An Integrated Approach to Estimate Pedestrian Exposure to Roadside Vehicle Pollutants

by

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A thesis submitted in conformity with the requirements for the degree of Master of Applied Sciences

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Abstract

At many urban intersections, pedestrians and vehicles share the same space, where interactions between pedestrians and vehicles may hinder vehicle turning movements. This changes the amount of emissions generated by the vehicles, to which the pedestrians are exposed. This research investigates the pedestrian-vehicle interaction at the intersection of St. George Street and College Street in downtown Toronto. A microscopic vehicle simulation is integrated with a microscopic pedestrian simulation. Emission generation and dispersion are modelled to obtain concentration maps for emitted pollutants. The spatial-temporal data of the pedestrians are then integrated into these concentration maps to calculate pedestrian exposure to vehicle pollutants. Lastly, this framework is applied to test the effects of implementing a scramble signalling system at the intersection of St. George Street and College Street. It is found that the implementation of a scramble phase would increase exposure to Nitrogen Oxides and decrease exposure to Carbon Monoxide.
Acknowledgements

Writing the thesis acknowledgement feels good, because it means the hard work of actually producing the thesis is complete. Looking back through the last 20 months, I realize that my research would not be the same without the support I’ve received from all of these people.

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Chapter 1

1 Introduction

1.1 Background and Motivation

In modern society, where the movement of goods and people is vital for a prosperous economy, transportation plays a key role in maintaining the wellbeing of its people. Over the past century, the internal combustion engine and the personal car has revolutionized transportation. As more cars have taken to the streets, vehicle emissions also have increased in urbanized areas.

In the chemical process of a perfect combustion, the only chemical products are carbon dioxide (CO₂) and water vapour (H₂O). However, perfect combustion is not fully achieved in reality. Impurities in the gasoline, imperfect air-to-fuel ratios, and imperfect combustion chamber temperatures can lead to imperfect combustion of fuels. The products of incomplete combustion include carbon monoxide (CO), nitrogen oxides (NOx), volatile organic compounds (VOCs), sulphur dioxide (SO₂), lead, and particulate matters (PM), most of which present health hazards if inhaled (Environmental Protection Agency, 1994)(BC Air Quality, 2013).

CO is a clear and odourless gas that is considered very poisonous. It prevents the proper absorption of oxygen by blood and can lead to loss of consciousness and even death. NOx can cause adverse respiratory effects in healthy people, which worsen for people with asthma. In addition, NOx react with moisture and ammonia in the air to form small particles. If inhaled, these particles can cause emphysema and bronchitis, aggravate existing heart issues, and cause premature death. NOx and VOCs can also react in sunlight to form ground level ozone. Ground level ozone is also the main component of smog, which causes reductions in lung functions as well (Canadian Council of Ministers of the Environment, 2008). Sulphur Dioxide causes respiratory issues for asthmatics and people engaged in physical activities. Lastly, lead can severely affect the nervous system, kidney function, and immune system. Fortunately, the
emission of lead from mobile sources decreased drastically with the introduction of unleaded gasoline in 1990 (Environmental Protection Agency, 2012; Environment Canada, 2013).

Modern vehicles are designed to minimize the output of these pollutants by improving the internal combustion engine, as well as with the introduction of catalytic converters, which convert CO and hydrocarbons to CO₂ and water, and reduce NOx to N₂ and O₂ (Environmental Protection Agency, 1994). However, traces of these products still exist in vehicle emissions, and they may still create health issues for pedestrians who are exposed to them. Despite recent policies aimed to reduce vehicle emissions, transportation still contributes to 17% of all NOx and 40% of all CO emissions in Canada (Environment Canada, 2014).

In urban centres, pedestrians along busy urban streets are particularly susceptible to vehicle emissions due to their proximity to large volumes of vehicles. Under the stop-and-go conditions seen in urban settings, the internal combustion engines of these vehicles are at their lowest efficiencies, thus generating large amounts of emissions within a small area. In addition, roads in urban centres are generally lined with buildings that restrict air flow, thus reducing the dispersion of emitted pollutants. This is known as the street canyon effect, and it further increases the concentration of pollutants to which pedestrians in these areas are exposed (Leitl & Meroney, 1997; Chan et al., 2002; Vardoulakis et al., 2007).

Studies involving vehicle emission generation range from urban land use simulations aimed to determine vehicle movements and route choices to micro simulations considering vehicle behaviour on a real-time basis. Emission dispersion models are also present in the literature, these models range in complexity from Gaussian Plume models that present dispersion on a steady state basis to Lagrangian Dispersion models that study pollutants as particles interacting with their surroundings in real-time.

Misra (2012) has developed an integrated approach to estimate urban traffic emissions and emission dispersion to calculate concentrations of roadside pollutants due to vehicle emissions. He was able to predict the concentrations of CO and NOx from a set of data including vehicle OD matrices, vehicle type distribution, roadway geometry, and building geometry. In his study, a
microscopic simulation of vehicle traffic was performed in conjunction with a vehicle emission model to calculate emission factors along streets in an urban setting. The emission factors were then used as input to emission dispersion models (AERMOD and QUIC) to determine the concentration of pollutants in the study area and the effects of street canyons (Misra, 2012).

However, Misra’s (2012) approach does not account for the interaction between vehicles and pedestrians. In Canadian urban intersections, vehicles are often required to yield to pedestrians. This is especially true for turning vehicles at controlled intersections. This interaction is highly likely to reduce the capacity of controlled intersections, which results in more congestion at major intersections with significant pedestrian volumes.

As the volume of pedestrians increase, vehicle turning movements are hindered with increasing severity. Abdelgawad, et al.’s work on pedestrian-vehicle conflicts in the city of Madinah’s First Ring Road after major congregational prayers, where vehicle volumes were estimated at 20000/hour and pedestrian volumes were estimated at 140000/hour, shows severe deterioration of service, indicated by significant pedestrian delays and low vehicle speeds (Abdelgawad, Shalaby, Abdulhai, & Gutub, 2012).

The intersection of St George Street and College Street is a much less congested intersection than the First Ring Road in Madinah. However, pedestrian-vehicle interactions may still cause a significant change in vehicle behaviour. For a society that values healthy living and the importance of active transportation, it is important to investigate the impact of pedestrian-vehicle interactions in urban streets, their effects on vehicle emissions, and the exposure of pedestrians to said emissions.

1.2 Purpose and Potential

This study further builds upon Misra’s work by implementing a microscopic simulation of pedestrian traffic in the study area. This incorporates two additional features to this approach of modelling traffic emissions. By simulating pedestrian movement and capturing the interaction between pedestrians and vehicles, it is possible to model the delay experienced by vehicles when
they are yielding to pedestrians. One of the most prominent examples of this occurs when turning vehicles at signalized intersections yield to pedestrians on crosswalks. As pedestrian volumes increase, the delays experienced by turning vehicles increase as well. These vehicles then create queues behind them, causing additional congestion and increase emission generation. Some city planners combat this phenomenon by disallowing turning vehicles on urban streets or by dedicating lanes and phases to turning vehicles. Others implement “scramble” phases at signalized intersections. During these “scramble” phases, pedestrians are allowed to cross in any direction. However, pedestrians are not allowed to cross in any direction outside the “scramble” phase, while vehicles are moving. Intersections like these are prominent in Japan, where pedestrian volumes are high (Glionna, 2011).

In addition to modelling the interaction between vehicles and pedestrians, the availability of information on the positions of the pedestrians as they make their way through the network makes it possible to calculate pedestrian exposure to vehicle emissions as they navigate along the streets in urban environments. This makes it possible to explicitly assess the “healthiness” of an intersection based on the generation and dispersion of vehicle emissions, as well as the position of the pedestrians in relation to the airborne pollutants. The “healthiness” measure of this study area can be used to assess different intersection design policies based on their impacts to vehicle emissions and the amount of exposure to such emissions. In a society that aims to promote healthy living and active transportation, this measure can be useful in differentiating good and healthy intersection designs from an unhealthy one.

1.3 SCOPE AND FRAMEWORK

This study is an extension of the work done by Misra (2012) to include the micro-simulation of pedestrians in the urban vehicle emission model. Misra (2012) established a framework to estimate roadside pollutant concentration based on the micro-simulation of vehicles by integrating three different software models. The two pollutants being investigated were CO and NOx. The proposed scope of this framework includes the following:
• The integration of a vehicle micro-simulation software with a pedestrian-simulation software
• Modelling of vehicle emission generation and modelling of emission dispersion in the study area
• Validation of predicted pollutant concentrations with observed concentrations and National Ambient Air Quality Objectives (NAAQO), Environment Canada
• Policy analysis of the implementation of a scramble phase signalling system in the study area

1.4 STRUCTURE OF THESIS

This thesis is organized into ten chapters. The first chapter gives a brief introduction to the topic. Chapter 2 briefly outlines the process of estimating pedestrian exposure. Chapter 3 describes the process of creating the vehicle micro-simulation network in Paramics and the pedestrian micro-simulation network in MassMotion. Chapter 4 describes the mechanism through which the two models are integrated and the software structure of the integrated model, as well as the results of the pedestrian and vehicle simulations. Chapter 5 describes the emission generation model and the results. Chapter 6 describes the emission dispersion model and its results. Chapter 7 describes the process through which the pedestrian locations are integrated into the pollutant density map. Chapter 8 proposes a sample intersection design policy that is tested with this new approach to urban emission modelling. Chapter 9 discusses the limitations and the errors of this approach. Chapter 10 summarizes the research effort and presents potential for future development.
Chapter 2

2 Overview of Method

The proposed framework for calculating the exposure of pedestrians to concentrations of roadside pollution due to vehicle traffic and pedestrian-vehicle interaction includes the following components:

- Data collection of pedestrian and vehicle volumes in the study area, and the estimation of Origin-Destination matrices for pedestrian and vehicle traffic using the collected data.
- Development of a Paramics network to model vehicle movement and the development of a MassMotion model to simulate pedestrian movements, and interfacing MassMotion with Paramics and implementing pedestrian-vehicle interactions in the interface.
- Modelling of vehicle emission using CMEM
- Modelling emission dispersion and calculate concentrations of roadside pollutants using QUIC.
- Estimation of the pedestrians’ exposure to vehicle emissions as they navigate around the study area and generation of an exposure map to determine locations where pedestrian exposure is the greatest

Figure 2-1 briefly describes the integration of all software models in this framework.
The vehicle and pedestrian micro-simulation provide spatial-temporal information of all vehicles in the study area. The microscopic emission generation model uses the spatial-temporal information to derive vehicle power requirements and consequently determine the amount of each pollutant generated on each road segment. The dispersion model uses weather data and building geometry information to calculate the dispersion of the generated pollutants within the study area to form pollutant concentration maps for CO and NOx. Lastly, the positions of all pedestrians are used to determine their exposure to said pollutants as they navigate through the study area to form exposure maps for CO and NOx. Each of these components requires extensive inputs. Figure 2-2 shows the inputs required for each step of the process.
2.1 Description of Study Area

The study area of this thesis is centred at the intersection of St. George Street and College Street. College Street is a four lane road running east-west. St. George Street is a two lane street running north-south. It changes into Beverley Street on the south side of College Street. This intersection lies on the southern part of the University of Toronto’s St. George Campus. College Street is considered the major street in this network, with an average peak hourly flow of 1400 vehicles (Misra, 2012).

The study area stretches west to Spadina Avenue, east to McCaul Street, north to Russell Street, and south to Cecil Street. The study area is approximately 800 m from the east end to west end, and 600 m from the north end to the south end. In addition to the main St. George and College Street intersection, there are 9 additional minor intersections in this area. Since this study area is part of the University of Toronto campus, several university buildings operate near this
intersection. These buildings generate a significant amount of pedestrian traffic at 9:00 and 10:00 am as university students travel to their classes.

### 2.2 Explanation of Terms

There are two major outputs of this study; they are the concentration maps of roadside pollutants and exposure maps showing the amount of exposure at each location. They are defined as follows:

- **Roadside Concentration Map** – shows the concentrations of CO and NOx in the study area, the concentration maps show modelled concentrations that are output from the QUIC dispersion model. There are four concentration terms in total:
  - Observed or Measured Concentrations: Concentrations of CO and NOx obtained from sensors readings located in the study area. There is one sensor located at 200 College Street at 3m above the ground.
  - Modelled Concentrations: Concentrations of CO and NOx that are obtained from emission dispersion models based on vehicle emission generation rates, meteorological data, and building geometry.
  - Ambient Concentrations: Concentrations of CO and NOx which are present naturally in the atmosphere. These concentrations are assumed to be uniform throughout the study area with respect to space and time.
  - Predicted Concentrations: the sum of modelled concentrations and ambient concentrations. These values should match with the observed or measured concentrations.

- **Roadside Exposure Map** – shows the amount of exposure within the study area. Exposure occurs when pedestrians are present in locations with concentrations of CO and NOx. Exposure to a pollutant increases with increases in concentration, as well as with increases in the number of pedestrians in the area.
Figure 2-3 - Roadways and major buildings in the study area

Vehicle Data Collectors
3 Vehicle and Pedestrian Micro-Simulation Models

This chapter outlines the building of the vehicle and pedestrian micro-simulation models. The vehicle micro-simulation model is built in Quadstone Paramics, and the pedestrian micro-simulation model is built using MassMotion. The sections in this chapter outline the software selection, data collection, and the model building process.

3.1 Vehicle Modelling

3.1.1 Literature Review

Traffic modelling is the process of determining traffic behaviour such as vehicle speed, vehicle flow, and the level of congestion in a network. Traffic modelling can be categorized depending on their level of detail in to macroscopic models, mesoscopic models, and microscopic models.

Macroscopic models are focused on average conditions such as average speeds and average flow over time along a length of road. Such models simplify platoons of vehicles as fluid flowing through a pipe. The first macroscopic traffic model investigated the relationship between flow speed, flow volume, and vehicle density (Lighthill & Whitham, 1955). Combined with the law of conservation of flow, macroscopic models can explain the different phenomena taking place at bottlenecks and traffic nodes. Macroscopic models have been incorporated into transportation software packages with varying levels of additional details. These software packages include Aimsun (TSS-Transport Simulation Systems, 2013), PTV Visum (PTV Group, 2013), and Emme (INRO, 2013).

