VALIDATION OF AN EMISSIONS-DISPERSION MICROSIMULATION MODEL USING SENSOR DATA

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Introduction

Air pollution is known to be a major health issue for people in Toronto, as well as other major jurisdictions in the world. The US EPA specified criteria pollutants have severe health impacts on human population (US EPA, 2012). Research indicates that high density traffic locations in urban areas are a major source of vehicular emissions (Campbell, et al., 1995) and locations in close proximity to busy roads typically have higher emission concentrations (Hoek, 2002). Thus, it is essential to understand the spatial distribution of pollutants that are emitted from vehicles, such as carbon monoxide (CO), hydrocarbons, and nitrogen oxides (NOx), in order to quantify effects of air pollution on the local population. Since there are very few pollutant measuring stations in Toronto, an integrated modelling framework has been developed to simulate traffic, emissions and the dispersion of emissions to specific locations at various times of day (Roorda, et al., 2011). This research investigates the application of a similar three-step methodology on a small network to model the spatial variation of CO concentrations in the near-field. Emissions sensors installed in the study area measure actual atmospheric pollutant concentrations for the study period, and these measured concentrations are used to validate the modelling framework.

A combination of Quadstone Paramics traffic microsimulation model (Quadstone Paramics) and CMEM emissions model (University of California, 2009) is used in this research. CMEM is a microscopic emissions model that applies a power-demand modal modelling approach to estimate emission factors on network links. The process of emission generation within a vehicle is divided into components that are representative of the physical vehicle operation and emissions generation. Thus, it takes into account the micro-simulated driving profile as well as engine specifications of individual vehicles (Scora, et al., 2006). As a result, it is known to perform better when compared to average speed emission models such as MOBILE6 (Ahn, et al., 2008). MOVES is another emissions model capable of estimating microscopic traffic emissions (US EPA, 2010). However, for this project CMEM was selected as the emissions model due to its seamless integration with the Paramics traffic microsimulation model.

Numerous studies have been conducted to assess the individual accuracy and performance of microscopic emission and traffic microsimulation systems; however, either the modelled results have not been verified against local measurements or the systems have not been integrated. For instance, (Barth, et al., 2001) compared CMEM outputs to observed vehicular emissions in different traffic situations. However, the system accuracy was verified only for individual vehicles, and not for multiple vehicles progressing through a system.

Population exposure to vehicular emissions has also been studied, however, these studies use pre-existing dispersed pollutant data, so the simulation of atmospheric pollution due to vehicular traffic is entirely bypassed. (Ishaque, et al., 2008) applied a similar modelling process that involved traffic microsimulation, emissions modelling, and dispersion modelling on a small network; although the modelled pollutant concentrations were not compared with observed values.

CMEM provides emission factors within the microsimulation network that are subsequently input into dispersion models to observe the movement of pollutants in the atmospheric under the given meteorological conditions. Dispersion models have been generally classified into Box Models, Gaussian models, Lagrangian or Eulerian models and Computational Fluid Dynamics (CFD) models by (Holmes, et al., 2006) who performed a detailed review of dispersion models. Gaussian plume models are the most popular models that have been applied to evaluate vehicular emissions. Several studies have used Gaussian plume based line source models such as CAL3QHC, CALINE4 and AERMOD to evaluate pollutant concentrations in the near-field. For instance, (Vincent, et al., 2010) used CALINE4 to compare highway generated ultrafine particles with observed values; however, their traffic data was not based on traffic microsimulation modelling. Further, (Chen, et al., 2009) evaluated and compared the performance of CALINE4, CAL3QHC and AERMOD for prediction of PM2.5. Even though AERMOD is data intensive, it can handle larger networks compared to CAL3QHC (Roorda, et al., 2011) and can better model atmospheric conditions (Chen, et al., 2009). AERMOD is also the current US EPA regulatory model for near-field dispersion evaluation (Cimorelli, et al., 2004). In this research, a custom built Gaussian plume model was developed and compared with sensor observations within the study network. AERMOD was also used to generate concentration contours for the network, and the observed values were analysed.

Methodology

Traffic Count Survey

A small road network was identified at the intersection of College Street and St. George Street, near the University of Toronto. Traffic was monitored from 6:30 am to 9:00 am on June 8, 2011 in five minute intervals at 10 locations within one to two blocks of the intersection, shown in Figure 1. Nine vehicle classes were counted separately including cars, motorcycles, light trucks, medium trucks, buses, school buses, heavy trucks, streetcars, and other vehicles. Using this method of traffic counting, a 2.5 hour long count was performed to gather the requisite data for running the traffic microsimulation.

