation between predicted and measured concentration values.
- 2) QUIC performs very well for NO_x with a fairly high positive correlation between the predicted and measured concentration values.
- 3) QUIC predicts higher concentrations compared to AERMOD for both pollutants possibly because it can explicitly take the effect of street canyon into account. Therefore, the recirculation of pollutants is modelled more comprehensively by QUIC.

Chapter 7

7 Sensitivity Analyses

Sensitivity analyses is undertaken to better understand the behaviour of the QUIC dispersion model and observe the scale of variation in modelled concentrations as input parameters are altered. QUIC is selected for the following reasons:

- 1) The validation results obtained for CO and NO_x indicate that QUIC outperforms AERMOD for NO_x. Although AERMOD performs better for CO, it has a negative correlation indicating that pollutant trends are not being modelled properly by AERMOD. A visual analysis of the overall spatial distribution suggests that concentration contours in QUIC are much more realistic and do not exhibit peaks / troughs of extremely high / low concentrations as observed for AERMOD results.
- 2) Using QUIC, concentration plots can be generated at a fine time scale, that could be used to analyse ‘hot-spots’ of population exposure within a given peak hour period. Such an analysis is not possible in AERMOD due to hourly average concentration outputs.
- 3) The finer time averaging period exploits the benefit of using a traffic microsimulation model to simulate traffic movement better. Thus, QUIC seems to have functionality that better suits a micro-modelling approach.

7.1 Input Parameters

Randomly selected weekdays are used to perform these sensitivity analyses. All modelled concentrations are generated at the observed sensor location. Ambient concentrations are not added to the modelled concentrations, since the intent of this analysis is to only capture the scale of variation in modelled concentrations. The following parameters are analysed:

- 1) Horizontal Wind Speed / Direction
- 2) Total Traffic Volume
- 3) Vehicle Type Distribution
- 4) Atmospheric Stability
- 5) Time Step

7.1.1 Mean Wind Speed and Direction

The hourly mean horizontal wind speed is specified at the St. George and College Street intersection at (X=353.6 m, Y=222.7 m) in the QUIC modelling domain. The experimental design for this sensitivity is given in Table 7-1. 12 different cases are analysed for different wind speeds and directions. The range of wind speeds to be tested is based on observed wind data analysis. Approximately 90% of all observed winds, for the morning peak period between 7:00 – 9:00 AM for June and July 2011, are in the range of 0.5 m/s - 5.7 m/s. It should be noted that the wind speed / direction values are hourly averages, even though concentrations are being averaged at 15 minute intervals in QUIC. June 3, 2011 is randomly selected for this analysis. All input parameters, including traffic volume and other meteorological data are kept constant, and the wind speed / direction are varied based on the experimental design. The results obtained are shown in Figure 7-1.

Table 7-1 Wind Speed Sensitivity Experimental Design

Wind Speed / Direction (blowing from, clockwise from north)	1 m/s	3 m/s	6 m/s
0°	✓	✓	✓
90°	✓	✓	✓
180°	✓	✓	✓
270°	✓	✓	✓

As observed, QUIC is highly sensitive to wind conditions. The highest concentrations are observed for 1 m/s wind speed, while the lowest concentrations are observed at the highest wind speed of 6 m/s due to transport of pollutants away from the modelling receptor location. The 270° wind angle results in the highest concentration for a given wind speed possibly due to effect of recirculation of pollutants in the street canyon at that wind angle and location of the measuring sensor on the north side of College Street. The standard deviation of concentration obtained for different wind speed and direction combinations is plotted at 15 minute intervals as shown in Figure 7-2. The standard deviation values imply that the variation in modelled concentration is high for different wind conditions. This implies that horizontal wind speed is a critical factor in

pollutant dispersion. The average coefficient of variation is very high (0.96), which highlights the underlying need to accurately model wind for a dispersion analysis.

Figure 7-1 Wind Sensitivity, QUIC Modelled CO Concentrations, June 3, 2011

Figure 7-2 Wind Speed, Standard Deviation, June 3, 2011

7.1.2 Traffic Volume

The total traffic volume on the network can be varied by changing the divisor of the O-D matrix in PARAMICS. Modelled concentrations are analysed using five traffic volumes for randomly selected days in June (for CO) and July (for NO_x). The following cases are evaluated:

- 1) 70% of current traffic (0.7x, where x = current O-D matrix input)
- 2) 80% of current traffic (0.8x)
- 3) 100% of current traffic (1x, existing O-D matrix input)
- 4) 120% of current traffic (1.2x)
- 5) 130% of current traffic (1.3x)

The results obtained are shown in Figure 7-3 and 7-4. Since all other input parameters are kept constant, if the total traffic volume is increased, the total emissions on the network should increase. Both CO and NO_x generally show this trend. A few anomalies are observed in NO_x results; however, it should be noted that NO_x concentrations are generated at 70% confidence interval with 37% error on mean. Nonetheless, the NO_x analysis is redone with a different random seed input and the results are plotted again as shown in Figure 7-5. The new NO_x results show the expected trend of increasing concentrations with increase in traffic.

Figure 7-3 Impact of Traffic Change on CO Concentration, June 24, 2011

The average coefficient of variation is 0.45 for CO and 0.36 (-100 random seed) / 0.41 (-367 random seed) for NO_x. This indicates that emission variations due to traffic are roughly half of the variations observed due to changing wind speed. The variation observed for NO_x concentrations is smaller than CO, likely due to a very small presence of heavy vehicle / trucks

(which are a major source of NO_x) on the network; the net increase in total heavy vehicle traffic for the five traffic conditions analysed is insignificant, causing the modelled concentrations to not vary a lot.

Figure 7-4 Impact of Traffic Change on NO_x Concentration, July 12, 2011; Random No. -100

Figure 7-5 Impact of Traffic Change on NO_x Concentration, July 12, 2011; Random No.-367

7.1.3 Vehicle Type Distribution

The objective of this sensitivity is to test the impact of varying the distribution of vehicle types on modelled concentration. The randomly chosen days for this analysis are June 10 (CO) and July 27 (NO_x), 2011. The different vehicle distributions used are shown in Table 7-2. Four cases are analysed as follows:

- 1) The base case represents the original vehicle type distribution used for validation.
- 2) Case 1 is a 'clean' scenario where 65.13% of vehicles in Light Vehicle (LV) matrix are ultra low emissions vehicle. The tier 1, High P/W passenger car (CMEM categories 9 and

- 11) proportion is reduced to zero in LV matrix. All heavy duty trucks are assigned to CMEM category 7 in the Medium/Heavy Vehicle (MHV) matrix, which is the latest version of heavy duty truck available in CMEM.
- 3) Case 2 is a ‘very clean’ scenario where 97.59% of vehicles in LV matrix are ultra low emissions vehicle. All medium duty trucks are assigned to CMEM Category 40, which is a diesel powered truck, in MHV matrix.
- 4) Case 3 is an ‘unclean’ scenario where the ultra low emission vehicle proportion from Case 2 is distributed among all the other vehicle categories within LV matrix. MHV matrix composition is unchanged from Case 2.

Table 7-2 Vehicle Type Distribution for Sensitivity Analyses

		BASE CASE	Case 1 CLEAN	Case 2 VERY CLEAN	Case 3 UN- CLEAN
MEDIUM/HEAVY VEHICLE MATRIX (MHV)					
CMEM Category	Description	(PERCENTAGE OF TOTAL)			
25	Truck, Gasoline powered, LDT (>8500GVW)	10.02	10.02	0.00	0.00
40	Truck, Diesel powered, LDT (>8500GVW)	66.45	66.45	76.47	76.47
5	HDD 1994-1997, 4 stroke engine, Electric, FI, Normal emitting	4.8	0.00	0.00	0.00
6	HDD 1998, 4 stroke engine, Electric, FI, Normal emitting	1.11	0.00	0.00	0.00
7	HDD 1999-2002, 4 stroke engine, Electric, FI, Normal emitting	17.62	23.53	23.53	23.53
CAR/LIGHT VEHICLE MATRIX (LV)					
CMEM Category	Description				
8	Tier 1, >50K mi, Low P/W ratio	9.97	9.97	0.00	10.00
9	Tier 1, >50K mi, High P/W ratio	37.53	0.00	0.00	10.00
19	Runs Lean	0.5	0.50	0.00	10.00
20	Runs Rich	0.5	0.50	0.00	10.00
21	Misfire	0.8	0.80	0.00	10.00
22	Bad Catalyst	0.5	0.50	0.00	10.00
16	1988-1993,>3750 LVW	0.57	0.57	0.57	3.00
17	Tier 1 LDT2/3 (3751-5750 LVW or Alt LVW)	1.84	1.84	1.84	3.00
4	3 way catalyst, FI, >50K mi, Low P/W ratio	2.69	2.69	0.00	4.00
5	3 way catalyst, FI, >50K mi, High P/W ratio	10.67	10.67	0.00	10.00
10	Tier 1, <50K mi, Low P/W ratio	6.83	6.83	0.00	10.00
11	Tier 1, <50K mi, High P/W ratio	27.31	0.00	0.00	10.00
26	Ultra Low Emissions Vehicle	0.29	65.13	97.59	0.00

Figure 7-6 Vehicle Type Distribution Sensitivity, CO Concentration, June 10, 2011

Figure 7-7 Vehicle Type Distribution Sensitivity, NO_x Concentration, July 27, 2011

Figure 7-6 and 7-7 show the modelled concentration estimates for the different cases evaluated for CO and NO_x. The highest concentrations for both pollutants are observed for Case 3, when the high emitting passenger car proportion is increased and ultra low emission vehicle percentage decreased. The lowest concentrations are obtained for Case 2 which has the cleanest mix of vehicles. The average coefficient of variation for CO is 0.85 and for NO_x is 0.35. The difference in variation can be attributed to the fact that the distribution of MHV matrix is not varied very much compared to the LV matrix. Since trucks are the chief contributors of NO_x, the corresponding coefficient of variation for NO_x is less compared to CO.