Microscopic models focus on the behaviour of individual vehicles. Each vehicle is treated as an agent within the study area, with its own set of rules to adjust its speed and direction. One of the first microscopic traffic models was the car following model, where vehicles adjust their speed based on the speed and position of the vehicle in front (Pipes, 1953). In microscopic models,
simulated vehicles are tallied in the model to determine the overall performance of the network. Due to the complexity of these models, implementing them over large areas is only made possible recently by advancements in computation power. Software packages that model traffic on a microscopic level include PTV Vissim (PTV Group, 2013), Paramics (Quadstone Paramics, 2013), CORSIM (University of Florida, 2006), ARCADY (TRL Limited, 2013), Aimsun (TSS-Transport Simulation Systems, 2013), and SimTraffic (Trafficware, 2013). Microscopic traffic models often require more information and data than their macroscopic counterparts in order to study the same area.

Mesoscopic models have properties of both macroscopic and microscopic models. These models are designed to simulate individual vehicles with less emphasis on their dynamic spatial-temporal positions, but more emphasis on route choices and average conditions. These conditions may be determined based on macroscopic calculations, such as speed-flow relationships and queues at intersections. Software packages that model traffic on a mesoscopic scale include MATSIM (MATSIM, 2012), Dynameq (INRO, 2014), and OmniTRANS (Omnitrans International, 2013).

In addition to levels of detail, traffic models can be further categorized by their scale of independent variables (continuous/discrete), representation of process (deterministic/stochastic), operation characteristics (analytical/simulation), and scale of application (networks/links/intersections). Using these types of categorization, a car-following model would be a continuous, deterministic, analytical model used to study single lane stretches. A more comprehensive listing of models is presented by Hoogendoorn & Bovy (Hoogendoorn & Bovy, 2001).

3.1.2 VEHICLE MODEL SELECTION - PARAMICS

The vehicle modelling software is required to have high level of detail to interact with the pedestrian model and provide input data to the emission model, thus a microscopic traffic model is preferred over a macroscopic model. The model would also be required to have a working interface with the pedestrian simulation and the emission model. With these criteria, Quadstone Paramics was chosen as the vehicle simulator. Paramics is a comprehensive network microscopic
traffic simulation software package, which is based on the car following model. It is also highly configurable with its API system, where users can develop their own plugins to change the function of the program. The configurability of this API system makes Paramics a highly desirable choice for integrating pedestrians into the system. In addition, the University of Toronto has been working with Paramics over several years, and a network for the study area is already developed by Hoy et al. at the University of Toronto (Hoy, 2012).

### 3.2 Pedestrian Modelling

#### 3.2.1 Pedestrian Modelling Literature Review

The earliest of the many attempts to understand and quantify pedestrian behaviour investigated the capacity of facilities to accommodate pedestrians, such as subways stations and shelter entrances. For example, Hankin and Wright investigated pedestrian flow as a function of pedestrian density, thus providing estimates of facility capacity for pedestrian hallways of different widths (Hankin & Wright, 1958). Preliminary studies of pedestrian behaviour such as this gave way to more sophisticated models that followed in the next few decades. There are many different attempts to quantitatively understand the behaviours of pedestrians that resulted in different pedestrian models. However, these different models can be put into three different categories of approaches. They are sketch plan models, network analysis models, and agent based models (Raford & Ragland, 2006).

Sketch plan models are high-level aggregate analysis tools to estimate pedestrian volumes for an activity area. These models often use regression analysis to associate pedestrian volumes to measurable factors such as land uses, vehicle volumes, and population and employment densities of adjacent areas in order to advise on changes in pedestrian volumes as a result of changes in surrounding environment (Federal Highway Administration, 1999). Sketch plan models are relatively simple to create with data that can be easily obtained through observations, however, its lack of accuracy and detail makes it only effective as a preliminary tool to estimate pedestrian volumes at specific nodes from a number of relevant attributes.
Sketch plan models were widely adapted before the popularization of computers, Pushkarev and Zupan, as well as Behnam and Patel, were one of the firsts to use regression models to determine pedestrian volumes on urban areas as a function of land use attributes (Behnam & Patel, 1977)(Zupan & Pushkarev, 1971). Today, sketch plan models are still being estimated and used to investigate the relationship between pedestrian counts and environmental attributes such as job density, land use, population density, slope, etc. as guidelines to determine pedestrian friendly streets (Liu & Griswold, 2009).

Network analysis models are more complex and powerful than sketch plan models. Network analysis often aims to determine pedestrian volumes on specific links in a study area. Most of the network analysis models use a different variation on the well-known four-stage model that is popular in transportation trip generation (Raford & Ragland, 2006). Network analysis models are more complex than sketch plan models, and they can provide adequate estimates on pedestrian volumes through a network from inputs such as trip origin and destination data.

Ness et al. examined the movements of pedestrians in the central business district of Toronto by calibrating a gravity model to assign pedestrians on routes from the transportation system terminal and office locations within Toronto (Ness, Morrall, & Hutchinson, 1969). Other studies supporting network analysis models include pedestrian behaviour surveys conducted to determine the factors affecting route choices for pedestrians (Seneviratne & Morrall, 1985).

Agent based models are also known as microscopic pedestrian simulation models. Agent-based models recreate the environment in a virtual setting, and generate virtual agents that follow a set of rules in order to mimic the walking behaviour of pedestrians. The application of these models is made possible by the availability of computing power with recent advancements in computing hardware. Agent based models are complex, and require significant initial data in order to cover a relatively small area. They are highly accurate, detailed, and visually communicative. Since this study is focussed on the interaction of pedestrians and vehicles at intersections, a high level of detail is needed from the model. Thus, a microscopic pedestrian simulation is required for this study.
3.2.2 Pedestrian Model Selection - MassMotion

There are a number of agent-based pedestrian simulation packages that are commercially available. Four of the most prominent packages are Vissim, Paramics Urban Analytics Framework (UAF), Legion, and MassMotion.

Microscopic pedestrian simulation can be broken down into two major components: strategic routing choices and operational decisions. In many of the microscopic pedestrian simulations today, these components are either defined by the user or simulated by the software packages.

Strategic routing is fairly analogous to network analysis stated above, where agents with origin and destinations are assigned routes to follow based on a number of attributes. Strategic routing, if simulated, generally considers the distances of different routes, the level of congestion along these routes, and the type of terrain to be encountered on these routes.

MassMotion explicitly uses these variables in the strategic routing choices of its agents. MassMotion is capable of routing all of its agents using information provided in an origin-destination matrix. Vissim can also perform strategic routing to a certain extent by analyzing the geometry of walkable areas that are defined by the users. Paramics and UAF, however, require the users to define waypoints to which the pedestrians must travel. It may not be able to handle complex routing choices for pedestrians involving large amounts of obstacles and turns between adjacent waypoints. To get around this, Paramics users are required to add waypoints along the pedestrian paths for strategic routing. It is also required to have direct line-of-sights between adjacent waypoints. Vissim also incorporates intermediate destinations to help define routes around obstacles.

Operational decisions are the real-time decisions that each pedestrian makes while they are traversing the study area. These generally consist of micro-adjustments to their speed and direction in order to avoid collisions. In MassMotion, Paramics, and Vissim, the general form of these operational decisions follows the social forces model that was described by Still (2000).
Legion uses a multi-agent system, called “auto-navigation” by the developers. It gives all its agents a set of rules with which they will determine their next steps (Alexandersson & Johansson, 2013). Other models for operational decisions also exist in literature. Cellular Automata models define a floor field on which cells represent discrete grids in a walkable space. These cells are then assigned values for the presence of pedestrians and their attributes, including the likely next steps of the pedestrians. Burstedde et al. implemented Cellular Automata models to capture evacuation dynamics and lane formations in long corridors (Burstedde, Klauck, Schadschneider, & Zittartz, 2001). Operational decisions can also be modelled using discrete choice models. Antoninia et al. and Robin et al. (Antoninia, Bierlaireb, & Weberb, 2006) (Robin, Antonini, Bierlair, & Cruz, 2009) have specified models to describe a pedestrian’s choice for their next bearing and movement speed based on the positions of their destinations, other pedestrians, and obstacles.

All four pedestrian simulation software packages, Paramics UAF, Vissim, Legion, and MassMotion, are suitable candidates for this study. However, MassMotion is chosen for its ability to perform strategic routing for its agents, and for its efficiency in simulating large numbers of agents in real time. There exist also several MassMotion models for the Toronto Central Business District and key infrastructure nodes in the area such as Union Station, Yonge/Bloor Subway Station, and St. George Subway station (Oasys Software, 2014). MassMotion is also highly efficient in modelling a large number of pedestrian behaviour around obstacles and other pedestrians (Morrow, 2013). The availability of technical support from the development team of MassMotion also makes integration of MassMotion and Paramics a technically feasible undertaking.

3.2.3 Social Forces Model for Pedestrian Simulation

The social force model revolves around the following principles:

- Pedestrians normally choose the shortest route to their next destination
- Pedestrians prefer to walk with a comfortable speed
• Pedestrians keep a certain distance to other pedestrians and borders of obstacles. This distance is smaller the more a pedestrian hurries and decreases with pedestrian density.

• Pedestrians normally do not reflect their behavioural strategy in every situation (e.g. pedestrians trying to enter elevators when others are trying to get off)

To capture this, social force model adapts the following force equation (Johansson & Helbing, 2009):

\[
f_{\alpha}(t) = \frac{1}{\tau_{\alpha}} (v_{\alpha 0} e_{\alpha 0} - v_{\alpha}) + \sum_{\beta \neq \alpha} f_{\alpha \beta}(t) + \sum_{i} f_{\alpha i}(t)
\]

Where:

\( \tau \) is the reaction time;
\( v_{\alpha 0} e_{\alpha 0} \) is the desired velocity vector, and \( v_{\alpha} \) is the current velocity vector;
\( f_{\alpha \beta} \) and \( f_{\alpha i} \) are the repulsive forces between the agent \( \alpha \) and all other pedestrians \( \beta \) and objects \( i \)

\( f_{\alpha \beta}(d_{\alpha \beta}) = A_{\alpha} e^{-\frac{d_{\alpha \beta}}{\beta_{\alpha}}} \frac{d_{\alpha \beta}}{||d_{\alpha \beta}||}\)

This exponential function describes a repulsive force that is symmetric in all directions. If applied to the agents as is, it results in the simulated pedestrians to exhibit a collision-like behaviour when conflicting paths occur. Figure 3-1 shows the paths of two pedestrians with the social force model as is, where the blue path is taken by an agent originating from the bottom travelling upwards, and the red path is taken by an agent originating from the top travelling downwards. It is seen that the agents slow down significantly when encountering each other, and change direction abruptly. This does not coincide well with how pedestrians normally interact with each other.
This function can be modified by implementing relative velocities between $\alpha$ and $\beta$ to reflect the effect of velocities of oncoming pedestrians to represent smoother manoeuvres in collision avoidance behaviour in pedestrians. The resultant function is as follows (Johansson, Helbing, & Shukla, 2007):

$$f_{\alpha\beta}(d_{\alpha\beta}) = A e^{-\frac{b_{\alpha\beta}}{\beta} ||d_{\alpha\beta}|| + ||d_{\alpha\beta} - y_{\alpha\beta}||} \cdot \frac{1}{2} \left( \frac{d_{\alpha\beta}}{||d_{\alpha\beta}||} + \frac{d_{\alpha\beta} - y_{\alpha\beta}}{||d_{\alpha\beta} - y_{\alpha\beta}||} \right)$$

Where:

$$2b_{\alpha\beta} = \sqrt{(||d_{\alpha\beta}|| + ||d_{\alpha\beta} - y_{\alpha\beta}||)^2 - ||y_{\alpha\beta}||^2}$$

$$y_{\alpha\beta} = (v_\beta - v_\alpha) \Delta t$$

With this adjustment to account for the velocities, the agents exhibit a much smoother manoeuvre when avoiding conflicts with each other. Figure 3-2 traces the paths of the same two
agents with the adjusted social forces; it shows the two agents gliding past each other much more smoothly.

![Figure 3-2 - Plotted pedestrian locations using modified repulsive force (social forces)](image)

This equation is further modified by the pedestrian's sensitivity factor to obstacles in front vs. obstacles behind him/her. This is expressed by the equation

\[
\mathbf{w} (\varphi_{\alpha\beta}(t)) = \left( \lambda_{\alpha} + (1 - \lambda_{\alpha}) \frac{1 + \cos(\varphi_{\alpha\beta})}{2} \right)
\]

Where

\( \varphi_{\alpha\beta} \) is the angle of the obstacle with relation to the pedestrian's bearing.

\( \lambda_{\alpha} \) is a parameter with \( 0 \leq \lambda_{\alpha} \leq 1 \), which indicates the pedestrian's sensitivity to obstacles directly behind him/her.

The combination of these mechanics of pedestrian behaviour yields to a number of phenomena evident in observed crowd dynamics (Hohansson & Helbing, 2009):

- Lane formation
- Oscillatory flows at bottlenecks
• Stripe formation in intersecting flows

The above social forces theorem is the basis for many pedestrian microscopic simulation software packages. PTV Vissim, Paramics UAF, CrowdDynamics Event Planner, and MassMotion employ the principles of social forces model with variations that are proprietary to their respective developing companies. In some cases, simplifications do occur depending on the required fidelity of the model. For example, Vissim provides the modellers with the option of using a simple version of pedestrian simulation where pedestrians are regarded as vehicles and obey the car-following model. This, according to Vissim’s training manuals, is more suitable for simulating pedestrian behaviour at crossing or on sidewalks (PTV, 2011). At the same time, Vissim has the option to allow modellers to model pedestrians on real 2-dimensional space with the above social forces mechanics, should there be the need for high-fidelity pedestrian interaction to be simulated.

3.2.4 CALIBRATING THE SOCIAL FORCE MODEL

In order for the social force model to be useful in pedestrian simulation, the parameters must be estimated. Johansson suggests the following method to calibrate the social force model from available pedestrian path data (Johansson, Helbing, & Shukla, 2007):

• From the dataset of a crowd’s movement, select one of the pedestrians to be simulated as the agent
• Define the starting location and desired destination of the agent from the available data
• Determine the agent’s desired speed from the max observed speed
• Given the tracked trajectory of the surrounding pedestrians, simulate the agent’s movement and estimate parameters that would minimize the relativistic distance error defined by

$$\frac{\|r_{a, \text{simulated}} (t + T) - r_{a, \text{tracked}} (t + T)\|}{\|r_{a, \text{tracked}} (t + T) - r_{a, \text{tracked}} (t)\|}$$

Where t is the initial time and T is the elapsed time in the simulation.
This same process is to be repeated over different agents across different datasets in order to obtain a good estimate for the parameters in the social force model.