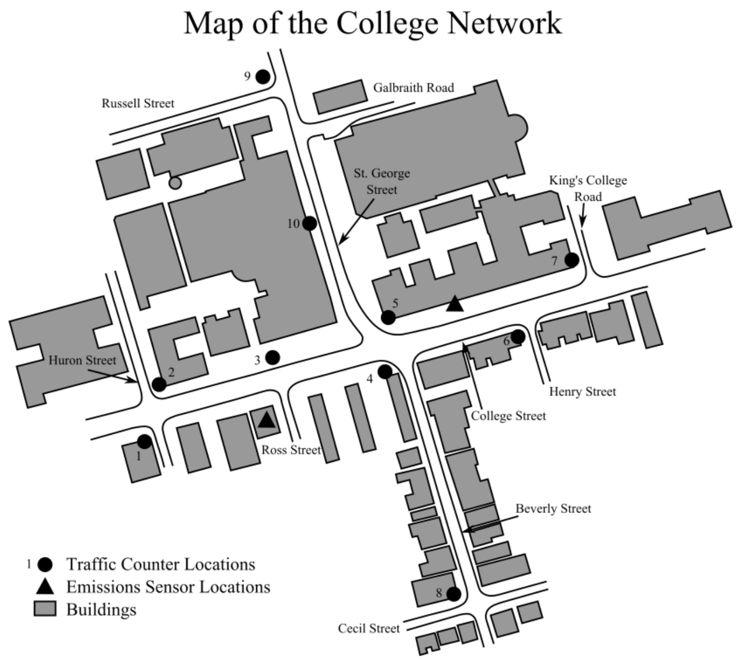


Figure 1: Map of the College Network, Showing Traffic Counter Locations, Emissions Sensor Locations, Buildings, and Roads

<u>Traffic Microsimulation and Emissions Modelling</u>

Using this information, traffic counts were aggregated into three vehicle classes- light vehicles (cars, motorcycles, light trucks), medium vehicles (medium trucks, buses, school buses) and heavy vehicles (heavy trucks). Monte Carlo simulation was then used to simulate the path of each vehicle travelling through the network, based on the percentage of vehicles exiting each intersection through each available path. Using these simulated trips, an origin-destination (OD) matrix was created for every vehicle class for each five-minute time period.

The study network was created within Paramics using satellite imagery of the area and geometric representation; all roadways were given accurate lane widths, speed limits and traffic control signals.

Traffic signal timings were calibrated with observed timings from the count day, streetcar traffic along College Street was recreated, and incidents blocking lanes during the traffic count were reproduced. In order to improve the resolution of the emissions dispersion model, each roadway was divided into 10-15 m long link segments. All OD matrices were assigned in Paramics in five minute intervals. Virtual loop detectors were coded within the simulation network in order to assess the accuracy of the traffic simulation. Comparing the data from these sensors, it was determined that a time-step value of 2 within Paramics created the most accurate representation of traffic from the count period. A time-step value indicates the frequency of time at which Paramics adjusts individual vehicle behaviour.

The CMEM emissions model was integrated with the Paramics traffic simulation. Emission profiles were assumed in the CMEM model for each vehicle category, based on observed vehicle characteristics and the light-duty car and truck classification flowchart (Scora and Barth, 2006). The CMEM time aggregation for result generation was set to five minutes to match the resolution of data obtained from the traffic count. Simulation runs were conducted using Paramics/CMEM in order to obtain emissions data for carbon monoxide (CO) for each roadway link in the given network.

Dispersion Modelling

Two dispersion methodologies were tested to estimate CO concentrations at pre-defined receptor locations in the study area. Both models are based on the Gaussian plume equation which models the pollutant concentration contours as a normal distribution, decreasing in magnitude as the receptor moves away from the road link. The general equation for calculating net pollutant concentration at any given location is given as:

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

Where, C is the pollutant concentration, in gm/m^3; Q is the emission rate (from emission model), in gm/sec; u is the horizontal wind speed at point of release, in m/sec; σ_y is the standard deviation of the concentration distribution in the crosswind direction at the downwind distance x, in m; σ_z is the standard deviation of the concentration distribution in the vertical direction at the downwind distance x, in m; H is the effective height of the plume, in m; Z is the receptor height (assumed to be 1.6 m to reflect breathing height).