7.1.4 Atmospheric Stability

Five different stability conditions, ranging from ‘highly unstable’ to ‘highly stable’, are developed for input into QUIC as shown in Table 7-3. Golder (1972) developed empirical relationships, relating the inverse Monin-Obukhov (M-O) length with surface roughness and stability classes defined by Pasquill (1974), which are employed by QUIC. The inverse M-O length is also used to develop the mean vertical wind profile in QUIC-URB. The potential temperature profile is developed based on the vertical variation in temperature. This vertical variation is assumed such that it generally represents the corresponding atmospheric stability.

Table 7-3 Atmospheric Stability Sensitivity Analysis Inputs

Stability Class	Inverse M-O length (in m^{-1})	Vertical Variation in temperature
Highly Unstable	-0.1	-0.8 degrees/50m height increase
Slightly Unstable	-0.01	-0.8 degrees/50m height increase
Neutral	0	-0.5 degrees/50m height increase
Slightly Stable	0.01	+0.8 degrees/50m height increase
Highly Stable	0.1	+0.8 degrees/50m height increase

The randomly selected day for this analysis is June 22, 2011. The results obtained from this analysis are presented in Figure 7-8. Apart from one high concentration value observed for the neutral condition, modelled concentrations are in the range of 0.5-2.0 mg/m^3 for all stability classes. Theoretically, highly stable conditions may cause higher concentrations due to low turbulence in the atmosphere; however, the results obtained do not reciprocate this particularly well. The average coefficient of variation is 0.56, which suggests that atmospheric stability is an important parameter, however no clear trend is observed from the graphical analysis. It is recommended to generate distributions for each estimated value in order to reduce error on modelled values and develop a more accurate graph depicting the pollutant concentration trend.

Figure 7-8 Atmospheric Stability Sensitivity, CO Concentration, June 22, 2011

7.1.5 QUIC Simulation Time Step

The simulation time step defines the interval after which the random walk model updates particle positions and turbulent velocities. When the modelling domain scale is of the order of life-sized buildings, it is recommended to use a time step of a few seconds (Los Alamos National Laboratory, 2010). For validation purposes, a fixed time step of 5 seconds is used, as described in Chapter 5. To test the sensitivity of the simulation time step, five cases are analysed; the value of the time step is varied from 0.1 - 8 seconds. The average coefficient of variation is 0.12 which illustrates that simulation time step is relatively less significant than other parameters evaluated in this study. However, care should be taken while selecting the time step. It is recommended to err on the positive side of time step due to presence of auto time step reduction algorithms within QUIC (Los Alamos National Laboratory, 2010).

Figure 7-9 Simulation Time Step Sensitivity, CO Concentration, June 13, 2011

7.2 Summary of Effects

The QUIC model was selected for further sensitivity analysis on account of its comprehensive methodology and applicability to the study area. Model sensitivity analysis indicates that horizontal wind speed is the most critical component in dispersion and hence, estimating this parameter correctly is essential to performing a satisfactory dispersion modelling study.

Characterising the full scale of variability caused due to each of these parameters is a cumbersome process. The complexity of comparing different parameters on the same scale is accentuated by the difference in sample space for each parameter. This sample space could be based on either scientific principles (for example, wind speed) or data limitations (for example, limited vehicle type distribution data availability). Future work includes reducing variability in estimates by generating distributions for each modelled concentration value to reduce stochastic model error. The summary of sensitivity analyses is illustrated in Table 7-4. Key remarks on each of these sensitivities are as follows:

- 1) The horizontal wind speed and direction is evidently the most dominating effect during dispersion of pollutants; the high coefficient of variation suggests that the impact of higher traffic volume or a polluting vehicle type distribution can be possibly offset by favourable wind characteristics that accelerate dispersion.
- 2) Vehicle type distribution is found to be a fairly significant input; only four cases are evaluated to obtain the coefficient of variations. These cases attempt to capture the maximum variation possible within the fleet; however, it is limited by the vehicle type availability within CMEM and practical considerations (for example, not all vehicles on the network can be heavy duty trucks).
- 3) Traffic volume is a significant factor when modelling traffic emissions. The coefficient of variations calculated for CO and NO_x are considerably high, indicating the need to have a good estimate of traffic volumes for input into traffic microsimulation.
- 4) The coefficient of variation for atmospheric stability is high. Theoretically, high instability should result in increased turbulence and better dilution of pollutants while high stability should result in calm periods where higher concentrations are observed.

Results obtained using QUIC do not show any clear trend. Performing a spatial distribution assessment coupled with better estimation of modelled concentration (with reduced error), could possibly provide a better understanding of the net impact of stability on overall concentrations in QUIC.

- 5) The simulation time step is observed to be the least significant among the factors analysed. Nonetheless, selecting a reasonable time step value is essential to obtain correct results in QUIC.

Table 7-4 Summary of Sensitivities and Average Coefficient of Variations

	Randomly Selected Day	Number of cases evaluated	Average Coefficient of Variation
Horizontal Wind Speed/Direction	June 3	12	0.96
Traffic Volume	June 24, July 12	5	0.45 (CO), 0.41 (NO _x)
Fleet Distribution	June 10, July 27	4	0.85 (CO), 0.35 (NO _x)
Atmospheric Stability	June 22	5	0.56
Simulation Time Step	June 13	5	0.12

Chapter 8

8 Limitations and Perspective

This chapter discusses the data errors and limitations within the modelling framework. It also contains a comparison of the predicted concentrations, with the National Ambient Air Quality Objective (NAAQO) standards of Environment Canada. This comparison is performed to give some perspective on the scale at which the modelling framework is estimating emissions.

8.1 Errors

Any model is an attempt to simulate processes that occur in real life using mathematical expressions. The air quality modelling framework proposed in this research uses three models to simulate the concentration of traffic pollutants in the study area. Inaccuracies are present in each model of the framework.

Modelling errors can be generally classified into data errors and model formulation errors. A quantitative analysis of all errors within the modelling framework is beyond the scope of this research. However, a subjective analysis is performed. Data errors associated with the modelling framework are listed in Table 8-1. The errors are classified into primary (errors that originate at a certain juncture in the methodology), and secondary (errors that are carried downstream in the process flow). The main secondary errors that form inputs to a downstream process in the methodology are italicized in the table.

It is difficult to quantify the errors associated with the mathematical behaviour of models individually. Each mathematical formulation that is used in the process of simulating emissions across all three modelling methodologies is subject to errors, and every equation contributes some error to the total value. There is likely some effect of ‘negative’ and ‘positive’ biases cancelling each other. Some of the mathematical model errors include - use of car following model to simulate driver behaviour (in PARAMICS), power demand modelling to estimate emission rates on roadway links (in CMEM), Gaussian formulation for approximating pollutant plume (in AERMOD), and Lagrangian formulation / parameterisation of turbulence for pollutant dispersion (in QUIC).