In order to compile the dataset from which model estimation is performed, continuous and dynamic data must be collected. Infrared and video data collections have been used in recent literature (Kerridge, Keller, Chamberlain, & Sumpter, 2007) (Hoogendoorn, Daamen, & Bovy, 2003) (Teknomo, 2002). Infrared video data collection looks for pedestrians by tracking differences in temperatures in the recording. By employing sensors that detect changes in temperatures, it is possible to eliminate the background from the data. However, its drawback is that pedestrians must have sufficiently different temperatures from the environment, and it also requires that the pedestrians are constantly moving for the system to work (Kerridge, Keller, Chamberlain, & Sumpter, 2007).

As advancements in image recognition are made, the possibility of recording pedestrian locations from video files is also explored. Hoogendoorn et al. used video cameras to study the behaviour of 60-90 pedestrians who participated in the study by filming their movements from a camera pointed straight down perpendicular to the ground. In order to minimize error in video data extraction, the participants are provided with red and green hats to act as visual markers for the camera to pick up (Hoogendoorn, Daamen, & Bovy, 2003). Due to limitations automatic image recognition, visual markers were often needed to reliably determine the position of each pedestrian from a video file. It is not until recently that video extraction algorithms were powerful enough to extract pedestrian positions and velocities without the aid of markers. These algorithms are highly accurate and they involve the application of contrast-enhancing algorithms, as well as a neural network trained to recognize heads. In addition, a set of heuristics is followed to predict the locations of each pedestrian in subsequent frames based on velocity estimates from their previous locations, this makes it easier to track pedestrians from frame to frame (Helbing, Johansson, & Al-Abideen, 2007)(Johansson A. , Helbing, Al-Abideen, & Al-Bosta, 2008).
3.3 Data Collection and OD Estimation

3.3.1 DATA COLLECTION

As input to the MassMotion and Paramics software, data on vehicle and pedestrian volume were collected. There were two methods in which traffic flow data could be collected. One way was to count the number of pedestrians and vehicles entering and leaving the network at all origin and destination zones. For vehicles, these zones would be the nodes at the fringes of the study area; for pedestrians it would also include all of the buildings/exits. This method would provide the total numbers of trips generated in the study area, also known as the total number of origins and destinations at each zone in the network. This information forms the marginal values of an OD matrix for the pedestrians, onto which a gravity model can be applied to generate the OD matrix, very much like the second step in the four-step model (Hensher & Kenneth, 2007). This OD method would be able to generate an OD matrix with marginal values that match the total number of pedestrians and vehicles entering and exiting the network at each zone, while the total flow of pedestrians and vehicles on each link may be different from the observed flows.

The second method was to count the number of pedestrians and vehicles travelling on the links in the network. For vehicles, each link would be the stretch of road between adjacent intersections; for pedestrians, each link would be defined as the stretch of sidewalk between adjacent nodes in the network. These nodes can be building entrances/exits, pedestrian crossings, intersections, etcetera. An OD matrix can then be estimated to minimize the difference between calculated link flows and observed link flows. This method would generate an OD matrix with link flows that match well with the observed flows, but the total numbers of pedestrians entering and leaving the network at each zone may be different from the observed values.

This study aims to simulate the interaction between pedestrians and vehicles on urban streets and the amount of vehicle emissions generated on each stretch of road in the study area. The volumes of vehicles and pedestrians travelling on each link are important in accurately replicating the number of pedestrian-vehicle conflicts at intersections and crossings, as well as the amount of vehicle emissions generated on each link. Therefore, for the purpose of this study, it is more
important to replicate the number of vehicles and pedestrians travelling on each link. Consequently, the second method was adapted to generate the OD matrix.

The data collection took place on April 2\textsuperscript{nd}, 2013, from 7:30 AM to 10:30 AM. The intent was to capture the peak-hour vehicle traffic, expected to be between 8:00 am and 9:00 am. In addition, April 2\textsuperscript{nd} was chosen as a typical weekday during the winter semester. This captured the peak in pedestrian volumes as students and staffs make their way to their 9 am and 10 am classes. The data collection process involved 11 vehicle data collectors, 17 pedestrian data collectors, 2 signal timers, and 2 additional persons as back-up. Figure 3-3 shows the intersections which were monitored for vehicle movement and the locations of the pedestrian data collectors. 32 data collectors, consisting of mostly undergraduate and graduate students, were hired from the Department of Civil Engineering. Training was provided on April 1\textsuperscript{st}, 2013, the day prior to the data collection.

![Figure 3-3 - Position of vehicle data collectors (left) and pedestrian data collectors (right)](image)

Misra, et al. (2012) and Hoy, et al. (2012) collected vehicle turning information on all major and minor intersections in the study area. This method was more robust than simply collecting
Vehicle link flows, because it explicitly provides the number of left and right turns from all approaches at each intersection. Since turning vehicles are the most affected by crossing pedestrians, it was important to collect this data.

Vehicle data collection was conducted with the TrafficDuco™. TrafficDuco™ is a traffic surveying software that allows real-time turning movement counting for intersections. It is able to count up to three types of vehicles, as well as including pedestrian movements. However, TrafficDuco™ is an iOS based software, and required full time internet connection and iOS 6 or higher. This limited the number of TrafficDuco™ users and consequently limited the use of TrafficDuco™ to vehicle data collection only.

Pedestrian data was collected on paper. Each pedestrian data collector was given two bidirectional links to monitor, resulting in each pedestrian counter being responsible for four movements. Upon detecting these movements, the counter records these movements in corresponding boxes in the data collection sheet. Each pedestrian collector had 36 sheets with an intersection described in Figure 3-4. Each sheet was designed for every 5-minute intervals between 7:30 AM and 10:30 AM. It was noted that College Street is prone to jaywalkers, especially the stretch between St. George Street and McCaul Street. The data collectors were instructed to not count these jaywalkers, as the scope of this study does not currently include the dynamics of jaywalking.
3.3.1.1 Vehicle Data Collection – Instrument Failure

During data collection, there were three instances of instrument failure, in which the batteries on iPhones of the data collectors failed due to cold temperature. This resulted in 26 minutes lost on the St. George and GB South intersection, and 25 minutes lost on the College and Huron intersection.

Fortunately, both of these intersections have low numbers of turning vehicles. The majority of the vehicle volumes were observed as through traffic on St. George Street for the St. George and GB South intersection, and the majority of the vehicle volumes were observed as through traffic College Street at the College and Huron intersection. In these cases, the major roadways at these intersections were St. George Street and College Street, respectively.

Because of this, data from the missing time frames were extracted from adjacent intersections. The volumes of through traffic on the major roadways at these intersections were taken as the minimum of outbound vehicles from the upstream intersection and the inbound vehicles from the downstream intersection. The turning movement at these intersections was calculated from the difference between the inbound and outbound vehicle volumes. It was assumed that left turns and right turns were being made with the equal probability. Lastly, the through volumes on the minor roadways at these intersections were assumed to be zero during these times.
3.3.1.2 Vehicle Data Collection – Additional Adjustments

Additional adjustments were made to ensure zero accumulation on each segment of the major roadways. These adjustments were made by balancing inbound and outbound vehicle flow in each direction along the major roadway at each intersection. The procedure for balancing one direction in a major roadway is as follows:

- Starting from the first of n intersections in the roadway, balance intersections downstream with
  \[ \Delta V_{i+1,T} = V_{i+1,T} - (V_{i,T} + V_{i,C} + V_{i,D} - V_{i+1,L} - V_{i+1,R}) \]
  assign \( V_{i+1,T} = V_{i+1,T} + \Delta V_{i+1,T} \)

- Adjust through volumes for all \( i \) to ensure total volume through one street does not change
  \[ V_{i,T} = V_{i,T} + \frac{\Delta V}{n} \]

Where

\[ \Delta V = \sum_{i=1}^{i=n-1} \Delta V_{i+1,T} \]

In this case, the measure of accuracy for the data collection is the ratio between the difference between the originally counted numbers and the adjusted numbers. In this network, this is expressed as a percentage of the total volume. The majority of the changes to the matrix were under 10% of the original volume (Figure 3-5). A large portion of the changes were in the
medium and heavy vehicles. Due to the low number of medium and heavy vehicles in the area, a small change in absolute value leads to a large percentage change.

![Percent Change during Vehicle Volume Adjustments](image)

**Figure 3-5 - Histogram of percent difference between adjusted vehicle counts and raw vehicle counts for all links in the study area**

### 3.3.2 OD Estimation

#### 3.3.2.1 Pedestrian OD Estimation

There exists a number of ways to estimate an OD matrix. The gravity model is one of the standard methods for OD matrix estimation. It utilizes total trip production at origin zones, total attraction at destination zones, and friction factors, which are typically based on travel distance or travel time, to estimate the number of trips between each origin-destination pair (Oregon State University; Portland State University; University of Idaho, 2003). This model is usually best suited for scenarios where there is known information about the attributes of each location that helps determine its ability to generate outbound and inbound trips. In addition, this model would
generate an OD matrix with accurate marginal values, but link volumes may differ significantly from the actual values, as described in section 3.3.1.

Another method for estimating OD matrices is using available link volume data. When there are previously estimated OD matrices, it can be updated using link counts with the following equation (Cascetta & Nguyen, 1988)

\[
d^* = \arg \min_{d_{od}} [z_1(d_{od}, d') + z_2(f(d_{od}), f')]
\]

Where \(z_1\) and \(z_2\) are the differences measured between (1) the previously estimated OD matrix and the updated matrix, and (2) the difference between flow volumes resulting from the updated OD matrix and the measured link flows. This method is also the preferred method for this study as it generates an OD matrix that would yield accurate link volumes, as described in 3.3.1.

Without the availability of an a priori OD matrix, maximizing entropy was used to estimate OD matrices (Xie, Kockelman, & Waller, 2011), where entropy is defined as follows:

\[
- \sum_{ij} (V_{ij} \ln V_{ij} - V_{ij})
\]

where \(V_{ij}\) are the flow volumes from origin \(i\) to destination \(j\). This method works best when the only information available is link volume, which was the extent of the data collected.

As a result, entropy maximization was used to estimate the OD matrices for this study. The OD estimation process for pedestrians was carried out as an optimization problem, where the objective was to minimize difference between calculated link volumes and measured link volumes and to maximize entropy. The final objective function was defined as follows:

\[
\text{Min} \left( \sum_k (x_{k,\text{calculated}} - x_{k,\text{observed}})^2 + \sum_{ij} (V_{ij} \ln V_{ij} - V_{ij}) \right)
\]

Where \(x_{k,\text{calculated}}\) and \(x_{k,\text{observed}}\) are the calculated and observed volumes, respectively, on link \(k\); and \(V_{ij}\)'s are the entries in the OD matrix from origin \(i\) to destination \(j\). The OD matrix
contains 31 nodes, and there are 34 links within the network, as shown in Figure 3-6. This objective function was minimized using a genetic algorithm.

Figure 3-6 - Pedestrian OD Nodes and links to be used in the genetic algorithm

The genetic algorithm used in this case used an initial population of 300 randomly generated OD matrices over 2000 generations. At every generation, the following steps are taken:

- Calculate link flows for each OD Matrix using shortest path assignment, use these link flows for objective function calculation. In the genetic algorithm, shortest path assignment was used instead of the MassMotion simulation to maintain efficiency.
- Define fitness function as the inverse of the objective function, and rank all OD Matrices according to the fitness function. The most fit function being the first one in the list.
- Mating I – 60% of the population
Select parent 1 from the parent generation sequentially from most fit to the 30th percentile
Select parent 2 from the parent generation randomly, where each candidate’s probability of selection is proportional to its fitness function
Convert every entry in both parents into 6-bit binary for gene swap:
Randomly determine $x$ between 1 and 6, based on a uniform distribution
Swap the right $x$ number of bits of the two binary numbers in each entry between the two parent OD matrices
Convert back into decimal form and store in new matrix and form 60% of the child generation
Mutation – 20% of the population with worst fitness function from the parent generation
Randomly select 25% of the entries in the OD matrix, and convert into 6-bit binary for mutation
Randomly determine $x$ between 1 and 6 based on a decreasing distribution. This is to discourage drastically changing the values of the entries in the OD matrices. The distribution is as follows:
- $P(x=1) = 0.42$
- $P(x=2) = 0.29$
- $P(x=3) = 0.17$
- $P(x=4) = 0.08$
- $P(x=5) = 0.03$
- $P(x=6) = 0.01$
Flip the right $x$ bits in the bits in the binary code
Convert back into decimal form and store back into parent generation. These OD matrices were not passed directly into child generation, instead, they are set aside for Mating II
Mating II – 40% of the population
Select parent 1 from the parent generation sequentially from most fit to the 20th percentile
Select parent 2 randomly from:
- The children from Mating I (60% of the population)
- The mutated parents (20% of the population)
- The OD matrices ranked between the 60th percentile and the 80th percentile in the parent generation (20% of the population)
  - Convert every entry in both parents into 6-bit binary for gene swap:
  - Randomly determine x between 1 and 6, based on a uniform distribution
  - Swap the right x number of bits of the two binary numbers in each entry between the two parent OD matrices
  - Convert back into decimal form and store in new matrix to form the remaining 40% of the child generation

The values of objective function of the matrices in the first few generations of solutions were around $10^7$. After 2000 generations, the objective function decreases to under $10^4$ (Figure 3-7). The difference between observed link flows and calculated link flows for the final solution were mostly within 10% of each other (Figure 3-8 and Figure 3-9).