The simplified custom-coded Gaussian model that was developed for this project ignored plume rise and building downwash effects, and assumed links to be point sources located at the centre of each link on the network. However, this model could provide concentration outputs averaged for every five minute interval, synonymous with the traffic data collected. In comparison, AERMOD only provided hourly concentration values.

The Paramics network was exported into ArcGIS and the custom-coded dispersion model was run to estimate CO concentrations at the sensor locations. The CO sensor (Southern Ontario Centre for Atmospheric Aerosol Research, 2011) was located on a building at the north east corner of St. George Street and College Street, indicated by the centroid in Figure 2. Atmospheric pollutant concentrations were modelled at five minute intervals and were compared to sensor measurements of CO concentration.

College Network Showing Road Links and Sensor Location

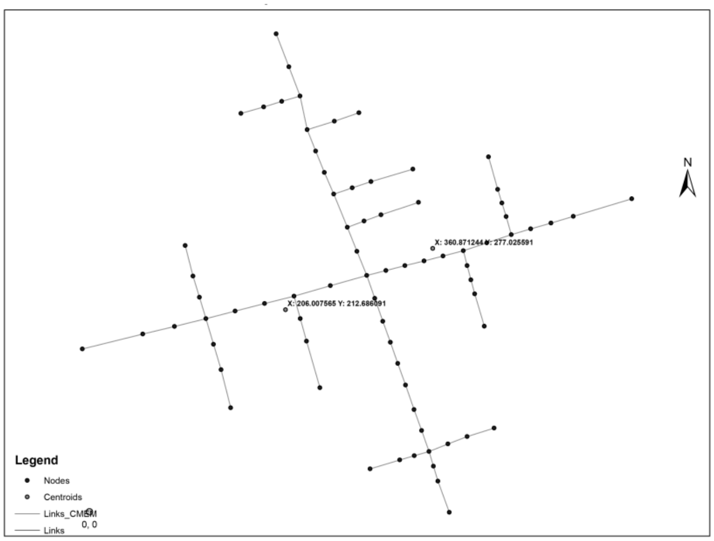


Figure 2: Paramics Network Exported into ArcGIS Showing Sensor Location

AERMOD View, developed by (Lakes Environmental Inc., 2011) provides a Graphics User Interface to use AERMOD and was applied in this project. AERMOD is a steady state plume model that uses an atmospheric stability characterisation to establish wind profiles in the planetary boundary layer to cause dispersion of pollutants using the Gaussian distribution equation. It consists of AERMET, a meteorological processor, AERMAP, a terrain pre-processor and the Building Profile Input Program (BPIP) that helps in calculation of building downwash. Details on the model can be obtained in (Cimorelli, et al., 2004).

Meteorological data sets for AERMET were purchased from (Lakes Environmental Inc., 2011). These data sets were generated for a hypothetical met-station located at the St. George and College intersection, developed using MM5 prognostic meteorological model (Lakes Environmental Inc., 2010) (Pennsylvania State University , 2008). AERMAP processed the terrain elevations even though there is negligible effect of varying terrain within the study network since it is relatively plain. Elevation information and building heights for the network were available from the (Map and Data Library, University of Toronto , 2011). The line sources were modelled as a series of point sources developed based on the network links from Paramics. The model was run for a period of 2 hours for the study period, one hour at a time, and maximum average concentrations contours were plotted for the network.

Results & Discussion

Simple Custom Coded Gaussian Plume Model

Using the custom coded Gaussian plume model, the calculated values were compared with the measured values once every five minutes. Two wind speed cases were analysed. One with an assumed average wind speed of 1 m/s east to west and one with specific wind data processed using AERMET. The results are shown in Figures 3 and 4. It can be seen that the values of wind speeds are critical in deciding the amount of dispersion that occurs on the network. For the 1m/s wind speed condition, the modelled concentrations showed a linearly increasing trend comparable to the observed values. It must be noted that this sensitivity to heavy emitting vehicles is unrealistically high and can be attributed both to the classification of such vehicles within CMEM and the dispersion model used. The difference between observed and measured values can be attributed to the presence of ambient concentrations and sources outside of the network that were not considered in this study. However, when the AERMET generated data was input into the simple Gaussian model, the observed concentration values decreased by approximately 4 times, since the average velocity generated by AERMET was 4.23 m/s for the 2.5 hours of simulation period. This shows the sensitivity and the underlying importance of collecting relevant meteorological data when performing a dispersion modeling study.