Table 8-1 Sources of Data Errors

Component	Errors
Traffic Microsimulation (PARAMICS)	- Network development in PARAMICS - Manual traffic survey count error - Regression modelling for estimation of traffic on network and turning percentage estimation - Monte-Carlo simulation for estimation of O-D matrices - Core simulation input parameters (mean headway, mean driver reaction time)
Emission Modelling (CMEM)	- Vehicle Type Distribution in CMEM; Local distribution estimate - <i>Driving Profile Output From PARAMICS; Network errors (eg. Grade)</i> - Modelled emission rate: Error on mean emission rate due to model stochasticity in PARAMICS.
Dispersion Modelling (AERMOD and QUIC)	- Network Development in AERMOD/QUIC - Building Data, Terrain Data - Modelled receptor Vs Observed sensor location - Emission source placement, (Line Sources: QUIC, Series of point sources: AERMOD); Source release height; <i>Input Source Emission Rates (from CMEM)</i> - Other parameters: Simulation time step, Boundary Layer Height, Grid size and resolution (QUIC); Bowen Ratio, (AERMET); Surface Roughness - <i>MM5 Prognostic Model Error in estimating meteorological dispersion inputs (horizontal wind, stability parameters, temperature, pressure, humidity, et cetera)</i> - Modelled Concentration (QUIC): Error on Mean Concentration due to model stochasticity
Observed Data (SOCAAR)	- Observed pollutant concentration data - Observed traffic data on College Street

8.2 General Limitations

In addition to the limitations associated with data availability and data quality listed in Table 8-1, other general limitations of the study include the following:

- 1) The complex chemistry of NO_x transformation in the atmosphere is not modelled.
- 2) Dry and wet deposition of pollutants is not considered. Wet deposition is not relevant to this study, especially, due to negligible or no rain during the study period.
- 3) Only the morning peak traffic period between 7:00 - 9:00 AM is evaluated for ten selected weekdays during the months of June and July 2011. A continuous daily analysis is not performed due to restrictions on detailed traffic data availability for other periods of time.
- 4) All modelled concentrations are compared with sensor observations for a single location; spatial distribution of pollutants is not analysed in this study.
- 5) Traffic induced turbulence is not accounted for, even though it can be a significant parameter in urban pollutant dispersion (Kastner-Klein, et al., 2003).

8.2.1 Comparison of Dispersion Models

QUIC and AERMOD form the most significant component of this modelling framework. A comparison of the two methodologies gives some insight on which model is better for dispersing traffic pollutants in urban areas. Some of the major differences and limitations in methodologies are highlighted in the following sub sections.

8.2.1.1 AERMOD

- 1) AERMOD is steady state Gaussian model; therefore, it is insensitive to time in modelling concentrations. The model is run separately for each of the two hours during the morning peak period, such that concentrations in the following hour are not affected by concentrations from the previous hour.
- 2) AERMOD simulates atmospheric phenomena much more comprehensively than QUIC. However, it uses a single value of wind speed, turbulent coefficients, and temperature

gradient to represent the layer in which dispersion occurs. Thus, vertical inhomogeneity is diluted to obtain 'effective' values.

- 3) AERMOD provides better results for CO (albeit with a negative correlation compared to observed concentrations), but estimates unrealistically high concentrations very close to the emission source. This is a result of modelling line sources as a series of point sources.
- 4) In AERMOD, building downwash is only estimated for point sources; the effect of buildings cannot be incorporated with volume / area sources, which are better representative of roadway emissions. The effect of buildings is not modelled entirely in AERMOD.
- 5) AERMOD model runs are faster. Total runtime for simulating morning peak period traffic emissions for two pollutants for ten weekdays is ~10 hours.

8.2.1.2 QUIC

- 1) QUIC is a Lagrangian particle model and tracks the movement of individual pollutant particles using a non-steady state approach. Thus, modelled concentrations are sensitive to previous time periods.
- 2) For continuous dispersion analysis of an entire day, the input meteorological parameters in QUIC would need to be revised (since their values change during the day); in such a case, some assumptions would have to be made regarding the dissipation of pollutants, so that model runs can be staggered to incorporate a longer continuous time period.
- 3) QUIC computes varying mean wind flow and turbulent velocity for each grid in the space, and stores that value for use during the dispersion computation. It has seemingly more realistic flow characterisation around buildings.
- 4) Consequently, QUIC concentration contours look visually reasonable compared to AERMOD. Concentration close to source does not increase to extremely high values as in AERMOD. The ability to model roadway links as line sources is an advantage in QUIC.
- 5) QUIC can model flow around buildings much more comprehensively than AERMOD and this makes it more relevant, as a dispersion tool, to be applied in urban areas; on the micro-scale, QUIC seems to be a promising tool for estimating traffic pollutant concentration.

- 6) QUIC model runs are slower compared to AERMOD. Total runtime for simulating morning peak period traffic emissions for two pollutants for ten weekdays is ~20 hours.

8.3 Comparison with NAAQO Standards

The performance evaluation of the modelling framework suggests that for the given receptor location, AERMOD and QUIC perform better for CO and NO_x, respectively. It is imperative to acknowledge the scale of concentration at which the modelling framework is operating. Interpreting model results is a challenging task, and therefore, predicted values are compared with air pollution standards to give some perspective on modelling framework results.

The hourly threshold values for the Maximum Acceptable Level (MAL) and for CO and NO₂ as specified in the National Ambient Air Quality Objectives (NAAQO) of Canada (Environment Canada, 2010) are plotted against the predicted and sensor observed values in Figure 8-1 and 8-2. NO_x emissions are compared to NO₂ values in the absence of separate criteria for total NO_x concentrations.

The predicted and observed CO concentrations are approximately 30 times smaller than the NAAQO MAL. The difference between predicted concentrations (both QUIC and AERMOD generated) and observed concentrations becomes indistinguishable at this scale. For NO₂, the MAL is approximately 8 times larger than the observed and predicted concentrations, yet again, setting the difference between observed and predicted values into perspective.

Figure 8-1 Predicted, Observed and NAAQO Hourly MAL, CO concentration

Figure 8-2 Predicted, Observed (NO_x) and NAAQO Hourly MAL (NO₂) concentration

Chapter 9

9 Conclusion

Urban air pollution modelling is an important exercise towards quantifying the adverse effects of traffic emissions on people. As the world population increases and more people begin to live in highly urbanized, densely populated cities, measuring the health impact of poor urban air quality has become extremely significant. With advancements in computing technologies that reduce model runtime, use of complex integrated methodologies for evaluating urban emissions is becoming a major area of research. This research applies a similar integrated methodology to evaluate emissions on a traffic network in Toronto with some encouraging results.

Pielke (1979) spoke of air pollution not just being an issue of poor emissions, but an inter-related weather associated phenomenon, a weather hazard. The integrated micro-modelling methodology adopted in this research stands in agreement with this observation. Horizontal wind is found to be the most significant factor causing advection and dispersion of pollutants, which is capable of negating the adverse impact of higher traffic volume or polluting engine technologies.

Availability of good quality observed pollutant concentration data is important and therefore accurate data monitoring continues to remain a key component of traffic emission modelling. Meteorological data quality is also of utmost importance to air pollutant dispersion studies. For a micro-modelling approach operating on a fine time resolution, availability of disaggregate weather data is useful to avoid generating erroneous outputs and inferring incorrect conclusions.

9.1 Summary and Contribution

Following is a list of key points summarising the work, contribution and findings of this research:

- 1) An integrated approach to estimate traffic related emissions on the micro-scale is adopted and successfully executed. The modelling framework consists of a combination of traffic microsimulation model, microscopic emissions model, and two dispersion modelling methodologies such that a consistent level of detail is maintained throughout the modelling framework.

- 2) Regression modelling is combined with a manual traffic count survey to generate synthetic micro scale traffic flows on the network for the entire study period for input into traffic microsimulation model.
- 3) The performance of AERMOD and QUIC, two different dispersion modelling methodologies is evaluated. AERMOD performs better for CO while QUIC performs well for NO_x. AERMOD predicts unrealistically high concentration levels very close to the roadway point source.
- 4) The applicability of the proposed modelling framework by comparing predicted concentrations for CO and NO_x with sensor observed concentrations is validated. Model predicted results are compared with sensor observed values with reasonable accuracy. Due to absence of multiple pollutant observing sensors on the network, a comprehensive analysis of the spatial variation of the pollutant concentrations could not be performed.
- 5) Comparison of results with the NAAQO standards brings the difference between observed and predicted concentrations into perspective for both pollutants and signifies the fine scale at which the modelling framework is estimating emissions.
- 6) A sensitivity analyses is performed on input factors and their effects on modelled concentrations. The key parameters are organised in accordance with their degree of importance to the modelling framework. It is affirmed that the horizontal mean wind speed is the most significant important parameter for dispersion.
- 7) Ambient concentration estimates are useful in making a consistent comparison between predicted and observed concentrations. Estimates of ambient concentrations from local monitoring stations confirm the reliability of using these values to augment modelled value to compute final 'predicted' values. If a correct estimate of ambient concentrations is available, the proposed modelling framework can be applied to estimate morning peak hour traffic emissions for other local areas. The location of the monitoring stations used for ambient concentration estimation should ideally represent similar traffic conditions / environment as the modelling area.

9.2 Future Work

There is significant benefit in amalgamating modelling systems that have historically been separated from each other. A robust system that could integrate micro-modelling methodologies for urban air pollution estimation will be valuable for jurisdictions across the world to analyse

local air quality, and take informed decisions to comply with air pollution standards. It is however important to acknowledge that model errors may increase with intensive input data requirements. This research is a step towards a truly integrated approach of micro-modelling exposure of population to pollutants in a dynamically changing environment where numerous parameters exhibit temporal and spatial variations. This research forms the first component of the street level exposure modelling framework shown in Figure 9-1.