It is seen that the link flows match well with the observed values, but the total number of pedestrians originating and exiting at each zone may be different from the actual values. For example, in the generated OD matrix, a large number of pedestrians are moving from one building to an adjacent building. In reality, it is expected that a large number of pedestrians should be entering and exiting the study area through the east and west ends of College Street (nodes 15, 16, 26, and 27) and north end of St. George Street (nodes 1 and 8); these pedestrians are then expected to move into different buildings in the study area. However, for the purpose of this study, replicating link volumes are of higher priority than matching total numbers of pedestrians at each origin and destination. Therefore, the generated OD matrices are considered as valid.
Figure 3-7 - Fitness Function over 2000 generations for the estimation of one pedestrian matrix

Figure 3-8 - Observed and calculated link volumes from pedestrian OD matrix estimation
3.3.2.2 Vehicle OD Estimation

The vehicle OD Matrix was estimated using turning movement percentages. Since there was available information for all turning movements, vehicle volume between OD pairs was calculated by the following equation:

\[ V_{ij} = x_O \prod_{k=0}^{K} P_k(\text{turning}) \]

Where \( x_O \) is the volume of vehicles counted leaving the origin point, and \( P_k(\text{turning}) \) is the probability of making the required turn at intersection \( k \) to get to the destination \( j \). This probability is calculated by dividing the number of vehicles making the specific movement by the total number of vehicles entering the intersection from the approach. \( K \) is the number of turning movements that is required between \( i \) and \( j \). One of the resultant vehicle OD matrices is shown in Figure 3-10 as an example. Since the vehicle OD matrices are estimated using turning movement data, which includes vehicle generation rates at all zones in the network, the vehicle
OD matrices would be able to produce link volumes that are similar to observed values, and the total number of vehicles generated in the network would be similar to actual values as well.

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</table>

Figure 3-10 - Sample vehicle OD matrix for light vehicles from 8:15 am to 8:30 am

3.4 Network development and inputs

3.4.1 PARAMICS MODEL DEVELOPMENT AND INPUTS

The Paramics network for the intersection of St. George Street and College Street was developed by Hoy, et al (2012). This network was based on satellite imagery and geometric interpolation. All characteristics of the roadways were incorporated by Hoy, et al. These characteristics include lane widths, speed limits, signal timings, and public transit schedules and stops (Hoy, 2012). Misra added additional input information such as vehicle origin-destination information, vehicle type distribution, and other core parameters to this network. Figure 3-11 shows the Paramics network used by Misra (Misra, 2012).
To update this Paramics model, the vehicle OD matrices were updated using the newly estimated matrices obtained through the process described in the sections above. Signal timings were also updated to reflect the following changes:

- A left-turn priority signal was added to the southbound traffic at St. George Street at the St. George Street and College Street intersection;
- The timings for the College and Huron Street intersection were adjusted;
- The timings for the pedestrian crossing on St. George Street north of the St. George and College Street intersection were adjusted.

In addition, it was noted that there was construction taking place on the eastbound lanes on the western approach on College Street at the St. George and College Street intersection (Figure 3-12). The construction site removed the right-most lane on College Street. The network was
updated to reflect this by closing the right-most lane at the intersection. It was assumed that this change in the road geometry did not alter the capacity of College Street enough to significantly decrease demand on the street.

Figure 3-12 - Construction site on College Street, looking east at the intersection of College Street and St George Street

3.4.2 MassMotion Model Development and Inputs

The MassMotion model was developed based on the geometries of the Paramics vehicle model to ensure a clean interface between the pedestrian movement and vehicle movement. Kerb points were extracted from the Paramics Model (Figure 3-13). These kerb points were then manually imported into Google Sketchup to be used as guidelines for sidewalks and other walkable areas for pedestrians. Sidewalks on roads with bicycle lanes, foliage, and on-road parking were offset and modified by the appropriate amount based on satellite imagery and geometric interpolation (Figure 3-14 and Figure 3-15). The Sketchup model was then imported into SoftImage’s MassMotion workbench to add pedestrian OD points, to which the pedestrian OD matrix was applied (Figure 3-16). These OD points include entry points to the study area, as well as entrances and exits of buildings in the study area.
Pedestrian crossings at intersections and crosswalks were added as links into the MassMotion Model. Crossings at signalized intersections and signalized crosswalks were gated and timed to synchronize with the Paramics signal timings. It is noted that all controlled pedestrian crossings have a significant "do not start" time, where a flashing red light indicates to the pedestrian to not begin crossing on a crosswalk. To emulate this, the gates for controlled crosswalks are closed 10 seconds before the end of the green phase to prevent more agents from entering the crosswalk.
Figure 3-13 - Coordinates of extracted kerb points from Paramics, as presented in Microsoft Excel

Figure 3-14 - Overall view of Sketchup model containing roadway and sidewalks
Figure 3-15 - Details of the Sketchup model, at the intersection of St. George Street and Ross Street

Figure 3-16 - MassMotion's workbench in SoftImage showing the pedestrian simulation model
4 Pedestrian-Vehicle Interaction

4.1 Literature Review

As society moves away from the car-centric urban form, an increasing amount of attention is being placed on the interaction between pedestrians and vehicles. A large portion of the research on pedestrian-vehicle interactions has been on pedestrian-vehicle conflicts and collisions. There exist several indices that measure the severity of pedestrian-vehicle conflicts. One of such proposed indices is the Time to Collision (TTC), which is the amount of time before two road users collide, if they were to continue on their current paths with the same velocities (Hayward, 1972). Post Encroachment Time (PET) is the amount of time after the first road user exits the conflict area and before the second road user enters the conflict area. It is also used to assess the safety factor of a pedestrian-vehicle conflict (Allen, Shin, & Cooper, 1978). Similar to this, Deceleration to Safety Time (DST) was defined as the rate of deceleration that is needed by the second road user to avoid a collision (Hupfer, 1997). More modern indices, such as the Pedestrian Risk Index (PRI), use several factors, such as driver reaction time, travelling speed, and the time when he/she notices a pedestrian in the conflict zone to calculate the risk and severity of collision (Cafiso, García, Cavarra, & Rojas, 2010).

Recent advancements in computation power also make it possible to detect pedestrian-vehicle conflicts in real time using video data. Ismail, et al. implemented such a framework for an intersection in downtown Vancouver. Video data was processed with image recognition software to track the motion of pedestrians and vehicles. These paths are then analyzed to calculate conflict indicators such as TTC, PET, and DST (Ismail et al., 2009).

Under most circumstances, conflicts can be avoided by adjustments of the speeds and paths of the road users. This study is focused mainly on these types of conflicts, where vehicles and
pedestrians easily avoid collisions by slowing down and stopping. On most North American streets, pedestrians and vehicles interact in two different cases. The first case occurs at signalized crosswalks and stop signs, where vehicles must yield to pedestrians. The second case occurs at non-signalized intersections, where pedestrians are to wait for gaps between vehicles before crossing. In both cases, traffic regulations in North America clearly assign the right of way to one of the two groups. The goal of this research is to accurately implement this assignment in the pedestrian-vehicle interaction model that integrates MassMotion and Paramics.

4.1.1 Pedestrians affecting vehicle movements (Case I)

This type of interaction occurs most prominently for turning vehicles at intersections. In these cases, vehicles simply slow and stop and wait for the lane to be cleared of pedestrians to avoid collisions. The drivers assess the positions and velocities of the pedestrians on the crosswalk and look for opportunities to proceed. This is most commonly known as gap and lag acceptance, where drivers predict a period of time where their lane in the crosswalk is clear of pedestrians. Alhajyaseen, et al. examined this with video data collected on an intersection in a number of intersections in Japan and determined left turning drivers’ acceptance to gaps between pedestrians for driving through a crosswalk (left hand traffic) (Alhajyaseen et al., 2012) (Alhajyaseen et al., 2011). Alhajyaseen et al (2012) categorizes the gaps and lags into five different groups and estimated gap and lag acceptance for each. From their data, the average gap and lag that was accepted ranged from 2.9 seconds to 6.7 seconds, depending on the type of lags and gaps.

4.1.2 Vehicles affecting pedestrians (Case II)

This type of interaction occurs most prominently for jaywalking pedestrians. It also applies to pedestrians at crosswalks where they do not have right of way over vehicles, such as at crosswalks with a “Wait for Gap” sign. In these cases, the pedestrians wait on the curb for all lanes on the road to be cleared with an acceptable gap between vehicles before stepping onto the road. In the literature, work has been done to determine the length of the acceptable gap for jaywalkers, and it was found that the age of a pedestrian influences this value. Oxley et al. used observed data from an arterial road in Melbourne, Australia to determine the average distance of
gap that was accepted by jaywalkers (Oxley et al., 1996). By dividing by the average speed of the vehicles on that road, the average length of gap (in time) that was accepted by jaywalkers is found to be between 8 to 9 seconds. Wang et al. used observed data from an arterial road in Beijing, China to estimate a binary logit model to determine the probability of crossing as a function of vehicle gap, age, and number of pedestrians in the group (Wang et al. 2010). Their study shows that the gap length that yields 50% probability of crossing for a single young pedestrian is 4.75 seconds. This large difference between the two values of acceptable gap time is likely caused by the cultural difference between the two cities.

4.2 Software structure

For the purpose of this study, MassMotion is modified and compiled as an API to Paramics. The two major types of interactions between vehicles and pedestrians are represented by two different mechanisms in MassMotion and Paramics. Figure 4-1 shows the structure of the software that is used to model the two mechanisms. This structure allows a two-way communication to take place between the MassMotion pedestrian model and the Paramics vehicle model, thus allowing for a two-way interaction between the vehicles and pedestrians.
4.2.1 Pedestrians affecting vehicle movements (Case I)

This is the most common case on Toronto's roads. It occurs on almost all signalized intersections, pedestrian crossings, and stop signs. For the St. George and College Street study area, this case prevails on almost every pedestrian crossing. The vehicles’ pedestrian gap acceptance is represented by implementing “watch areas” for vehicles in which they detect pedestrians’ expected locations based on their current positions and velocities. These watch areas are defined as trapezoids extending forward from the front of each vehicle (Figure 4-2). These trapezoids are tapered outward at 5°, and their lengths are based on the stopping distance of the vehicles as a function of their speed. The relationship between stopping distance and a vehicle’s speed is taken from Paramics UAF’s stopping sight distance (SSD), which is adapted from the latest UK Guidance – Manual for Streets 2 (CIHT, 2010). The equation is as follows:

\[ SSD = vt + \frac{v^2}{2d} \]

Where

SSD is the minimum stopping sight distance in m
\( v \) is the vehicle’s speed in m/s
\( t \) is the driver’s reaction time in seconds
\( d \) is the vehicle’s deceleration in m/s\(^2\)

Paramics uses 3.68 m/s\(^2\) for \( d \) and 2 s for \( t \), thus the equation becomes

\[
SSD = 2v + \frac{v^2}{7.4}
\]

For turning vehicles, the “watch area” is turned to cover an additional area in the direction of turning. In addition, left turning vehicles have their watch areas extended to monitor pedestrian crossings on the far end of the intersection. These modifications are added to make turning vehicles check for pedestrians on adjacent crosswalks before attempting to make the turn. Without these modifications, turning vehicles would partially make its turn and be stopped right before the crosswalk. For left turning vehicles, this often means the vehicle would be stopping in the middle of opposing through traffic.

![Figure 4-2 - Watch area definition for vehicles moving straight (left) and turning vehicles (right)](image)

For all controlled pedestrian crossings, where pedestrians have clear right of way over vehicles, vehicles consider the current positions of pedestrians, as well as the predicted position of pedestrians for the next 4 seconds based on their current velocities. This is to reflect the vehicles’ gap acceptance for pedestrians. The value of 4 seconds was chosen as it was between the 2.9 seconds and 6.7 seconds of the accepted gap in Alhajyaseen, et al.’s (2012) findings. The value is
skewed closer towards the low side because the outward taper of the watch area adds a certain level of safety for the drivers’ ability to detect pedestrians.

4.2.2 VEHICLES AFFECTING PEDESTRIANS (CASE II)

This case is less prevalent in the St. George and College Street study area. The locations in which this case is applicable are outlined in the map shown in Figure 4-3, where the intersections are neither signalized nor are the opposing vehicle traffic controlled by a stop sign.

The pedestrians’ vehicle gap acceptance for crossing at uncontrolled crossings is modelled by opening and closing gates to these uncontrolled crosswalks. These gates are controlled by the MassMotion API. At each simulation frame, MassMotion’s uncontrolled crosswalk gates check for oncoming vehicles and evaluate whether the crossing is safe. This is accomplished by drawing a rectangle in front of each vehicle to signify a “danger area” (Figure 4-4), and checking whether this rectangle intersects with any uncontrolled pedestrian crossings. This rectangle has a width of a vehicle lane (3.4m), and a length that reflects the pedestrians’ gap acceptance of 10 seconds. That is, the length of the “danger area” (in metres) of each vehicle is 10 times the vehicle’s speed (in m/s). If any uncontrolled pedestrian crossings intersect with these “danger areas”, the gate on these crossings closes, which prevents any pedestrians from crossing the road.

This method does not ensure that all uncontrolled crossings are free of pedestrians when vehicles approach them. To avoid collisions, the “watch areas” of vehicles are still active for these crossings. However, instead of considering the current and predicted positions of all pedestrians, as they do at controlled crossings, vehicles only consider the current position of pedestrians. This is analogous to drivers braking for pedestrians to avoid imminent collision.
Figure 4-3 - Locations of uncontrolled pedestrian crossings where pedestrians do not have right-of-way over vehicles

Figure 4-4 - Definition of "danger area" in front of vehicles to close gates at uncontrolled crosswalks
4.2.3 OVERVIEW OF A SIMULATION TIME STEP IN PARAMICS

To integrate all the functionalities together, the following tasks are executed in each time frame in the pedestrian-vehicle micro-simulation:

1. Paramics updates vehicle positions, velocities, bearing, and acceleration using its car-following model;
2. Paramics defines "danger areas" in front of all vehicles (as described in 4.2.2), and passes this information into the MassMotion Plugin;
3. MassMotion Plugin checks with all the uncontrolled pedestrian crossings against these "danger areas", if any of these areas intersect with an uncontrolled crossing, the gate is closed and pedestrians are no longer allowed to enter the road to cross;
4. MassMotion updates pedestrian positions, velocities, and bearing using its social forces model;
5. MassMotion passes all pedestrian position and velocity information into Paramics;
6. Paramics calculates the expected positions of all pedestrians, based on their current position and velocities, assuming pedestrians are not accelerating or changing directions;
7. Paramics generates "watch areas" in front of all vehicles (as described in 4.2.1), and checks for pedestrians in these "watch areas" using the following rules
   a. For pedestrians who are expected to cross at a controlled pedestrian crossing (i.e. they have the right-of-way and are legally entitled to cross), vehicles will slow and stop for the pedestrians if their current position and expected future positions in the next 4 seconds fall in the "watch area"
   b. For pedestrians who are approaching an uncontrolled crossing (i.e. they should be waiting for a gap in vehicle traffic before crossing as described in 4.2.2), vehicles will not slow and stop if their expected future positions fall in the "watch area"; vehicles will only slow and stop for pedestrians if the pedestrians themselves are in the "watch area" indicating a possible collision if the vehicle continued in its course
8. Update signal lights and record pedestrian coordinates for further analysis, new pedestrian agents and vehicles are generated by MassMotion and Paramics for the next frame.