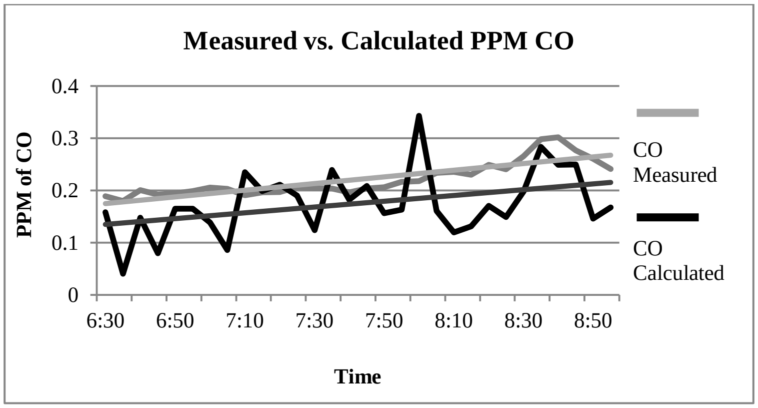


Figure 3: Comparison of Measured CO with Calculate Simulation Output for Custom Built Simple Gaussian Plume Model

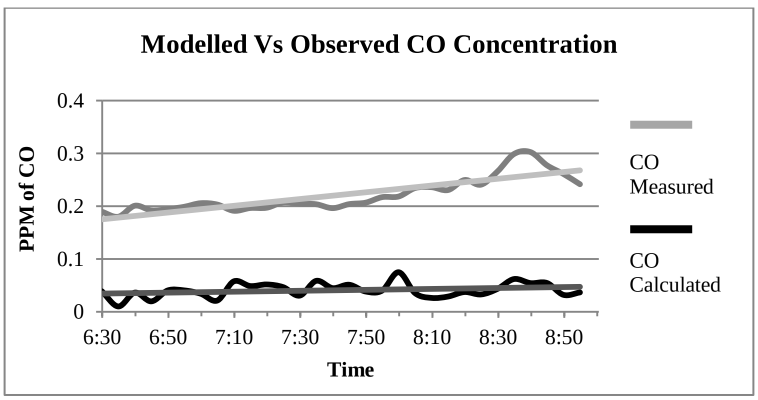


Figure 4: Modelled vs. Observed CO Concentration Values Based on AERMET Inputs

To better visualise the correlation between the measured and calculated concentrations of CO, the data for wind speed of 1m/s was smoothed using a weighted rolling average, calculated as:

$$c_{iAV} = 0.4c_i + 0.2(c_{i-1} + c_{i+1}) + 0.1(c_{i-2} + c_{i+2})$$

Also, an atmospheric concentration of 0.045 PPM CO was added to each value to compensate for a lack of ambient CO being factored in to the modelling process. In addition, the raw CO measurements were used (where measurements were taken once per minute) in order to visualise smaller changes in measured values and to see if these have any correlation with the calculated values. The result of these adjustments can be seen in Figure 5, where the averaged and incremented calculated values are plotted against the measured values of atmospheric CO in PPM. It can also be seen that the linear trend of the calculated CO values is slightly less steep than that of the measured values, indicating a slower increase in CO concentration due to only vehicular emissions.

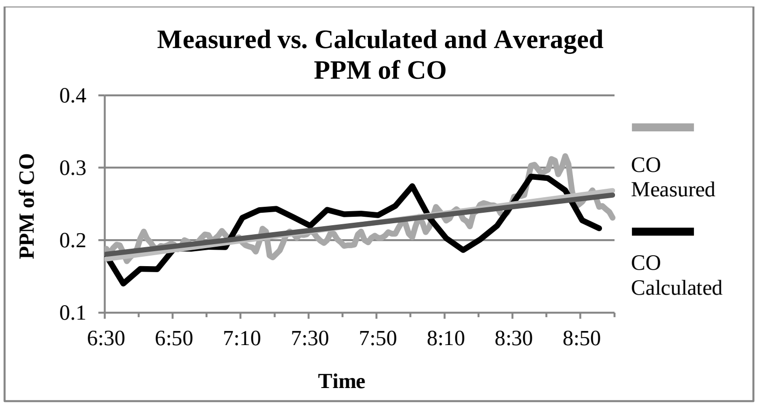


Figure 5: Measured CO (1 Minute Intervals) Compared with an Incremented Rolling Average of Calculated CO (5 Minute Intervals), both in PPM

<u>AERMOD Model</u>

The concentration contours obtained from AERMOD View are shown in Figure 6. Since line sources were modelled as a series of point sources, certain high emitting links on the network created high concentration zones as observed for the 1.6m height contour. Since the values obtained from AERMOD were maximum hourly averages, a comparison between the two dispersion modelling approaches was not considered appropriate since there was a possibility of developing a bias in the comparison due to effects of averaging out higher concentrations. Figure 7 shows a CO concentration cross-section for the westbound lane on College Street. The peaks correspond to regions of higher concentrations on the network. However, as observed they do not necessarily occur at the intersection. The effect of micro-simulated driving cycle can thus be captured in AERMOD. It is interesting to note that the traffic volume on St. George was a small fraction of total traffic on College Street and hence the modelled concentrations on St. George were correspondingly small.