Figure 9-1 Street Level Exposure Micro-Modelling Framework

One important area that requires further attention in this field is developing methods for estimating accurate local vehicle type distribution including corresponding emission data. This research warrants a further investigation into each component of the modelling framework to develop a better understanding of the complexity involved in modelling urban traffic emissions. This work could be further developed by installing multiple sensors in the study area and validating spatial patterns of air pollutants. Spatial microsimulation of pollutants for sustained periods of time can provide useful data that could be used for evaluation of population exposure to local traffic emissions. This requires a fourth component that deals with data collection and modelling of pedestrian movements on the street network. It is a strong hope that this research will lead to the development of a comprehensive, well defined population exposure modelling system for traffic emissions.

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Appendices

Appendix A

A1. O-D Matrix Estimation

Regression models developed to generate synthetic traffic flows on the study network based on traffic sensor observations made on the College Street (slightly west of the intersection) are shown. CL: Cars / Light Vehicles (CL), MH: Medium / Heavy Vehicles. 'Total College' = total eastbound and westbound traffic observed west of the intersection; EB: Eastbound, WB: Westbound, SB: Southbound, NB: Northbound; the straight line denotes the regression model predictions.

MH EB Russell

CL EB Russell

CL WB Galbraith

CL SB KC Circle

MH WB College (East of Intersection)

CL WB College (East of Intersection)

MH SB Huron

CL SB Huron

NB St. George MH

NB St. George CL

SB St. George MH

SB St. George CL

NB Beverly MH

NB Beverly CL

SB Beverly MH

SB Beverly CL

Figure A1 Regression Models for OD Matrix Estimation

For truck regression models, only data with non-zero values are used for estimation. All estimated traffic volumes are rounded down to the lower integer value; a sample of the table generated for some locations within the network for the June 3, 7:00-8:00 AM is shown below.

Table A1 Synthetic Traffic Generated using Regression Models (some locations)

Time	CL	MH	CL	MH	CL	MH	CL	MH	CL	MH	CL	MH	CL	MH	CL	MH
Date/Time	EB College		WB College		NB St. George		SB St. George		NB Beverley		SB Beverley		SB Huron		SB KC Circle	
03/06/2011 7:15	177	1	144	4	56	1	106	0	50	1	77	0	18	0	9	0
03/06/2011 7:30	215	1	128	6	60	1	113	1	53	1	82	1	19	0	10	0
03/06/2011 7:45	200	1	162	8	63	1	119	1	56	1	87	1	20	0	11	0
03/06/2011 8:00	227	2	132	7	63	1	118	1	56	1	86	1	20	0	11	0

Table A2 Sample Turning Percentage for Cars and Light Duty Vehicles between 7:15 – 7:30 AM; S: South, W: West, E: East, N: North; L: Left, R: Right, T: Through

			STI			WTI			NTI			ETI	
		SL	ST	SR	WL	WT	WR	NL	NT	NR	EL	ET	ER
Russell	In												
Russell			0.87	0.13				0.12	0.88		0.00		1.00
Galbraith	In												
Galbraith		0.20	0.80		0.15		0.85		0.96	0.04			
ISC N	In												
ISC N		0.01	0.99		0.00		0.00		1.00	0.00			
ISC S	In												
ISC S		0.00	1.00		0.00		0.00		1.00	0.00			
College	In												
College		0.48	0.44	0.08	0.01	0.75	0.24	0.27	0.51	0.22	0.01	0.93	0.06
Cecil	In												
Cecil		0.06	0.91	0.03	0.00	0.00	0.00	0.09	0.85	0.07	0.33	0.17	0.50
Huron	In												
Huron		0.33	0.33	0.33	0.06	0.80	0.14				0.01	0.97	0.02
Ross	In												
Ross						1.00		0.00		0.00		1.00	
Henry	In												
Henry					0.02	0.98						0.99	0.01
King's	In												
King's		0.00		1.00		0.92	0.08				0.02	0.98	

Table A3 Traffic Distribution on College Street East of Bathurst – City of Toronto Cordon Count Data (Database: toro09)

Table A3 City of Toronto Cordon Count Data

	start	end	CAR and LIGHT TRUCKS									MEDIUM AND HEAVY DUTY TRUCKS				
	time	time	auto1	auto2	auto3	auto4	cab1	cab2	cab3	cab4	truck_l	truck_m	truck_h	truck_tr	oth_bus	sch_bus
225E EB	701	900	803	353	17	4	97	11	5	0	25	17	11	0	6	11
225W EB	701	900	413	136	2	2	124	15	1	0	54	9	5	1	3	5

Appendix B

B1. CMEM Emission Output Processing

Snapshot of emission summary file below shows the first time step of 15 minutes from 7:00-7:15 AM for July 7, 2011 (PARAMICS random seed 6)

Time Slice: 1 Time Gap 900 (sec.) Simulation Time 900 (sec.)

Cummulative Emissions (grams)

Link ID:	Sample Size:	CO2	CO	HC	NOx	Fuel
1:59	135	826.46	4.33	0.20	2.64	261.56
1:74	342	1338.51	11.75	0.40	1.56	428.19
1:60	85	401.37	3.76	0.14	0.54	128.54
1:44	390	1870.05	16.28	0.70	2.57	598.30
2:73	193	295.56	5.46	0.11	0.20	95.99
2:74	396	607.90	1.49	0.11	0.47	192.48
3:71	18	30.91	0.12	0.02	0.03	9.82
3:70	285	767.54	7.99	0.39	0.82	246.33
3:69	39	160.36	1.69	0.03	0.18	51.42
3:72	389	1318.60	26.32	0.79	2.07	429.54
4:5	15	19.69	0.02	0.00	0.01	6.21
6:7	12	18.33	0.03	0.00	0.00	5.80
6:71	295	389.24	3.68	0.23	0.37	124.77
7:6	24	82.10	0.57	0.04	0.14	26.20
8:9	130	197.96	0.39	0.15	0.14	62.76
8:70	236	1767.30	320.71	3.28	3.55	719.46
9:8	285	1839.34	47.61	1.06	3.39	604.52
10:64	93	645.20	1.50	0.14	3.14	202.45
10:66	1	0.85	0.00	0.00	0.00	0.27
10:67	37	57.56	0.13	0.01	0.01	18.22
10:65	8	7.77	0.00	0.00	0.00	2.45
11:12	1	0.85	0.00	0.00	0.00	0.27
11:66	0	0.00	0.00	0.00	0.00	0.00
12:11	0	0.00	0.00	0.00	0.00	0.00
13:67	74	1084.31	22.83	0.43	3.99	351.89
13:14	15	24.86	0.05	0.00	0.00	7.87
14:13	78	422.70	2.28	0.11	1.20	134.09
15:65	0	0.00	0.00	0.00	0.00	0.00
15:16	7	6.46	0.00	0.00	0.00	2.04