4.3 Vehicle and Pedestrian Simulation Results

To account for random variations, the models are run 16 separate times with different seeds in Paramics and the MassMotion API. 16 trial runs are chosen such that the t-stats generated to test the significance of pedestrian impact on vehicle speeds were high enough to reject the null hypothesis in a one-tail test with degree of freedom of 15 at 95%. Figure 4-5 shows a screenshot of the simulation at the intersection of St. George Street and College Street.

To validate the model, simulated and measured vehicle flows are compared for vehicle volumes on College Street at the St. George and College Intersection. Figure 4-6 shows the measured vehicle flows compared with simulated vehicle flows. From these volumes, it is seen that the vehicle flow does not vary significantly in the 2.5-hour peak period, and that the simulated and measured volumes follow each other fairly well. For the Eastbound traffic, 9 out of 10 measured data points lie within the 5th-95th percentile range of the simulated flows; for the Westbound traffic, 7 out of 10 measured data points lie within the 5th-95th percentile range of the simulated flows.

Pedestrian volumes are validated using the same procedure. Figure 4-7 shows pedestrian volumes crossing (in all directions) at the St. George and College Intersection. From this graph, it can be seen that there are two distinct peaks for pedestrian volumes. One peak occurs between 8:45 and 9:15, where pedestrians make their way to their work or school destinations. A second peak occurs between 9:45 and 10:15; this peak is the expected peak in pedestrian flow as the University of Toronto students and lecturers make their way to their 10AM classes. It is seen that the measured and simulated pedestrian volumes follow each other fairly well. 73% of the measured data points fall within the 5th-95th percentile range of the simulated flows. The
correlation between the average simulated volume over the 16 trials and the measured volume is 0.93, indicating a good level of replication of the actual link flows.

In order to examine the impact of pedestrians on vehicle movements, the average speeds of all vehicles in the network were recorded and presented in Figure 4-8. It is seen that pedestrians do significantly hinder vehicle movement in this network, since the average vehicle speeds in the network with pedestrians are significantly lower than those in the network without pedestrians. It is seen that the decrease is most significant between 8:30 am and 9:00 am, where average vehicle speeds were decreased by more than 7%. This is likely to impact vehicle emission generation of the vehicles, which is described in the next chapter.
Figure 4-5 - Paramics simulation with vehicles (rectangular boxes) and pedestrians (yellow dots) and their predicted locations (red dots) at the intersection of St. George Street and College Street.

Figure 4-6 - Counted and simulated vehicle volumes (error bars denoting 5th and 95th percentile) eastbound (left) and westbound (right) on College Street at the intersection of St. George Street and College Street.
Figure 4-7 - Comparison between measured pedestrian volumes and simulated pedestrian volumes as a function of time in the morning peak period (error bars denoting 5th and 95th percentile)

Figure 4-8 - Average vehicle speeds in the study area with and without the effect of pedestrians hindering turning vehicles
Chapter 5

5 Vehicle Emission Generation

5.1 Literature Review

A variety of studies have been done to investigate vehicle emission generation. These studies have produced macroscopic and microscopic models to estimate vehicle emission rates. Macroscopic models generally focus on using average vehicle operation characteristics over a large study area. Such models include MOBILE5a, MOBILE6 and EMFAC (Koupal, Michaels, Cumberworth, Bailey, & D., 2013) (CARB, 2006). Both models use operation characteristics such as average vehicle speeds, vehicle type, vehicle age, temperature, altitude, vehicle load, air conditioning usage, and vehicle operating mode to produce emission factors, which are then multiplied by total distance travelled to calculate emission generation (Rakha et al., 2003).

Without considering more detailed vehicle operation characteristics such as instantaneous speed, instantaneous acceleration, idling, and history effects, these models may be inaccurate in representing actual vehicle behaviours. However, due to the simplicity of aggregate models, it is possible to model large study regions quickly.

Microscopic emission models use instantaneous driving behaviour and traffic conditions to calculate emission generation. The Virginia Tech Microscopic Energy and Emission Model (VT-Micro) model uses regression to estimate vehicle emission as a function of speed and acceleration (Ahn, 2002). Other microscopic emission models include Comprehensive Modal Emission Model (CMEM) and Motor Vehicle Emission Simulator (MOVES). Both CMEM and MOVES can model vehicle emission on a second-by-second basis. MOVES was the Environmental Protection Agency’s replacement for MOBILE6 to better represent driving behaviour, rather than having to use average driving behaviour (Koupal, Michaels, Cumberworth, Bailey, & D., 2013). Through comprehensive comparisons between MOVES and EMFAC, Bai et al. have determined MOVES to be a superior modelling tool (Bai, Eisinger,
Niemeier, 2009). In addition, comparisons of MOBILE5a, MOBILE6, VT-MICRO, and CMEM by Rakha et al. found VT-MICRO to be superior to MOBILE5a and MOBILE6 (Rakha et al., 2003).

Due to the versatility of these microscopic models, they have been integrated with vehicle micro simulation software packages in several cases. MOVES is used in the United States to test environmental policies by the EPA (United States Environmental Protection Agency, 2013). CMEM has been used with Vissim to investigate vehicle emissions at railroad crossings and to determine the effects of different traffic control strategies at urban areas (Tydlacka, 2004) (Chen & Yu, 2007) (Kilbert, 2011). CMEM has also been used with Paramics to investigate air quality impacts of HOV lanes and freight corridors in Southern California (Boriboonsomsin & Barth, 2008) (Lee, et al., 2009). A more thorough review of emission generation models can be found in the thesis by Misra (2012).

5.2 Software Selection

It was found in the literature that microscopic simulation is more suitable for capturing driving behaviour in different traffic conditions. This study is focussed on pedestrian-vehicle interactions at urban intersections and its effect on emissions. Therefore, it requires a large amount of detail in dynamic vehicle behaviour. Pursuant to this, microscopic models were considered for this study. Two microscopic vehicle emission modelling software packages were considered. They are MOVES and CMEM.

MOVES is developed by the United States Environmental Protection Agency (Office of Transportation and Air Quality (OTAQ), 2012). The software package is capable of simulating vehicle movements as well as vehicle emissions generation in the modelled area. MOVES can estimate emissions from a variety of vehicle types and vehicle ages. In addition, MOVES is offered with a database of vehicle fleet composition for a large number of counties in the United States. However, since the study area is in Canada, the database could not be used directly for this investigation.
CMEM is developed by UC Riverside (University of California Riverside, 2006). It uses vehicle operation characteristics, as well as vehicle attributes, to determine the engine power requirement of the vehicles in the network. Using this data, CMEM determines fuel consumption and emission generation. Similar to MOVES, CMEM is able to estimate emission generation from a variety of vehicle types and vehicle age. However, CMEM requires the user to input vehicle fleet composition of the modelled region, which makes it more configurable to match the composition of any city. In addition, CMEM is readily available as a plugin for Quadstone Paramics, which makes it the software of choice for this project.

5.3 CMEM Settings

CMEM runs concurrently with Paramics as a plug-in. Figure 5-1 shows the general workflow between Paramics and CMEM. A coding limitation in CMEM only allows it to be run properly with Paramics models using frame rates at powers of 2. That is, CMEM only functions properly when the Paramics model uses 2, 4, 8, or 16 frames per second. In addition, MassMotion’s social forces model is only applicable at frame rates higher than 5. As a result, the lowest usable frame rate in this configuration is 8 frames per second. Thus, the model is run at 8 frames per second to minimize run time.

CMEM is highly sensitive to the type of vehicles and their age, and it breaks down vehicle fleets into 31 possible categories based on their emission patterns. To use these vehicle categories, Misra (2012) used vehicle distribution percentages from the Canadian Vehicle Survey from Statistics Canada and augmented it with the City of Toronto cordon count data (Misra, 2012; DMG, 2004; Stats Can, 2009). Using the same approach as Misra’s study (2012), “medium” and “heavy” vehicle types are combined into the “Medium and Heavy Vehicle” OD matrix, to be used alongside with the “Light Vehicle” OD matrix. The two OD matrices are then used as Paramics input files, and the vehicle distribution of the two OD Matrices are presented in Table 5-1.
Figure 5-1 Components required for the calculation of vehicle emission generation

### Medium and Heavy Vehicle Matrix

<table>
<thead>
<tr>
<th>CMEM Category</th>
<th>Description</th>
<th>Proportion</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>Truck, Gasoline powered, LDT (&gt;8500GVW)</td>
<td>10.02%</td>
</tr>
<tr>
<td>40</td>
<td>Truck, Diesel powered, LDT (&gt;8500GVW)</td>
<td>66.45%</td>
</tr>
<tr>
<td>5</td>
<td>HDD 1994-1997, 4 stroke engine, Electric, FI, Normal emitting</td>
<td>4.80%</td>
</tr>
<tr>
<td>6</td>
<td>HDD 1998, 4 stroke engine, Electric, FI, Normal emitting</td>
<td>1.11%</td>
</tr>
<tr>
<td>7</td>
<td>HDD 1999-2002, 4 stroke engine, Electric, FI, Normal emitting</td>
<td>17.62%</td>
</tr>
</tbody>
</table>

### Light Vehicle Matrix

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

Table 5-1 - CMEM categorization of Light and Medium/Heavy vehicles
Based on the vehicle type distributions and the vehicles’ instantaneous speed and acceleration information, CMEM calculates power consumption and tabulates CO₂, CO, HC, NOₓ emissions, as well as fuel consumption for every link on in the Paramics model. For the purpose of this study, CO and NOₓ emissions are exported to be used as inputs to the emission dispersion model.

5.4 Emission Generation Results

CMEM tabulates the amount of emissions generated on each link and reports the total mass of the emitted pollutants over the study period. To be consistent with the demand periods in Paramics, CMEM was set to report on 15-minute intervals. The Paramics model contains 146 links, all of which have emission factors reported by CMEM. Figure 5-2 and Figure 5-3 show snapshots of the pollutants generated for one 15-minute interval during one of the trials. To simplify the graph, multiple links belonging to certain road segments were grouped together. It is seen that College Street is the major contributors to vehicle emissions. This is expected as all other streets are two-lane streets while College is a four-lane arterial road. Some of the smaller driveways have close to zero emissions for CO and NOₓ. These small driveways had low traffic volumes during data collection, therefore their emission factors were expected to be very low.
Figure 5-2 - Total CO Emissions for trial 1, comparison emissions with and without pedestrians

Figure 5-3 - Total NOx Emissions for trial 1, comparison emissions with and without pedestrians
Figure 5-4 and Figure 5-5 show the total emitted CO and NOx over the 16 different realizations of the simulation as a function of time. Emission results were tallied for the network with and without pedestrians to investigate whether the presence of pedestrians influenced vehicle emissions. Table 5-2 summarizes the fuel consumption, CO2 emission, CO emission, and NOx emission. It is seen that fuel consumption, CO2 emission, and NOx emission are significantly higher in the scenarios with pedestrians than scenarios without pedestrians. These factors have been increased by 8-10% by the addition of pedestrians. However, the same cannot be said about CO emissions. In fact, although the t-stat is not significant enough to reject the null hypothesis for the two-tail test at 95%, CO emissions seem to have decreased in the scenarios with pedestrians.

![Total CO Emission](image)

**Figure 5-4** - Total CO Emission with and without pedestrians (error bars denote expected error in average emission values over 16 trials)
This apparent decrease in CO emissions seems counterintuitive, as one might expect for all vehicle emissions to have a positive correlation with each other, as well as with fuel consumption. However, studies in vehicle emission patterns do suggest that CO emissions for vehicles are significantly decreased at lower speeds, despite an increase in fuel consumption. According to other studies in literature, CO emissions, measured in g/km travelled are the lowest
as vehicle speeds are low, even when there is significant amount of acceleration (Figure 5-6 and Figure 5-7) (Rakha & Ding, 2003; Ding, 2000). This may possibly explain the counterintuitive result from the simulation.

Figure 5-6 – CO (right) and NOx (left) emissions (mg/s) as a function of vehicle speed (Rakha & Ding, 2003)

Figure 5-7 - Fuel Consumption (top left), CO2 emission (top right), CO emission (bottom left), and NOx emission (bottom right) per km (g/km) as a function of vehicle speed (Rakha & Ding, 2003)
Chapter 6

6  Emission Dispersion Modelling

6.1 Literature Review

The dispersion of emission is carried out by the movement and turbulence of air in which the pollutants reside. As a result, the study of emission dispersion involves understanding atmospheric conditions. This ranges in scale from global atmospheric conditions, such as jet streams, air masses, and cyclones, to local weather conditions, such as urban heat island effects and obstacle wakes (Arya, 1999). To study the dispersion of emissions at these different scales, a number of models have been developed in literature. They range from simple box models to complex and resource intensive computational fluid dynamics (CFD) models.

Holmes and Morawska have categorized dispersion models into four groups in an overall review of these models. The simplest form of emission dispersion models is the box model. In box models, the fluids are contained homogenously in a box, where they are allowed to interact physically and chemically amongst themselves. AURORA and CPB are such models (Mensink, Colles, Janssen, & Cornelis, 2003). At higher complexity levels, Gaussian plume models work under steady state conditions to calculate the expansion of emission plumes as they progress through time and space. AERMOD, BLP, and CAL3QCR are such models (Council for Regulatory Environmental Modeling, 2011)(Eckhoff & Braverman, 1995). At even higher levels of details, Lagrangian models mathematically follow the emission plumes and calculate new positions of emission parcels based on their previous locations and probability distributions of their propagation (Holmes & Morawska, 2006). QUIC is one of such emission models (Pardyjak & Brown, 2003). Lastly, Computational fluid dynamic (CFD) models provide highly detailed analysis by resolving the Navier-Stokes equation using finite difference and finite volume methods (Holmes & Morawska, 2006). CFD models include ARIA Local, MSIKAM, and MICRO-CALGRID.
6.2 Model Selection

For this study, a Lagrangian model is utilized to investigate the dispersion of emissions. A similar study conducted at the University of Toronto by Misra (2012) used AERMOD and Quick Urban & Industrial Complex (QUIC) for this purpose (Misra, 2012). AERMOD is an EPA-approved dispersion model that is suitable for a multitude of purposes, including industrial and mobile emission generation (Jungers, Kear, & Eisinger, 2006). QUIC is a fast response model that calculates wind fields around obstacles such as buildings and canopies. It is designed to calculate dispersion for chemical, biological, and radiological material for single buildings or for neighbourhoods (Pardyjak & Brown, 2003). A more thorough review of emission dispersion models can be found in the thesis by Misra (2012). In the study by Misra (2012) it was determined that the NOx concentrations calculated by AERMOD matched the observed values better, whereas the CO concentrations calculated by QUIC had a better match with the observed values (Misra, 2012).

Both models have advantages and limitations. AERMOD’s ability to use high-altitude meteorological data allows it to be more comprehensive than QUIC in terms of air movements. However, this high-altitude data is not available and had to be obtained using interpolation techniques from Lakes Environmental. In addition, AERMOD is only able to incorporate building geometries into its dispersion model for point sources of pollutants. This makes it inadequate for modelling the dispersion of pollutants generated along a road. Misra (2012) also suggested that QUIC models flow around buildings more comprehensively than AERMOD, and the correlation between QUIC’s modelled concentrations and measured concentrations are better than that between AERMOD’s modelled concentrations and measured concentrations (Albeit QUIC’s predicted CO concentrations were consistently higher than measured CO concentrations). Thus, for the purpose of this study, QUIC is the software of choice for modelling emission dispersion.
6.2.1 QUIC SETTINGS

Following emission modelling from CMEM, the data on CO and NOx emission generation are processed and imported into QUIC for emission dispersion modelling. QUIC’s inputs include the dimensions and strengths of the pollutant sources, atmospheric conditions such as wind speed and direction, temperature, and humidity, and the arrangements of the buildings in the study area. Figure 6-1 shows the workflow from CMEM to QUIC.

![Figure 6-1 - Components required in modelling emission dispersion using QUIC](image)

6.2.1.1 Building Geometries

Building geometries are defined in QUIC’s City Builder tool. Building geometry information is obtained from the University of Toronto’s Maps and Data Library (Map and Data Library, University of Toronto). The data are imported into QUIC’s City Builder tool into a 900m x 900m
map. A grid size of 5m x 5m was used in the City Builder tool while importing the data. Because of this, buildings and features smaller than 5m x 5m are not included in the city model. The SOCAAR sensors for CO and NOx concentrations are located at coordinates (482.5, 442.5), shown in Figure 6-2 as a black circle. The sensors are located at 3 metres above the surface.

6.2.1.2 Meteorological Data

Meteorological data for the study area were obtained from SOCAAR’s weather sensors, located on the roof of the Wallberg Building at 200 College Street. These data include air temperature, relative humidity, wind speed, and wind direction reported on a minute-by-minute basis. The data were aggregated into 15-minute blocks by averaging the data points to be used in QUIC. As a result, 10 total time increments were used in QUIC for meteorological data.

QUIC’s wind profile requires additional inputs. These inputs include reference height and surface roughness. A reference height of 20 metres was used to reflect the height of the weather sensor, and a surface roughness of 1m was used based on Engineering Sciences Data Unit (Engineering Sciences Data Unit, 1972). A simulation time step of 10 seconds was used in QUIC.

6.2.1.3 Pollutant Sources

Pollutant source strengths are taken from the CMEM outputs. The Paramics network consists of 146 links, which results in 1460 different sources over the 10 time periods generated by CMEM. To reduce runtimes of QUIC’s dispersion model, links with low emission generation factors were combined to form fewer numbers of sources. The 146 links were grouped to form 16 sources, 11 of which were considered “high intensity” sources, and 5 of which were considered “low intensity” sources. The “high intensity” sources were treated as time varying sources, thus requiring an entry in the input file for each of the 15-minute timeframes in the study period, resulting in 10 entries each in the input file. The “low intensity” sources were treated as constant sources, thus requiring only one entry each in the input files. As a result, a total of 115 sources were used in the QUIC dispersion model.
Each source is considered as a constantly emitting line source, with uniform source density along the line and throughout its emitting duration. Both CO and NOx were treated as un-reactive, non-decaying ideal gases in the QUIC model. Figure 6-3 shows the placement of the “high intensity” and “low intensity” sources. A total of 208800 particles were generated for each realization of the dispersion simulation. Each particle represents a finite dosage of the emitted pollutant. The sources were set at a height of 0.3m above ground level.
Figure 6-3 - Locations of major emission sources (left) and minor emission sources (right)
Chapter 7

7 Emission Dispersion Results and Validation

7.1 Emission Dispersion Results

The emission simulation is run over 16 iterations with different random number seeds, corresponding to the 16 realizations of the vehicle and pedestrian simulation. A sample result from QUIC is in the figure below. It shows the pollutants following the wind (blowing from the southwest). Concentration for CO and NOx are modelled in g/m$^3$. These data are then validated with the observed CO and NOx concentrations on April 2$^{nd}$, 2013. The observed data are provided by SOCAAR’s sensors located at 200 College Street, at a height of 3 m above ground.

Figure 7-1 shows streamlines of air movement at 2.5m above ground. It is seen that wind flows around buildings at this height, and eddies of air current are formed behind buildings. This is expected to happen in this type of weather condition. During emission dispersion analysis, pollutants travel along streamlines such as these as they spread in the study area.

Figure 7-2 to Figure 7-9 show sample outputs of CO and NOx concentrations at 1m above ground level, and 3m above ground level. The pollutant density data at 3m above ground level are to be used in validation with Southern Ontario Centre for Atmospheric Aerosol Research (SOCAAR)'s measured pollutant densities, while the pollutant density data at 1m above ground level are to be used in calculating pedestrian exposure. In the pollutant diagrams at 1m above ground level, distinct lines can be seen on College Street, where the line sources for pollutants are defined. At 3m above ground level, these lines are no longer distinct as the pollutants are more evenly dispersed in the streets.
Figure 7-1 - Calculated Streamlines from QUIC’s QUICURB at a height of 2.5m above ground level
Figure 7-2 - CO Concentration contour at 8:15 am at 1m above ground

Figure 7-3 - CO Concentration contour at 9:00 am at 1m above ground
Figure 7-4 - CO Concentration contour at 8:15 am at 3m above ground

Figure 7-5 - CO Concentration contour at 9:00 am at 3m above ground
Figure 7-6 - NOx Concentration contour at 8:15 am at 1m above ground

Figure 7-7 - NOx Concentration contour at 9:00 am at 1m above ground
Figure 7-8 - NOx Concentration contour at 8:15 am at 3m above ground

Figure 7-9 - NOx Concentration contour at 9:00 am at 3m above ground
7.2 Result Validation

For data validation, modeled concentrations were added to an estimated ambient concentration to give a predicted concentration. The ambient concentrations for CO and NOx were assumed to be equal to the observed concentrations between 3:00-5:00 am on the same day. Therefore, the ambient concentrations of CO and NOx were estimated by calculating the average of the concentration readings from 3:00-5:00 am. As a result, the ambient concentration of CO was calculated to be $2.693 \times 10^{-4} \text{ g/m}^3$, and the ambient concentration of NOx was calculated to be $1.561 \times 10^{-5} \text{ g/m}^3$.

Figure 7-10 and Figure 7-11 show the observed concentrations and the average of the predicted values from the 16 simulation runs. It is seen that the variance between each simulation run is large. The coefficients of variation in each of the 16 data points range between 0.12 and 0.31. By plotting the observed and modeled concentrations, it is evident that the concentration of CO is consistently over-predicted, and the concentration of NOx is closer to the measured concentration (Fig. 3). This result is similar to the result obtained in Misra et al.’s study (2012), where the majority of the predicted CO concentration is considerably higher than the measured CO concentration, and the NOx concentrations were more accurate (Misra, 2012). Further examination using the correlation between the predicted data and measured data shows a coefficient of correlation of 0.31 for NOx and 0.03 for CO. This is also in accord with the findings of Misra et al. (2012), where NOx concentrations were predicted with significantly higher accuracies than CO concentrations.
To further validate this model, a “factor of two” comparison is used. The “factor of two” comparison calculates the percentage of predicted concentration values that fall within a factor of
two from the observed concentration values. This method is widely used to determine the significance of predicted concentrations for emission dispersion models (Arya, 1999). For NOx, 95.6% of the data points fall within this envelope (Figure 7-12), and for CO, 92.5% of the data points fall within the “factor of two” envelope (Figure 7-13).

These results are different from Misra, et al.’s findings, where only 20% of the data points of predicted CO concentrations fell within the “factor of two” envelope. The other 80% of the data points of predicted CO concentrations in Misra, et al's study were higher the “factor of two” envelops. This study uses the same approach as Misra et al's work; however, the predicted CO concentrations are lower. The decreased CO concentrations in this study may be caused by the following two reasons:

First, having a reduced number of lanes on College Street, as well as introducing pedestrians may have altered the way in which emission is generated. The construction may have reduced the speed at which vehicles travelled along College Street, and having pedestrians may have reduced vehicle speeds at all intersections. It is seen in literature that CO emissions are reduced by a larger amount when vehicles are operating at lower speeds, despite the increase in fuel consumption and CO$_2$ emissions (Rakha & Ding, 2003; Ding 2000). This same mechanism may have caused an increase in NOx generation, which may explain why some of the predicted concentrations for NOx are higher than the "factor of two" envelope.

The second reason may be in the difference in the building geometries used in the dispersion model. In Misra, et al.’s study, building geometries were manually defined in QUIC; some of the smaller houses south of College Street were aggregated into strips of structures (Figure 7-14). This study, however, did not make such aggregation (Figure 7-15). This may have allowed air currents to move more freely in the study area, thus dispersing CO more effectively, resulting in a lower CO and NOx concentration. However, having a reduced number of lanes and having pedestrians hinder vehicle movements may have increased the generation of NOx, as explained above. This may have balanced out the effect of having smaller buildings in the area for NOx concentration.
Figure 7-12 - "Factor of two" comparison between predicted and Measured NOx concentrations

Figure 7-13 - "Factor of two" comparison between predicted and Measured CO concentrations
Figure 7-14 - Building geometries used in Misra (2012)'s QUIC Model

Figure 7-15 - Building geometries used in current QUIC Model
7.3 Pedestrian Exposure

The calculation of pedestrian exposure to roadside pollutants involves the integration of pedestrian locations into the pollutant concentration map. By lining up pedestrian coordinates with the sidewalks of the street network, it is possible determine the different levels of concentrations of CO and NOx to which pedestrians are exposed as they navigate around in the study area. Figure 7-16 shows the path taken by a pedestrian agent entering the study area on the west end of Russell Street and leaving the study area on the east end of College Street. The concentrations of CO and NOx to which this agent is exposed are shown in Figure 7-17 and Figure 7-18. For this particular agent, it is seen that the concentrations before t=120s is relatively low. This is as the pedestrian travels along St. George Street, where the pedestrian is standing upwind from the road. Thus, the majority of the concentrations to which the pedestrian is exposed in the first two minutes are the ambient concentrations (denoted by the dotted lines). It is then seen that as the agent waits to cross St. George Street at College Street, the concentration values for both CO and NOx plateau and remain constant. After the agent crosses St. George Street and continues walking on College Street on the north side, concentrations of CO and NOx drops slightly, but remains at higher values than the concentration that the agent was exposed to while walking on St. George Street. This may be caused by a combination of two factors. First, the amount of emissions generated on College Street is significantly higher than those generated on St. George Street; Secondly, the agent travels on the north side of College Street, which is downwind from the road, where the emissions are generated.

There is significant variation in concentration values as the pedestrian walks along College Street. It is highly likely that this variation is caused by the stochasticity of QUIC’s dispersion model.
Figure 7-16 - Sample path of a pedestrian through the CO concentration map

Figure 7-17 - CO concentration levels along sample path of travel (trendline show 5-second averages)
7.3.1 **Total Pedestrian Exposure**

Total pedestrian exposure for this network is calculated by tabulating the total amount of pollutant to which the pedestrians are exposed as they move through this area. To show pedestrian exposure for the study area, an “exposure” map can be generated based on the following rules:

- The amount of exposure at each location increases as pollutant density at the location increases
- The amount of exposure at each location increases as pedestrian traffic increases

Each location can be considered as a cell in the map, and based on the rules above, the amount of “exposure” for each cell $i$ in the “exposure” map can then be calculated as

$$ \text{Exposure}_i = \sum_{t=0}^{T} \text{Population}_i(t) \times \text{Density}_i(t) $$

Where

$\text{Population}_i(t)$ is the number of pedestrians in cell $i$ at time $t$,
Density_i(t) is the pollutant density in cell i at time t, and

T is the end of the study period.

In this study, each location is a 5m x 5m cell used in the QUIC emission dispersion model. The unit for Exposure_i would be measured in g·s/m³ for each cell. In order to normalize this by the area of each cell, the unit for normalized exposure in the map would be persons·g·s/m⁵, denoting the sum of all pedestrians' exposure to different concentrations (g/m³) of pollutant over time (s) per unit area (1/m²).

It is expected that the amount of exposure at intersections and crossings be high compared to all other locations in the study area. Intersections are where vehicles idle and accelerate, thus a large amount of emission is generated. In addition, pedestrians also wait for their opportunities to cross at intersections, either by waiting for the signals or by waiting for a suitable gap in vehicle traffic. For this study area, this effect is expected to be especially true for the St. George and College Street intersection, as College Street is a major arterial road, and pedestrian crossings at this intersection experiences significant volume.