16:15	0	0.00	0.00	0.00	0.00	0.00
17:68	0	0.00	0.00	0.00	0.00	0.00
18:17	0	0.00	0.00	0.00	0.00	0.00
19:20	204	752.95	4.44	0.19	1.92	239.13
19:58	145	203.33	0.37	0.03	0.06	64.31
19:25	105	150.99	0.46	0.04	0.11	47.86
20:23	118	228.85	0.43	0.05	0.64	72.16
20:57	39	155.01	0.96	0.05	0.23	49.39
20:19	316	731.01	4.23	0.18	0.69	232.72
21:22	18	23.49	0.04	0.01	0.02	7.43
21:57	37	306.39	3.79	0.11	0.48	98.57
22:21	24	54.83	0.23	0.01	0.06	17.41
23:24	57	125.13	0.29	0.02	0.36	39.47
23:20	122	648.45	11.36	0.36	1.12	210.42
24:23	148	736.25	7.08	0.29	1.35	235.90
25:19	83	106.20	0.15	0.01	0.03	33.56
25:26	47	52.51	0.09	0.01	0.01	16.60
26:25	33	96.61	0.39	0.02	0.10	30.66
27:47	139	282.77	9.65	0.14	0.17	94.07
27:53	7	25.57	0.27	0.01	0.05	8.21
27:48	221	367.66	0.85	0.05	0.09	116.37
28:29	3	3.70	0.01	0.00	0.00	1.17
30:51	36	80.15	0.35	0.03	0.12	25.47
30:48	195	413.28	2.10	0.09	0.34	131.41
30:49	168	299.61	0.73	0.04	0.10	94.85
31:32	23	30.90	0.10	0.01	0.02	9.79
31:52	18	19.33	0.02	0.00	0.00	6.11
32:31	18	43.02	0.14	0.01	0.04	13.64
33:50	129	1392.03	329.69	3.13	3.03	605.46
33:34	171	314.11	0.73	0.07	0.17	99.45
34:33	249	1599.36	32.83	0.67	2.61	521.14
35:43	162	343.24	0.82	0.10	1.40	108.03
35:36	209	532.60	3.56	0.20	0.63	169.87
35:56	0	0.00	0.00	0.00	0.00	0.00
36:35	129	234.80	0.48	0.05	0.61	74.08
36:59	219	759.07	43.94	0.54	1.05	261.62
36:55	0	0.00	0.00	0.00	0.00	0.00
38:56	4	4.27	0.00	0.00	0.00	1.35
38:39	0	0.00	0.00	0.00	0.00	0.00
39:38	4	6.65	0.01	0.00	0.00	2.10
40:55	0	0.00	0.00	0.00	0.00	0.00
40:41	0	0.00	0.00	0.00	0.00	0.00
41:40	0	0.00	0.00	0.00	0.00	0.00
37:61	65	138.63	0.31	0.03	0.41	43.72
37:62	44	67.02	0.12	0.01	0.01	21.19
42:60	142	230.02	0.44	0.09	0.50	72.67
42:61	43	58.61	0.11	0.02	0.03	18.56
43:58	103	586.98	1.22	0.12	3.08	184.23
43:35	171	414.32	1.71	0.11	0.49	131.57
44:1	884	1226.94	3.19	0.22	0.64	388.57
44:45	135	942.26	64.41	0.81	1.45	329.79
45:44	350	526.98	1.52	0.11	0.50	166.99
45:46	200	1652.36	367.53	3.66	3.42	706.83
46:45	172	271.12	6.67	0.10	0.22	88.88
46:47	148	212.62	0.56	0.17	0.15	67.48
47:46	141	236.41	7.74	0.12	0.21	78.48
47:27	177	283.69	0.59	0.08	0.13	89.80

48:27	141	373.14	21.63	0.25	0.37	128.61
48:30	251	412.59	0.91	0.06	0.11	130.58
49:30	103	171.46	0.31	0.03	0.09	54.23
49:50	171	328.60	0.83	0.05	0.22	104.05
50:49	146	448.59	52.29	0.58	0.63	167.93
50:33	165	267.81	0.69	0.13	0.18	84.90
51:52	28	31.09	0.07	0.00	0.00	9.84
51:30	19	25.98	0.04	0.00	0.01	8.21
52:31	31	34.83	0.07	0.00	0.00	11.02
52:51	19	21.17	0.03	0.00	0.00	6.69
53:54	3	20.42	1.00	0.02	0.05	6.95
54:28	5	5.18	0.01	0.00	0.00	1.64
55:36	0	0.00	0.00	0.00	0.00	0.00
55:40	0	0.00	0.00	0.00	0.00	0.00
56:35	3	3.21	0.00	0.00	0.00	1.01
56:38	0	0.00	0.00	0.00	0.00	0.00
57:21	25	103.57	1.32	0.04	0.13	33.34
57:20	48	86.39	0.28	0.04	0.07	27.41
58:19	65	451.85	2.43	0.13	1.48	143.07
58:43	189	300.33	0.60	0.04	0.13	95.01
59:36	61	195.77	0.54	0.04	0.67	61.69
59:1	763	1346.70	156.77	1.64	1.53	503.92
60:1	540	1024.68	12.67	0.28	2.11	328.43
60:42	38	194.20	12.94	0.13	0.27	67.77
61:42	69	157.91	0.45	0.04	0.47	49.88
61:37	43	62.63	0.12	0.01	0.01	19.81
62:37	64	139.10	0.30	0.03	0.39	43.86
62:63	52	83.33	0.18	0.01	0.02	26.37
63:62	76	159.15	0.33	0.03	0.47	50.17
63:64	42	72.39	0.16	0.01	0.04	22.91
64:63	50	91.44	0.21	0.03	0.28	28.88
64:10	41	58.59	0.11	0.01	0.02	18.53
65:10	0	0.00	0.00	0.00	0.00	0.00
65:15	10	9.82	0.01	0.00	0.01	3.10
66:11	2	1.70	0.00	0.00	0.00	0.54
66:10	0	0.00	0.00	0.00	0.00	0.00
67:10	36	552.16	57.39	0.59	1.95	202.33
67:13	30	46.27	0.09	0.00	0.00	14.63
68:2	0	0.00	0.00	0.00	0.00	0.00
69:4	27	77.96	0.26	0.02	0.10	24.72
70:8	171	1382.46	234.71	2.46	2.80	554.68
70:3	535	784.97	26.48	0.63	0.59	261.23
71:6	19	26.41	0.05	0.00	0.01	8.36
71:3	515	594.85	1.29	0.13	0.17	188.29
72:3	395	522.13	0.96	0.09	0.20	165.17
72:73	209	1541.32	255.13	2.68	2.86	615.11
73:72	217	347.10	0.66	0.04	0.10	109.78
73:2	230	332.59	3.61	0.23	0.25	106.87
74:2	237	1672.73	285.26	2.78	2.97	671.56
74:1	1341	1857.38	9.45	0.38	1.25	590.58
2:68	0	0.00	0.00	0.00	0.00	0.00
4:69	0	0.00	0.00	0.00	0.00	0.00
5:4	0	0.00	0.00	0.00	0.00	0.00
17:18	0	0.00	0.00	0.00	0.00	0.00
28:54	0	0.00	0.00	0.00	0.00	0.00
29:28	0	0.00	0.00	0.00	0.00	0.00
53:27	0	0.00	0.00	0.00	0.00	0.00

54:53	0	0.00	0.00	0.00	0.00	0.00
68:17	0	0.00	0.00	0.00	0.00	0.00
69:3	0	0.00	0.00	0.00	0.00	0.00

These values are input into an Excel Spreadsheet Model that calculates emission rates for the point / line sources specified in AERMOD / QUIC. These models output the following:

- 1) Formatted excel input emissions worksheet (for AERMOD)
- 2) Input text emissions file 'QP_source.inp' (for QUIC)

Emission rate is specified as mass flow rate for both dispersion models, therefore the cumulative emissions are divided by the 'time gap' to obtain effective grams released per second for the particular time interval. In case of AERMOD, line sources are replaced by either single or double point sources evenly spaced across the line source. The emission rate is equally split for cases with two point sources for a single line source.

Table B1 Sample Emission Rates in g/s for AERMOD, July 7, 2011 7:00-8:00 AM

	CO	NO _x
P1	0.0020	0.0005
P2	0.0085	0.0012
P3	0.0037	0.0004
P4	0.0113	0.0016
P5	0.0023	0.0002
P6	0.0045	0.0004
P7	0.0010	0.0001
P8	0.0035	0.0007
P9	0.0016	0.0002
P10	0.0091	0.0011

Snapshot of the input emissions text file for QUIC is shown below:

```

"!QUIC 5.84
101                               !NUMBER OF SOURCES
202                               !NUMBER OF SOURCE NODES
!START OF SOURCE NUMBER 1
SOURCE 1 !SOURCE NAME
2                               !SOURCE STRENGTH UNITS (1 = G, 2 = G/S, 3 = L, 4 = L/S)
0.0141444                       !SOURCE STRENGTH
2                               !SOURCE DENSITY (KG/M^3) [ONLY USED FOR VOLUME BASED SOURCE STRENGTHS]
3                               !RELEASE TYPE: =1 FOR INSTANTANEOUS;=2 FOR CONTINUOUS; =3 FOR DISCRETE CONTINUOUS
0                               !SOURCE START TIME (S)
900                             !SOURCE DURATION (S)
2                               !SOURCE GEOMETRY (1 = SPHERICAL SHELL, 2 = LINE, 3 = CYLINDER, 4 = EXPLOSIVE, 5 =
AREA, 6 = MOVING POINT, 7 = SPHERICAL VOLUME, 8 = SUBMUNITIONS, 9 = 3D ARRAY, 10 = PIPE, 11 = HORIZONTAL
CYLINDRICAL TANK, 12 = VERTICAL CYLINDRICAL TANK, 13 = SPHERICAL TANK)
2                               !NUMBER OF DATA POINTS
!X (M)  Y (M)  Z (M)
261.401000 222.675000 1.000000
41.273000 222.675000 1.000000
!END OF SOURCE NUMBER 1
!START OF SOURCE NUMBER 2.." and so on.
```

B2. AERMET Outputs

Filter

Year: 2011Month: JuneDay: 1Julian Day:

	Year	Month	Day	Julian Day	Hour	Sensible Heat Flux (W/m ²)	Surface Friction Velocity (m/s)	Convective Velocity Scale (m/s)	Vertical Potential Temperature Gradient above PBL	Height of Convectively-Generated Boundary Layer - PBL (m)	Height of Mechanically-Generated Boundary Layer - SBL (m)	Monin-Obukhov Length (m)	Surface Roughness Length (m)	Bowen Ratio	Albedo	Wind Speed - Ws (m/s)	Wind Direction - Wd (degrees)	Reference Height for Ws and Wd (m)	Temperature - temp (K)	Reference Height for temp (m)	Precipitation Code	Precipitation Rate (mm/hr)	Relative Humidity (%)	Surface Pressure (mb)	Cloud Cover (tenths)
Min.	2011	Jun	1	152	1	-64.0	0.562	-9.000	-9.000	-999.0	982.0	-1152.4	1.000	1.62	0.21	3.60	234.0	14.0	289.9	2.0	0	0.00	25.0	997.0	2
Max.	2011	Jun	1	152	24	315.6	1.440	2.634	0.007	2331.0	3976.0	1099.3	1.000	1.62	1.00	9.30	284.0	14.0	300.2	2.0	0	1.02	82.0	1000.0	4
1	2011	Jun	1	152	1	-64.0	0.652	-9.000	-9.000	-999.0	1212.0	386.1	1.000	1.62	1.00	4.60	234.0	14.0	297.4	2.0	0	0.00	74.0	998.0	3
2	2011	Jun	1	152	2	-55.5	0.571	-9.000	-9.000	-999.0	999.0	298.0	1.000	1.62	1.00	4.10	255.0	14.0	297.2	2.0	0	0.00	77.0	998.0	4
3	2011	Jun	1	152	3	-57.5	0.568	-9.000	-9.000	-999.0	986.0	284.8	1.000	1.62	1.00	4.10	248.0	14.0	297.1	2.0	0	1.02	77.0	999.0	3
4	2011	Jun	1	152	4	-57.5	0.568	-9.000	-9.000	-999.0	986.0	284.4	1.000	1.62	1.00	4.10	257.0	14.0	296.8	2.0	0	0.00	80.0	998.0	3

Figure B1 Sample Surface File, AERMET View Output, June 1, 2011 0:00 – 4:00 AM

Table B2 Atmospheric Parameter Characteristics from Surface File for June and July 2011

		Surface Pressure (atm)	Wind Speed m/s	Inv. MO Length (1/m)	Wind Direction (degrees)	Temp. (C)
JUNE 2011 Atmospheric Parameters	Standard Deviation	0.0048	1.7524	0.1109	99.1770	3.4783
	Average	0.9850	3.2295	-0.0528	186.7955	294.2114
	Coefficient of Var.	0.0048	0.5426	-2.0985	0.5309	0.0118
JULY 2011 Atmospheric Parameters	Standard Deviation	0.0045	1.3037	0.0889	99.9236	3.0994
	Average	0.9846	2.4738	-0.0542	193.0000	298.0476
	Coefficient of Var.	0.0046	0.5270	-1.6414	0.5177	0.0104

Figure B2 Wind Frequency Distribution for June 2011 (left) and July 2011 (right)

B3. Source Attributes

Table B3 AERMOD and QUIC Source Attributes

Attribute	AERMOD	QUIC
Type	Point	Line
Release Height/ type	1m, horizontal	1m, directionless
Exit Temperature	500 K	Ambient
Diameter of Point Source	0.0762 m (~3 inches)	Not applicable

B4. Reporting Results

Sensor observed data are available in volumetric units (CO – ppm, NO_x – ppb). Modelled data from AERMOD and QUIC are in gravimetric units (CO, NO_x – mg/m³). Conversion between the two unit systems is carried out using the following formulas:

$$m = R \frac{T}{P}$$

$$C_{ppm} = C_{mg/m^3} \times \frac{m}{M}$$

Where, m: molar volume; R: Universal Gas Constant; T: Temperature; P: Pressure; M: Molecular Weight; C: Concentration (subscript denotes type of unit)

Temperature and pressure values obtained from AERMET are used for these calculations. CO comparisons are made in ppm while NO_x comparisons are in mg/m³. This is because NO_x comprises NO and NO₂ which have different molecular weights. Since modelled concentrations are only available in mg/m³, observed concentrations (in ppb) are converted to that unit.

B5. Coefficient of Variation Analysis QUIC

$$n' = (CV)^2 \frac{(CF)^2}{(\%)^2}$$

Where, n': Sample size, CV: Coefficient of Variation, CF: Confidence Factor obtained from the normal distribution curve; %: percent error on mean. Average coefficient of variation is obtained

from eight 15 minute intervals (one each for June and July). A hit and trial method is then used to estimate the percentage error for one model run. To estimate the mean and standard deviation of the sample, the distribution is initially established to be of the normal form. This is done using the Kolmogorov-Smirnov (K-S) test. The K-S test compares observed frequency with cumulative function of a known distribution (normal in this case) to test whether a given sample of data belongs to a particular distribution. Observed data is arranged in increasing order,

$$S_n = \frac{k}{n}$$

$$D_n = S_n - F_e$$

Where, k = current index, n = total sample number; F_e = Theoretical cumulative function; If $\max(D_n) \leq D_n^\alpha$ (α : significance value), then proposed theoretical distribution is accepted.

Table B4 K-S Test Sample, NO_x Concentration, 8:45 – 9:00 AM, July 13, 2011

n	GEH	Sn	FE	Dn
1	0.0016	0.0333	0.0417	0.0084
2	0.0020	0.0667	0.0816	0.0150
...	...	...	...	...
...	...	...	...	...
30	0.0076	1.0000	0.9984	0.0016
Mean=	0.0038	St. Dev.=	0.0013	
Normal	Max Dn=	0.07364	D45=	0.277513
			$\alpha=0.05$	Accepted

B6. Sensitivity Analyses Methodology Characteristics:

A single run is performed for the PARAMICS / CMEM combination for sensitivity analyses. No divisor is used to scale down the PARAMICS input O-D matrix for any of the sensitivity or random seed analyses. QUIC Emission rates are averaged over links that are aggregated to each of the 17 line sources for all sensitivity analyses and additionally, for the QUIC random seed analysis. The intent of sensitivity testing is to estimate the coefficient of variation as opposed to validating actual measurements.

Figure B3 Relationship between QUIC Modelled CO Concentration and Wind speed for different wind directions.

EB College, ~Sidewalk CO

EB College, ~Sidewalk NO_x

WB College, ~Sidewalk CO

WB College, ~Sidewalk NO_x

SB St. George, ~Sidewalk CO

SB St. George, ~Sidewalk NO_x

NB Beverley, ~Sidewalk CO

NB Beverley, ~Sidewalk NO_x

Figure B4 AERMOD View concentration plots 3m Height,
CO 7:00 – 8:00 AM, June 13, 2011 (Left) and NO_x July 18, 2011(Right)

CO June 13, 7:00 – 7:15 AM EB College

CO June 13, 7:00 – 7:15 AM WB College

Figure B5 QUIC CO Concentration Plots, 3m Height, June 13, 7:00-7:15 AM

CO June 13, 7:00 – 7:15 AM SB St. George

CO June 13, 7:00 – 7:15 AM NB Beverley

Figure B5 QUIC CO Concentration Plots, 3m Height, June 13, 7:00-7:15 AM

NO_x July 18, 8:15-8:30 AM EB College

NO_x July 18, 8:15-8:30 AM WB College

Figure B6 QUIC NO_x Concentration Plots, 3m Height, July 18, 8:15-8:30 AM

NO_x July 18, 8:15-8:30 AM SB St. George

NO_x July 18, 8:15-8:30 AM NB Beverley

Figure B6 QUIC NO_x Concentration Plots, 3m Height, July 18, 8:15-8:30 AM

Table B5 Sample QUIC Input Emission Rate File, July 7, 7:00-7:15 AM; Highlighted sections
16, 17, 20 and 21 are ignored due to negligible emissions

Section1		Average Rates from 700-715 in g per sec	
Link	Index	CO	NOx
3_72	10	0.016246667	0.002071
8_70	16	0.423711111	0.004009
9_8	17	0.050428889	0.003738
70_3	128	0.018486667	0.000689
72_73	132	0.365088889	0.003311
73_2	134	0.004513333	0.000327
		0.878475556	0.014144
Section2		Average Rates from 700-715 in g per sec	
Link	Index	CO	NOx
1_44	4	0.022255556	0.003058
2_74	6	0.008226667	0.000511
44_45	80	0.076708889	0.001664
45_46	82	0.418675556	0.003513
46_47	84	0.000577778	0.000162
47_27	86	0.000588889	0.00014
74_1	136	0.00856	0.001491
		0.535593333	0.01054
Section3		Average Rates from 700-715 in g per sec	
Link	Index	CO	NOx
27_48	50	0.002546667	0.000118
30_49	54	0.002342222	0.000138
33_34	59	0.001715556	0.00018
48_30	88	0.001013333	0.000171
49_50	90	0.006177778	0.000258
50_33	92	0.003326667	0.000216
		0.017122222	0.00108
Section4		Average Rates from 700-715 in g per sec	
Link	Index	CO	NOx
30_48	53	0.005666667	0.000411
33_50	58	0.381613333	0.004171
34_33	60	0.049071111	0.003987
48_27	87	0.022877778	0.00042
49_30	89	0.002264444	0.000562
50_49	91	0.047235556	0.001673
		0.508728889	0.011224

Section 5			Average Rates from 700-715 in g per sec	
Link	Index		CO	NOx
1_74	2		0.014637778	0.002456
27_47	48		0.009366667	0.000242
44_1	79		0.003835556	0.000889
45_44	81		0.001668889	0.000578
46_45	83		0.008066667	0.000362
47_46	85		0.003291111	0.000267
74_2	135		0.290404444	0.003847
			0.331271111	0.00864
Section 6			Average Rates from 700-715 in g per sec	
Link	Index		CO	NOx
2_73	5		0.005604444	0.000516
3_70	8		0.005444444	0.001142
8_9	15		0.001306667	0.000529
70_8	127		0.282946667	0.003647
72_3	131		0.001368889	0.00044
73_72	133		0.007711111	0.00036
			0.304382222	0.006633
Section 7			Average Rates from 700-715 in g per sec	
Link	Index		CO	NOx
19_20	33		0.009408889	0.00144
20_23	36		0.000591111	0.00034
23_24	42		0.000248889	0.000158
35_43	61		0.000577778	0.000509
36_35	64		0.000395556	0.000244
43_58	77		0.000933333	0.000984
58_19	105		0.002231111	0.000793
			0.014386667	0.004469
Section 8			Average Rates from 700-715 in g per sec	
Link	Index		CO	NOx
1_59	1		0.003097778	0.001224
42_60	75		0.001371111	0.000227
59_36	107		0.000415556	0.000253
60_1	109		0.006306667	0.000853
61_42	111		0.00036	0.000296
			0.011551111	0.002853

Section 9			Average Rates from 700-715 in g per sec	
Link	Index		CO	NOx
10_64	18		0.000664444	0.001011
13_67	25		0.016164444	0.00202
14_13	27		0.002593333	0.000747
37_61	73		0.000195556	0.000153
62_37	113		0.000208889	0.000149
63_62	115		0.000204444	0.00016
64_63	117		0.00014	0.000124
67_10	123		0.053946667	0.001071
			0.074117778	0.005436
Section 10			Average Rates from 700-715 in g per sec	
Link	Index		CO	NOx
10_67	20		0.000111111	1.33E-05
13_14	26		6.22222E-05	6.67E-06
37_62	74		0.00012	1.11E-05
61_37	112		0.000115556	1.56E-05
62_63	114		0.000162222	1.56E-05
63_64	116		0.000195556	3.56E-05
64_10	118		0.000106667	0.00002
67_13	124		0.000115556	8.89E-06
			0.000988889	0.000127
Section 11			Average Rates from 700-715 in g per sec	
Link	Index		CO	NOx
1_60	3		0.004788889	0.000609
36_59	65		0.05358	0.001087
42_61	76		0.000188889	4.22E-05
59_1	108		0.138404444	0.001342
60_42	110		0.007282222	0.000256
			0.204244444	0.003336
Section 12			Average Rates from 700-715 in g per sec	
Link	Index		CO	NOx
19_58	34		0.000448889	6.22E-05
20_19	38		0.003544444	0.00062
23_20	43		0.012002222	0.001096
24_23	44		0.007035556	0.00114
35_36	62		0.003128889	0.000596
43_35	78		0.00266	0.000587
58_43	106		0.000637778	0.000127

			0.029457778		0.004227
Section 13			Average Rates from 700-715 in g per sec		
Link	Index		CO		NOx
3_71	7		0.000337778		4.67E-05
3_69	9		0.001173333		0.000202
4_5	11		3.11111E-05		8.89E-06
6_7	12		2.66667E-05		0
6_71	13		0.002		0.000247
7_6	14		0.000444444		0.000122
69_4	126		0.000328889		9.56E-05
71_6	129		3.11111E-05		1.78E-05
71_3	130		0.000542222		9.56E-05
4_69	138		0		0
5_4	139		0		0
69_3	146		0		0
			0.004915556		0.000836
Section 14			Average Rates from 700-715 in g per sec		
Link	Index		CO		NOx
20_57	37		0.002264444		0.000311
21_22	39		7.33333E-05		1.56E-05
21_57	40		0.00252		0.000413
22_21	41		0.000291111		7.33E-05
57_21	103		0.001982222		0.000131
57_20	104		0.000306667		6.44E-05
			0.007437778		0.001009
Section 15			Average Rates from 700-715 in g per sec		
Link	Index		CO		NOx
19_25	35		0.000328889		0.00012
25_19	45		0.000411111		6.67E-05
25_26	46		5.11111E-05		1.33E-05
26_25	47		0.00076		0.000176
			0.001551111		0.000376
Section 16			Average Rates from 700-715 in g per sec		
Link	Index		CO		NOx
35_56	63		0		0
38_56	67		4.44444E-06		1.33E-05
38_39	68		0		0
39_38	69		1.11111E-05		3.56E-05

56_35	101		1.11111E-05		3.56E-05
56_38	102		0		0
			2.66667E-05		8.44E-05
Section 17			Average Rates from 700-715 in g per sec		
Link	Index		CO		NOx
36_55	66		0		0
40_55	70		0		0
40_41	71		0		0
41_40	72		0		0
55_36	99		0		0
55_40	100		0		0
			0		0
Section 18			Average Rates from 700-715 in g per sec		
Link	Index		CO		NOx
27_53	49		0.000215556		0.000231
28_29	51		1.55556E-05		2.89E-05
53_54	97		0.000377778		0.000184
54_28	98		2.88889E-05		2.89E-05
28_54	141		0		0
29_28	142		0		0
53_27	143		0		0
54_53	144		0		0
			0.000637778		0.000473
Section 19			Average Rates from 700-715 in g per sec		
Link	Index		CO		NOx
30_51	52		0.000853333		6.67E-05
31_32	55		4.88889E-05		1.56E-05
31_52	56		2.66667E-05		0
32_31	57		0.000157778		3.11E-05
51_52	93		3.77778E-05		4.44E-06
51_30	94		0.00004		2.22E-06
52_31	95		4.22222E-05		6.67E-06
52_51	96		2.88889E-05		0
			0.001235556		0.000127
Section 20			Average Rates from 700-715 in g per sec		
Link	Index		CO		NOx
10_66	19		8.88889E-06		2.22E-06
10_65	21		6.66667E-06		2.22E-06

11_12	22		2.22222E-06		2.22E-06
11_66	23		0		0
12_11	24		0		0
15_65	28		0		0
15_16	29		4.44444E-06		0
16_15	30		0		0
65_10	119		0		0
65_15	120		6.66667E-06		4.44E-06
66_11	121		2.22222E-06		0
66_10	122		0		0
			3.11111E-05		1.11E-05
Section 21			Average Rates from 700-715 in g per sec		
Link	Index		CO		NOx
17_68	31		0		0
18_17	32		0		0
68_2	125		0		0
2_68	137		0		0
17_18	140		0		0
68_17	145		0		0
			0		0

Table B6 Sample AERMOD Input Emission Rate File, July 7, 7:00-9:00 AM; Highlighted line sources are split into two point sources.

Link		Average Rates from 7-8 in g per sec		Average Rates from 8-9 in g per sec		
Index	#	CO	NOX	CO	NOX	
1_59	1	0.004004	0.000986	0.004582	0.000924	Z43
1_74	2	0.017016	0.002481	0.018443	0.002558	Z15
1_60	3	0.007408	0.000888	0.010441	0.001263	Z39
1_44	4	0.022679	0.003167	0.022565	0.003651	Z17
2_73	5	0.004504	0.00048	0.008583	0.000446	Z11
2_74	6	0.009053	0.000812	0.009179	0.000987	Z13
3_71	7	0.000992	0.00008	0.000768	7.94E-05	
3_70	8	0.007009	0.001471	0.008148	0.001541	Z5
3_69	9	0.001642	0.000202	0.002624	0.000393	
3_72	10	0.018273	0.002252	0.017664	0.002406	Z7
4_5	11	0.000045	6.11E-06	8.33E-05	1.28E-05	
6_7	12	3.94E-05	3.89E-06	2.89E-05	3.33E-06	
6_71	13	0.002641	0.000291	0.003137	0.000307	
7_6	14	0.000798	0.000144	0.001076	0.000162	
8_9	15	0.003029	0.000434	0.001657	0.000332	Z1
8_70	16	0.446164	0.004386	0.462992	0.005211	Z3
9_8	17	0.069731	0.004373	0.075013	0.004918	Z2
10_64	18	0.00098	0.000509	0.000497	0.00044	
10_66	19	1.56E-05	4.44E-06	0.000015	4.44E-06	
10_67	20	0.000178	3.61E-05	0.000277	5.72E-05	
10_65	21	8.89E-06	3.33E-06	0.00026	7.22E-06	
11_12	22	2.22E-06	1.11E-06	3.33E-06	1.11E-06	
11_66	23	0	0	0	0	
12_11	24	0	0	0	0	
13_67	25	0.01753	0.001519	0.020217	0.001503	
13_14	26	0.000102	2.06E-05	0.000362	4.22E-05	
14_13	27	0.002319	0.000595	0.002397	0.0006	
15_65	28	0	0	0	0	
15_16	29	0.000005	1.11E-06	3.89E-06	5.56E-07	
16_15	30	0	0	0	0	
17_68	31	0.00008	3.33E-06	0.000108	1.17E-05	
18_17	32	3.11E-05	5.56E-06	0.000116	2.78E-05	
19_20	33	0.008098	0.001129	0.007702	0.001219	
19_58	34	0.000892	0.000138	0.001086	0.000187	
19_25	35	0.000373	0.000135	0.000353	0.000148	
20_23	36	0.001057	0.000227	0.001365	0.000259	
20_57	37	0.00151	0.000231	0.001192	0.00035	