Figure 7-19 shows the exposure map for the study area from 8:00 am to 10:30 am. This map was obtained by averaging exposure values for all 16 runs of the simulation. It is evident from these figures that pedestrians on sidewalks are exposed to some emissions, but the majority of the exposure occurs at intersections and crossings. This is especially true for the intersection of St. George Street and College Street. The sidewalks along College Street experience 0.05-0.1 persons·g·s/m² of CO and 0.005-0.015 persons·g·s/m² of NOx, while the Northeast corner of the intersection of St George Street and College Street experiences 0.35-0.4 persons·g·s/m² of CO and 0.04-0.045 persons·g·s/m² of NOx. The signalized pedestrian crossing between the Bahen Centre for Information Technology and the Galbraith Building (north of the St. George and College Street intersection) also experiences significant exposure to emissions, at 0.2-0.3 persons·g·s/m² of CO and 0.03-0.035 persons·g·s/m² of NOx.
Figure 7-19 - Pedestrian exposure map (persons·g·s/m²) to predicted concentrations of CO (left) and NOx (right)
8 Policy Assessment and Scenario Testing

The development of this framework creates an additional tool to test the impact of a policy related to pedestrian-vehicle interaction, and investigate its effect on traffic flow, vehicle emissions, and pedestrian exposure to the emissions. One such policy is the decision to implement a “scramble” intersection, where pedestrians are given a phase in which they are allowed to cross the intersection in any direction.

At intersections where pedestrian volumes are high, pedestrian movements prohibit efficient movement of vehicles, as turning vehicles must yield to pedestrians. Some intersections implement advanced green for turning vehicles as a solution, where turning vehicles have a phase of their own, during which they have the right-of-way over all other movements. This works well when there are enough lanes on the roads to accommodate the different types of movements, but it becomes more difficult when lane numbers are limited and through-traffic must wait for turning traffic in the same lane.

The other way to reduce delays due to pedestrians is by adding a “scramble” phase in the signalling system. “Scramble” intersections are prominent in urban centres in Japan, where pedestrian volumes are high and space is limited (Glionna, 2011). At these intersections, pedestrian movements are not allowed during phases in which vehicle movements are allowed, and a designated “scramble” phase is added in the cycle, in which pedestrians are allowed to move in all directions, including moving diagonally across the intersection.

In Toronto, variants of such “scramble” intersections are located at Yonge and Bloor, Yonge and Dundas, and Bay and Bloor. This set of policy assessments can be used to investigate whether the pedestrian traffic at the intersection of College Street and St. George Street warrants the implementation of a “scramble” phase signalling system.
8.1 Description of Scenarios

Three scenarios were tested with this approach, to determine the effect of pedestrian-vehicle interactions on vehicle emissions and pedestrian exposure to vehicle emissions. The scenarios are as follows:

- Scenario I: Current Scenario: a construction site on the intersection of College and St. George Street takes out the right-most eastbound lane on College Street at the western approach of the intersection
- Scenario II: No Construction: the construction site is removed, restoring the intersection to its full capacity
- Scenario III: Type I Scramble intersection – an additional “scramble” phase is added to the College and St. George intersection, where pedestrians can cross in all directions, including diagonals; no vehicles movements are allowed during this phase. However, no pedestrian movements are allowed during any other phase. The timings of the phases are as follows:
  - College Street – Green time for East-West movement: 40s green, 3s amber, 2s all red
  - St. George Street – Advanced Green time for southbound left turning vehicles: 8s green, 2s amber
  - St. George Street – Green time for North-South: 30s green, 3s amber, 2s all red
  - Pedestrian Scramble – Green time for all pedestrians: 25s

This signalling system reduces the effective green time ratios of all vehicles, as well as pedestrians travelling in any direction. It has the potential to significantly decrease the capacity of the intersection and increase total travel time.

- Scenario IV: Type II Scramble intersection – this scenario is identical to Scenario III, with the exception that pedestrian movements are allowed during vehicle movement phases. That is, when eastbound and westbound vehicles are allowed to move, pedestrians are also allowed to cross eastwards and westwards. This scenario impedes vehicle movements even further by reducing their effective green time ratios, as well as
hindering turning movements. However, this type of scramble increases total green time ratios for all pedestrians to decrease total pedestrian travel time.

Scenario I is considered as a temporary scenario. It was used in this study as a benchmark to assess the accuracy and reliability of the modelling approach as the construction site was expected to be removed by May of 2013. Scenario II is considered as the default scenario, where all operations are executed normally. Scenario III and IV are considered the policy-sensitive scenarios, and they are being tested against Scenario II. In all four scenarios, pedestrian and vehicle OD demands remain the same, weather data is also held constant. Each scenario is run 16 times from vehicle and pedestrian simulation to pedestrian exposure. For each of the scenarios, average vehicle and pedestrian travel times, vehicle emission generation patterns, and total pedestrian exposure to emissions are compared.

### 8.2 Vehicle and Pedestrian Delays

The first and foremost effect of modifying a road network is the impact it has on the performance of the vehicles and pedestrians that use the network. These changes in performance lead to changes in efficiencies for the vehicles, and changes to the amount of time during which the pedestrians are exposed to vehicle emissions. It is expected that having construction and removing one of the lanes causes substantial vehicle delays. Thus, removing the construction site in Scenario II would greatly improve vehicle efficiency and vehicle speed.

In Scenario III, no pedestrian movements are allowed outside of the “scramble” phase. Turning vehicles would be allowed to turn freely without having to wait for pedestrians. This would reduce idling and decrease vehicle emissions generated by turning vehicles, but increase total idling time due to the additional red times experienced by each approach. However, having reduced the green time for pedestrians at the intersection means pedestrians are exposed to emissions for longer periods of time. It is difficult to assess whether the overall amount of exposure to vehicle emissions for the pedestrians would increase or decrease without quantitative analyses.
In Scenario IV, pedestrian movements are allowed outside of the “scramble” phase. Turning vehicles are required to wait for pedestrians crossing on adjacent sidewalks, just as in Scenario II. However, total idling time is increased due to the additional red times experienced by each approach. Pedestrians, in this scenario, would have a higher effective green time ratio at the intersection, therefore reducing the amount of time during which they are exposed to the pollutants. It is expected that the total exposure in Scenario IV to be lower than that in Scenario III.

The level performance of the network in terms of vehicle efficiency is indicated by vehicle travel speed as they navigate through the network. Figure 8-1 shows the average vehicle speeds on College Street and St George Street. The links on which these speeds were calculated are shown in Figure 8-2. A lower vehicle speed would indicate more congestion. From the graph, it is evident that having construction (Scenario I) yields lower vehicle speeds than having no construction (Scenario II). This is expected as having a reduced number of lanes reduces the capacity of the roadways. It is also evident that having a Type I Scramble intersection (Scenario III) also has lower vehicle speeds than having a normal signalling system (Scenario II). This may be caused by the fact that the number of pedestrians crossing at this intersection was not high enough to significantly hinder turning vehicle movement. Should the pedestrian volume be increased, it is possible for pedestrian impact on turning vehicles to be more severe, and having a scramble intersection to be more beneficial to the vehicle movement. Having a Type II Scramble intersection further reduces average vehicle speeds, due to decreased effective green time ratios as well as the requirement to yield to pedestrians. This effect is as expected.
Figure 8-1 - Average vehicle speeds as a function of time (error bars denote expected error in sample mean)

Figure 8-2 – Paramics links used in calculating average vehicle speeds
Pedestrian travel times are also affected by the changes introduced in Scenario III and Scenario IV. Figure 8-3 shows the average amount of time a pedestrian spends in the network for all three scenarios. By disallowing pedestrian movement in all but the “scramble” phase in Scenario III, pedestrians are required to wait for longer periods of time at the intersection of College Street and St. George Street for an opportunity to cross the intersection. While in Scenario IV, by granting pedestrians an increased effective green time ratio, their travel time is reduced. Over the 16 realizations of the simulation, it is evident that the average travel times for pedestrians in Scenario III are higher than those in Scenario II, and the average travel times for pedestrians in Scenario IV are lower than those in Scenario II. The t-stat values on the difference between Scenario II and Scenario IV, as well as that between Scenario II and Scenario III, are well above 1.75, which is the required value for a one-tail 95% confidence t-test.

![Average Pedestrian Travel Times (S)](image)

**Figure 8-3 - Comparison of pedestrian walk times**

From the vehicle and pedestrian movement data, it is seen that vehicles travel slower in Scenarios III and IV, and pedestrians also spend more time in the network in scenario III. This may be an indication that a scramble intersection at St George and College Street would increase pedestrian exposure to emission.
8.3 Vehicle Emission Generation

CMEM outputs for all 16 realizations in each of the three scenarios are aggregated below in Figure 8-5 to Figure 8-8. It is seen that, while fuel consumption and CO$_2$ emission is higher in the construction scenario than the no construction scenario, CO emission is significantly lower in the construction scenario than the no construction scenario. This negative correlation between fuel consumption and CO emission seemed counterintuitive, as one might expect the two be positively correlated. However, as suggested in Section 5.4, studies in literature do suggest that CO emission is significantly lower at low speeds, despite having higher fuel consumption (Rakha & Ding, 2003; Ding, 2000).

In comparing Scenario II with Scenario III and Scenario IV, it is seen that Scenario III and IV has slightly more NOx emissions and slightly less CO emissions. Due to the relatively large standard deviation in the individual data points across the 16 trials, the t-stats for these values are not strong enough to show a difference at 95% confidence for each of the time intervals. However, by summing up the CO and NOx emissions generated over the entire study period, it is seen that the generation of CO in Scenario III is 3.4% less than Scenario II (t-stat of 1.61), and the generation of NOx in Scenario III is 2.9% more than in Scenario II (t-stat of 5.55); the generation of CO in Scenario IV is 3.7% less than Scenario II (t-stat of 3.5), and the generation of NOx in Scenario IV is 7.0% more than in Scenario II (t-stat of 6.2).

<table>
<thead>
<tr>
<th></th>
<th>Scenario I</th>
<th>Scenario II</th>
<th>Scenario III</th>
<th>Scenario IV</th>
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</thead>
<tbody>
<tr>
<td>Total NOx Emission (g)</td>
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<td>2004.0±25</td>
<td>2063.4±27</td>
<td>2145.0±32</td>
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<tr>
<td>Total CO Emission (g)</td>
<td>22108±128</td>
<td>23968±102</td>
<td>23144±107</td>
<td>23066±103</td>
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</table>

Table 8-1- Comparison of NOx and CO emissions between all scenarios
Figure 8-4 - Average of total fuel consumption over 16 trials (error bars denote expected error in sample mean)

Figure 8-5 - Average of total CO₂ emission over 16 trials (error bars denote expected error in sample mean)
Figure 8-6 - Average of total CO emission over 16 trials (error bars denote expected error in sample mean)

Figure 8-7 - Average of total NOx emission over 16 trials (error bars denote expected error in sample mean)
8.4 Emission Dispersion and Pedestrian Exposure to Emissions

Emission dispersion modelling is carried out for all 16 trials of each scenario in QUIC using the same weather data. The same technique for assessing pedestrian exposure is also used to calculate the exposure map. The emission “exposure” maps, as generated in 7.3, are useful in terms of determining locations of maximum exposure. However, it is difficult to assess the total amount of exposure in a network based on the map alone. In order to quantitatively assess the amount of exposure and compare the health impacts of each scenario, the total amount of exposure is calculated by summing all the exposure values in each cell $i$ using the following equation

$$Total\ Exposure = \sum_{i} Exposure_{i}$$

This value was calculated for all 16 realizations of the three different scenarios. The unit of exposure in this case is persons·gs/m³. This is a measure of total exposure of certain concentrations of pollutants over all pedestrians within the time period. The data are presented as box plots in Figure 8-9 for CO exposure and Figure 8-10 for NOx exposure. It is seen that exposure to CO is the lowest in the scenario with construction, and highest in the scenario with the scramble signalling system. The exposure to NOx is lowest in the scenario with no construction and highest in the scenario with the scramble signalling system.

Table 8-2 quantitatively summarizes the total exposure to predicted concentrations of CO and NOx. While comparing Scenario II to Scenario III, CO exposure is increased in Scenario III by 6%, with a T-stat of 23.4, NOx exposure is also increased in Scenario III by 10%, with a t-stat of 7.58. While comparing Scenario II to Scenario IV, CO exposure is decreased in Scenario IV by 2.6%, with a T-stat of 8.5, NOx exposure is also increased in Scenario III by 4.2%, with a t-stat of 2.7.
Figure 8-8 - Box plots of all 16 data trials of calculated total exposure to predicted CO concentrations

Figure 8-9 - Box plots of all 16 data trials of calculated total exposure to predicted NOx concentrations
### Average NOx Exposure (persons·g·s/m³)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Average Exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario I</td>
<td>57.2±0.6</td>
</tr>
<tr>
<td>Scenario II</td>
<td>54.5±0.5</td>
</tr>
<tr>
<td>Scenario III</td>
<td>60.1±0.5</td>
</tr>
<tr>
<td>Scenario IV</td>
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*Table 8-2 - Average total exposure to predicted concentrations of CO and NOx for all scenarios*

This is within expectations. As shown in earlier sections, having construction and having a scramble intersection effectively slows down vehicles within the study area, thus increases the emission of NOx and decreases the emission of CO. However, having a Type I Scramble intersection increases the red times for the pedestrians, therefore keeping them waiting at the street corners for a longer period of time. They are then exposed to higher concentrations of pollutants, thereby increasing the total amount of pollutants to which they are exposed. Having a Type II Scramble decreases the amount of time a pedestrian spends at the intersection, thereby decreasing the total amount of pollutants to which they are exposed. This decreases total exposure for CO and offsets the effect of being exposed to increased concentrations of NOx.

At this intersection, where the number of pedestrians crossing is low, the presence of pedestrians do not hinder turning vehicles’ movement enough to increase vehicle emission generation by a large amount. It is more beneficial, in the perspective of minimizing pedestrian exposure to vehicle emissions, to have the pedestrians go through the intersection as quickly as possible.

### 8.5 Summary of Findings

Three scenarios are tested in this section. The default current scenario where construction has taken out one of the lanes on College Street (Scenario I), the standard scenario where construction is finished and the number of lanes has returned to normal (Scenario II), a scenario in which a Type I Scramble phase signalling system is implemented at the intersection (Scenario III), and a scenario in which a Type II Scramble phase signalling system is implemented at the intersection (Scenario IV). In terms of policies affecting intersection design, only scenario II, Scenario III, and Scenario IV need to be compared.
In both Scenario III and Scenario IV, it is seen that vehicles move through the study area at lower speeds. This increases the total generation of NOx and decreases the total generation of CO. By adding a Type I Scramble signalling system at the intersection, it is seen that pedestrians take more time to travel in the study area. As pedestrians are required to spend more time in the study area, pedestrian exposure to both CO and NOx is increased. Scenario IV is slightly different than Scenario III. As pedestrians are able to move outside of the scramble phase, the total time spent at the intersection is reduced. Therefore, total exposure to CO is decreased, and total exposure to NOx is increased by a lower amount than that in a Scenario III.

With these results, it is not recommended to implement such signalling system at the intersection of St. George Street and College Street purely on the standpoint of reducing pedestrian exposure to vehicle emissions. Neither of the scramble signalling systems yielded definitive decrease in exposure to both CO and NOx, and it is seen that total emission of NOx is significantly increased from having a scramble intersection.

### 8.6 Comparison of predicted and measured concentrations with NAAQO

To understand the level of details being investigated in this study, it is worthwhile to compare the results of the analysis and the measured concentrations with NAAQO standards for airborne pollutant concentrations obtained from Environment Canada (1999).

Measured and predicted concentrations of CO were plotted against the maximum desirable concentrations of CO for an 8-hour exposure period. Similarly, measured and predicted concentrations of NOx were plotted against the maximum acceptable concentrations of NOx for a 24-hour exposure period.

Through this comparison, it is seen that the concentrations of both pollutants at the intersection of St George Street and College Street are small compared to the levels presented in NAAQO. Measured and predicted CO concentrations are roughly 10% of the maximum desirable concentrations; measured and predicted NOx concentrations are roughly 16% of the maximum.
acceptable concentrations (Figure 8-11, Figure 8-12). At these levels, the differences between the measured and predicted concentrations of all scenarios are fairly indistinguishable. This should also be taken in consideration when examining the difference in total pedestrian exposure presented in Section 8.5. Although a scramble intersection leads to more total exposure due to longer exposure times, the total concentration in this study area is well below the NAAQO standards, even for prolonged periods of exposure. The amount of “harmful” exposure is essentially zero. From the standpoint of pedestrian health, the metric of total exposure may be more suitable when pollutant concentrations are high enough to pose health hazards through prolonged exposure.

Figure 8-10 Predicted and Measured CO Concentration vs NAAQO Standards for 8-h exposure
Figure 8-11 - Predicted and Measured NOx concentrations vs NAAQO Standards for 24-h exposure
Chapter 9

9 Limitations and Errors

As with all modelling approaches, the framework presented in this paper has its limitations and errors. This chapter outlines the general limitations of this approach and the sources of errors in this framework. The main limitation lies within the formulation of the pedestrian-vehicle interaction model. In addition, errors can exist in any component in this study, which includes the micro-simulation of pedestrians in MassMotion, the micro-simulation of vehicles in Paramics, the emission generation process, the emission dispersion process, and the integration of pedestrian locations into the pollutant density map generated by the emission dispersion model.

9.1 Limitation in the pedestrian-vehicle interaction model

As described in Section 4.2, the model for pedestrian-vehicle interaction is based on two types of interactions. The first type prevents vehicles from colliding with pedestrians on the road, and the second type prevents pedestrians from walking onto the road when there are incoming vehicles. Neither of these interactions would prevent a pedestrian who is already on the crosswalk from walking into a vehicle on the crosswalk.

To model the way a pedestrian would navigate around a stopped vehicle, it would require the pedestrians to consider the vehicle as an obstacle in its path. MassMotion’s social forces engine would not easily allow this as it does not allow obstacles to be movable. Upon the loading of a MassMotion network, the software pre-calculates walkable surfaces using floor geometries, link geometries, and obstacle locations. This process takes considerable computation time and recalculating this between each timeframe was considered infeasible. A proposed solution was to consider the vehicles as large pedestrians. However, MassMotion’s pedestrian agents are coded
to simply queue after each other instead of walk around each other. Therefore, this method was also considered as infeasible.

As a result, a workaround was developed in the software to open and close gates as pedestrians detect gaps in vehicle traffic before crossing. For this study area, where the volume of vehicles and pedestrians are relatively low and congestion is not prevalent, the occurrence of a pedestrian colliding with a stationary vehicle is also rare.

### 9.2 Sources of Errors

The main potential sources of errors associated with each component within this approach are listed below. These errors are categorized into primary sources of errors and secondary sources of errors. Primary sources of errors are generated by the current component in the overall approach, and secondary sources of errors are propagated from previous components. The secondary sources are presented in italics.

- **Data Collection**
  - Loss of data due to iPhone battery outage
  - Human errors in counting vehicles and pedestrian volumes
  - Errors in estimating OD matrices

- **Paramics Traffic Micro-simulation**
  - Network development and roadway geometry in Paramics
  - *Errors in vehicle OD matrices*
  - Core simulation input parameters (headway, reaction time, etc.)

- **MassMotion Pedestrian Micro-Simulation**
  - Network development, sidewalk geometries, and locations of building entrances and exits
  - *Errors in pedestrian OD matrices*
  - Errors in pedestrian routing algorithm and pedestrian movements in the MassMotion core simulation parameters
• Pedestrian-Vehicle Interaction
  o Errors in parameters of “watch area” and “danger area”
  o Errors in the rate of deceleration in vehicles when avoiding pedestrians

• Emission Generation in CMEM
  o Errors in vehicle type distribution
  o Error in link assignment from Paramics
  o Driving profile output from Paramics, including errors due to stochasticity in Paramics

• Dispersion Modelling in QUIC
  o Network development in QUIC
  o Building geometry and terrain data in QUIC
  o Input source emission rates from CMEM
  o Emission source placement and aggregation of emission sources
  o QUIC parameters, such as boundary layer properties, grid size, time steps
  o Variability in weather data, such as wind speed, wind direction, temperature, and humidity as a function of elevation
  o Errors due to stochasticity in QUIC

• Calculation of Pedestrian exposure to emissions
  o Errors in pollutant concentration map from QUIC
  o Errors in pedestrian positions from MassMotion
  o Geometric mismatches from MassMotion model to QUIC building geometries
  o Errors from stochasticity in QUIC and MassMotion

9.3 General Limitations

There are other limitations associated with this approach to model urban vehicle emissions other than the numerical errors described in 9.2. They are briefly listed below:

• The assumption that NOx behaves as an ideal gas in the dispersion model disregards the chemical reaction of NOx with VOCs, heat, and sunlight to form ozone and other chemical
by products. This may cause slight over-estimation of NOx concentrations in the study area.

- This approach does not consider the effects of precipitation. However, it is not relevant to this study as there was no rain or snow during the study period.
- Only morning peak traffic period between 8:00 am and 10:30 am on one day was considered due to the lack of available data on pedestrian and vehicle flows. This day was also an abnormally cold day \((-4^\circ)\) close to University of Toronto’s final exam period in the spring term, which may have decreased the total number of pedestrians counted in the area.
- Jaywalking is not modelled in this approach. Jaywalkers in the study area do not significantly hinder vehicle traffic, i.e. jaywalkers will only cross the road if the gap between vehicles is sufficient for the pedestrian to cross without causing the vehicle to slow down. Nonetheless, this research is only aimed at the legal moves that are made by pedestrians and vehicles.
- The presence of cyclists was not modelled in this approach. Cyclists may be exposed to higher concentrations of pollutants as they are located closer to vehicles on the roads.
- The weather data for the emission dispersion modelling was obtained from a single weather sensor located on top of the Wallberg Building. This is a single location and it may be highly affected by street canyon effects.
- Paramics vehicles are generated with zero velocity in the origin and destination zones. These vehicles then accelerate to their full speed in a short period of time, causing errors in emission generation rates.
- Traffic induced turbulence was not accounted for in this model, which is shown to be a significant factor in urban emissions (Kastner-Klein, 2003). Initial velocities of the emitted gases from tailpipes were also not accounted for by QUIC.
- The concentrations of CO and NOx investigated in this study are relatively low compared to the NAAQO standards for human wellbeing. Although pedestrian exposure varies between the scenarios, the concentration levels are well below the human threshold. This method of calculating total exposure to different concentrations of pollutants may be
more suitable when concentrations are higher, where prolonged exposure is detrimental to human health.

- This method compares pedestrian exposure to emissions only when they are travelling on the sidewalk. The recommendation made in Section 8.5 does not consider the amount of pollution to which people inside the buildings are exposed.
Chapter 10

10 Conclusion

Motor vehicles are a significant source of man-made hazardous airborne pollutants. Several models exist in literature to quantify the emission and dispersion of these pollutants. With the recent increase in computational power, integrated approaches in modelling and estimating vehicle emissions became more feasible and viable. Using a microscopic vehicle simulation and highly detailed emission generation and dispersion models, Misra, et al. (2012) created an integrated framework to estimate the concentrations of roadside pollution in an urban environment. It was found that the concentration of roadside airborne pollutants depended not only on vehicle engine technology and traffic conditions, but on weather data as well.

This study introduces additional components to the framework and incorporates the micro-simulation of pedestrians in the process. This makes for a better estimation of traffic behaviour as the interactions between vehicles and pedestrians are captured in the process. It also makes it possible to track the amount of exposure to roadside airborne pollutants of all pedestrians as they move through an area. This makes it possible to determine the potential health impact an area might have on its pedestrians based on the amount of pollutants to which the pedestrians are exposed. With this factor, transportation policy decisions can be made to improve the overall health impact of urban streets.

10.1 Summary and Contributions

The following is a list of key points summarizing the work, contributions, and findings of this research:

- A set of OD matrices for pedestrian movements were estimated from link flow information using an application of a genetic algorithm.
• A two-way interaction between pedestrians and vehicles has been successfully implemented to model the behaviour of vehicles yielding to pedestrians and pedestrians’ gap acceptance to vehicles as they approach uncontrolled pedestrian crossings.

• This two-way interaction was integrated into a complete framework to estimate pedestrian exposure to vehicle emissions as they navigate around in an urban area.

• Vehicle traffic performances from scenarios with and without pedestrians are compared with each other to investigate the impact of pedestrians on vehicle movements. It was found that NOx and CO₂ emissions, as well as fuel consumptions, are increased when the road network is congested, but CO emissions are decreased. This may be caused by the decreased amount of CO emissions when vehicle speeds are low.

• The following components in Misra, et Al.’s (2012) work are also included in the scope of this research:
  o Emission generation modelling using CMEM to calculate vehicle emissions generated on all links in the network;
  o Emission dispersion modelling using QUIC to calculate roadside pollutant concentrations;
  o Calculation of predicted CO and NOx concentrations by adding modelled and predicted concentrations together;
  o Validating roadside pollutant concentrations with observed concentrations by comparing predicted CO and NOx concentrations with measured concentrations by SOCAAR’s sensors on College Street. It was found that the correlation between predicted concentrations and measured concentrations are similar to that in Misra et al.’s research, but a larger ratio of predicted CO concentrations are within the “factor of two” envelope of the measured CO concentrations;
  o Comparison of predicted and observed concentrations with NAAQO standards to understand the level of detail in the prediction.

• The comparison of vehicle traffic performance, pedestrian travel times, vehicle emissions, and pedestrian exposure to emissions in three different scenarios with different intersection designs, including a scenario with reduced number of lanes and two
scenarios with two types of “scramble” signalling systems. It was found that CO emissions are decreased and NOx emissions are increased in the scenario with reduced number of lanes and both “scramble” scenarios. However, due to the prolonged exposure of pedestrians to the pollutants due to prolonged pedestrian travel times at the type I “scramble” intersection, total pedestrian exposure is increased for the Type I “scramble” scenario, and the decrease in pedestrian travel times at the type II “scramble” intersection is not enough to offset the effect of the increase in NOx generation.

10.2 Future work

The components introduced in this research constitute a significant addition to the existing integrated framework to estimate vehicle emissions in urban areas by Misra (2012). This research incorporates the positions and locations of pedestrians in vehicle emission generation as well as calculating pedestrian exposure to emissions. In today’s society, the framework presented in this research can be readily used to assess different roadway designs and their impact on pedestrian health. It is another step towards a truly comprehensive study of population exposure to vehicle emissions in urban areas. This research, along with Misra’s work, forms some of the core components (enclosed by the dashed line) of a framework to understanding population exposure to vehicle emissions shown in Figure 10-1.

One of the major components missing in this research is the modelling of jaywalkers. Using the current framework, jaywalkers may be incorporated by adding gated links in the pedestrian model, which can only be used by a certain portion of pedestrians and are closed when vehicles are in their proximity. The same concept can be used to model pedestrians with different levels of “aggression” as they approach crosswalks. Some pedestrians may accept higher gaps in vehicle traffic than others when crossing. This can be modelled by using multiple links to represent a single crossing, and assign these links to “danger areas” with different lengths.
Furthermore, the results of this study can be improved by addressing any of the limitations presented in chapter 9. One important limitation in this research is the lack of micro-scale interactions between pedestrians and vehicles as pedestrians navigate around temporarily stopped vehicles. The other limitation is the lack of multiple weather and pollutant concentration sensors in the area to effectively measure overall wind speed and pollutant concentrations. Having a more comprehensive wind speed data can greatly reduce the errors in horizontal wind speed measurements caused by local turbulences and street canyon effect.

In order for this framework to be used in an estimation of total population exposure to vehicle emissions, it is important to consider the cyclists who are also travelling alongside the vehicles and pedestrians. It may also be important to examine the infiltration of emissions in buildings and the exposure of those who are indoors. These additions to the framework would be substantial and requires separate components and multi-disciplinary expertise. It is with strong hope that further research can be built onto this framework to a form a truly comprehensive and well-defined tool for estimating population exposure to vehicle emissions.
11 Works Cited


## 12 Appendix

### 12.1 Collected Vehicle Flow Data

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12.3 Pedestrian OD matrix

The above is the pedestrian network, with Origin and Destination zones labelled from zone 1 to 31. The OD matrix below is the total OD matrix for the entire study period (2.5 hours).
12.4 CMEM Output for one 15-minute period

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Cumulative Emissions (grams)

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