20_19	38		0.004476	0.000753	0.005598	0.00086	
21_22	39		5.44E-05	1.28E-05	5.17E-05	4.94E-05	
21_57	40		0.003462	0.000471	0.004122	0.000444	
22_21	41		0.000497	0.000103	0.000607	8.72E-05	
23_24	42		0.000272	8.72E-05	0.000283	9.44E-05	
23_20	43		0.011564	0.001192	0.012347	0.001783	
24_23	44		0.006658	0.001155	0.00722	0.001486	
25_19	45		0.000326	6.89E-05	0.000386	7.67E-05	
25_26	46		5.17E-05	2.06E-05	5.78E-05	3.44E-05	
26_25	47		0.001093	0.000172	0.000945	0.000199	
27_47	48		0.015174	0.00036	0.017445	0.000383	Z25
27_53	49		0.000262	0.000202	0.000447	0.000378	
27_48	50		0.003588	0.000158	0.003179	0.000275	Z27
28_29	51		1.22E-05	1.94E-05	2.67E-05	3.72E-05	
30_51	52		0.000967	0.000075	0.001292	0.000138	
30_48	53		0.003382	0.000478	0.004523	0.000566	Z29
30_49	54		0.005268	0.000192	0.011805	0.000408	Z31
31_32	55		5.33E-05	1.72E-05	8.44E-05	0.00002	
31_52	56		3.06E-05	1.11E-06	2.33E-05	2.78E-06	
32_31	57		0.00031	5.17E-05	0.000179	0.00005	
33_50	58		0.437217	0.004474	0.504466	0.005422	Z35
33_34	59		0.003003	0.000262	0.002819	0.000322	Z37
34_33	60		0.063581	0.004446	0.069285	0.005518	Z38
35_43	61		0.000703	0.000398	0.000723	0.000537	Z49
35_36	62		0.004462	0.000719	0.004787	0.000943	Z47
35_56	63		2.22E-06	1.67E-06	1.11E-06	0	
36_35	64		0.000392	0.000124	0.000403	0.000187	Z48
36_59	65		0.058906	0.001171	0.059646	0.001447	Z45
36_55	66		0	0	0	0	
38_56	67		2.39E-05	4.44E-05	0.000025	6.06E-05	
38_39	68		0	0	5.56E-07	0	
39_38	69		6.89E-05	0.000104	8.33E-05	0.00017	
40_55	70		0	0	0	0	
40_41	71		0	0	0	0	
41_40	72		0	0	0	0	
37_61	73		0.000201	8.67E-05	0.000279	9.22E-05	Z53
37_62	74		0.000185	2.22E-05	0.000286	3.78E-05	
42_60	75		0.000917	0.000151	0.001458	0.000218	Z41
42_61	76		0.00058	8.11E-05	0.001481	0.000132	Z51
43_58	77		0.001141	0.000582	0.001158	0.000605	
43_35	78		0.002836	0.000667	0.003617	0.000843	Z50
44_1	79		0.006826	0.001094	0.009067	0.001346	Z18

44_45	80		0.089063	0.001983	0.07485	0.002264	Z19
45_44	81		0.003402	0.000633	0.006833	0.000789	Z20
45_46	82		0.484803	0.004017	0.440084	0.004318	Z21
46_45	83		0.005427	0.000411	0.006759	0.000512	Z22
46_47	84		0.00083	0.000231	0.003283	0.000484	Z23
47_46	85		0.002523	0.000279	0.002699	0.000351	Z24
47_27	86		0.000848	0.000181	0.002462	0.000268	Z26
48_27	87		0.023981	0.000548	0.027896	0.000639	Z28
48_30	88		0.001413	0.000174	0.002776	0.000379	Z30
49_30	89		0.002489	0.000511	0.001542	0.000457	Z32
49_50	90		0.008731	0.000309	0.020593	0.0005	Z33
50_49	91		0.055977	0.001527	0.062979	0.001958	Z34
50_33	92		0.002886	0.000269	0.002117	0.00034	Z36
51_52	93		5.89E-05	1.89E-05	7.22E-05	2.44E-05	
51_30	94		4.89E-05	8.33E-06	3.56E-05	9.44E-06	
52_31	95		5.89E-05	1.67E-05	7.83E-05	1.83E-05	
52_51	96		3.44E-05	5.56E-07	2.56E-05	5.56E-07	
53_54	97		0.000158	0.000114	0.00065	0.000367	
54_28	98		3.44E-05	6.44E-05	0.000157	9.17E-05	
55_36	99		0	0	0	0	
55_40	100		0	0	0	0	
56_35	101		2.17E-05	0.000045	2.61E-05	6.11E-05	
56_38	102		0	0	5.56E-07	0	
57_21	103		0.001297	0.000085	0.000863	0.000126	
57_20	104		0.000443	8.11E-05	0.000375	8.06E-05	
58_19	105		0.002691	0.000639	0.002896	0.000976	
58_43	106		0.000776	0.000152	0.000962	0.000303	
59_36	107		0.000725	0.000207	0.000798	0.000241	Z46
59_1	108		0.137278	0.001457	0.15829	0.001936	Z44
60_1	109		0.004444	0.000551	0.003431	0.000569	Z40
60_42	110		0.017035	0.00051	0.021111	0.000752	Z42
61_42	111		0.000503	0.000147	0.000602	0.000151	Z52
61_37	112		0.000168	3.33E-05	0.000268	5.28E-05	Z54
62_37	113		0.000193	7.11E-05	0.000211	7.44E-05	
62_63	114		0.000229	3.17E-05	0.000352	5.56E-05	
63_62	115		0.000192	7.11E-05	0.000213	0.000075	
63_64	116		0.000237	5.33E-05	0.000391	9.56E-05	
64_63	117		0.000126	7.06E-05	0.000159	0.000133	
64_10	118		0.000175	4.61E-05	0.000265	7.39E-05	
65_10	119		0	0	0	0	
65_15	120		6.67E-06	3.33E-06	0.000005	2.22E-06	
66_11	121		2.78E-06	3.33E-06	6.11E-06	2.78E-06	

66_10	122		0	0	0	0	
67_10	123		0.067033	0.000869	0.076059	0.000831	
67_13	124		0.000166	2.83E-05	0.000287	6.06E-05	
68_2	125		5.56E-07	1.11E-06	6.67E-06	3.33E-06	
69_4	126		0.000489	8.33E-05	0.000997	0.000166	
70_8	127		0.303705	0.003693	0.359414	0.004079	Z4
70_3	128		0.020731	0.000949	0.026222	0.001383	Z6
71_6	129		0.000387	3.06E-05	0.000226	2.78E-05	
71_3	130		0.000646	0.000108	0.001083	0.000117	
72_3	131		0.003633	0.000697	0.003647	0.00085	Z8
72_73	132		0.387906	0.003599	0.394935	0.004114	Z9
73_72	133		0.004152	0.000446	0.008819	0.000418	Z10
73_2	134		0.007038	0.000463	0.00861	0.000627	Z12
74_2	135		0.296633	0.00381	0.330991	0.004092	Z14
74_1	136		0.012849	0.002008	0.018346	0.002373	Z16
2_68	137		0	0	0	0	
4_69	138		0	0	0	0	
5_4	139		0	0	0	0	
17_18	140		0	0	0	0	
28_54	141		0	0	0	0	
29_28	142		0	0	0	0	
53_27	143		0	0	0	0	
54_53	144		0	0	0	0	
68_17	145		0	0	0	0	
69_3	146		0	0	0	0	