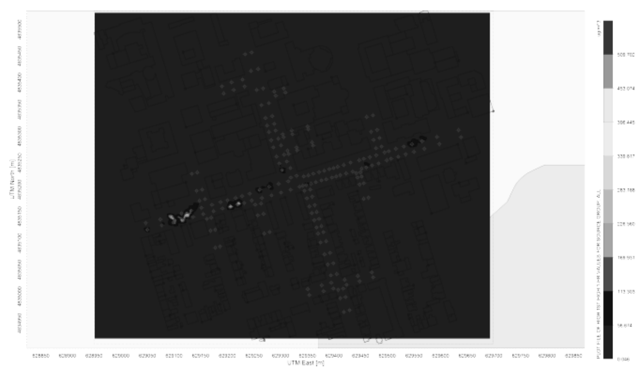
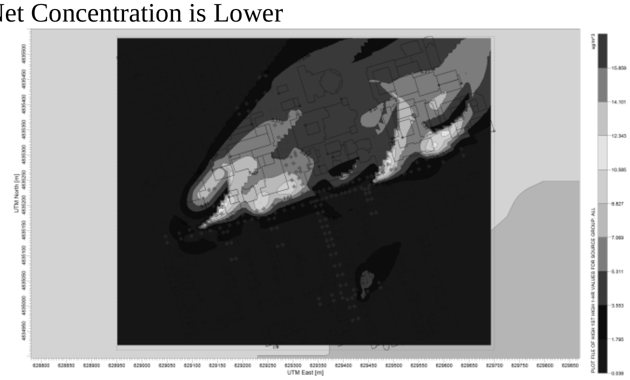


Figure 6: CO Concentration Contours Using AERMOD View, at 1.6m (Breathing Height) Above and at 10m Below. Note that with Increase in Height the Dispersion of Pollutants Increases; However the Net Concentration is Lower



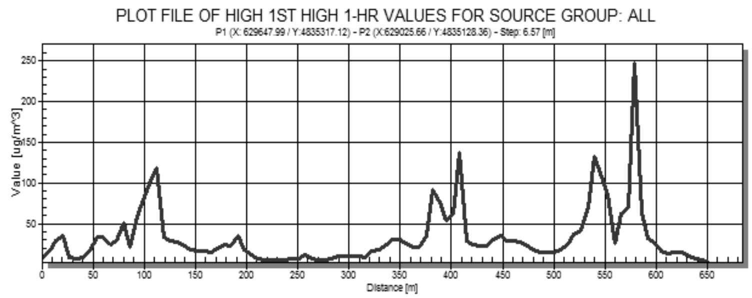
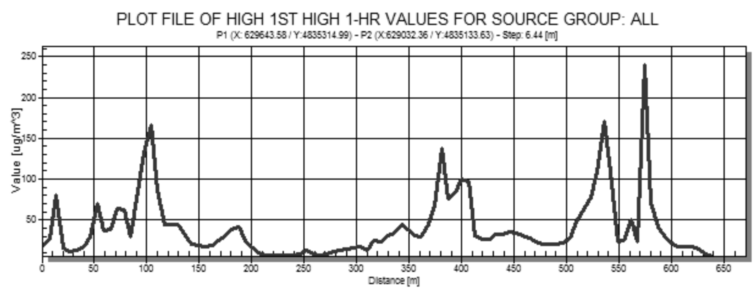


Figure 7: Average Maximum Hourly CO Concentration Variation at 1.6m for College Street on the Westbound Lane for 7-8 AM (Above) and 8-9 AM (Below)



Limitation and Conclusions

The modelling framework provides results that can help explain a considerable percentage of CO concentration in the atmosphere. As expected, presence of ambient concentrations and other sources outside the network prove a challenge when attempting to estimate concentrations on a small network. Traffic microsimulation provides an opportunity to capture local effects of moving traffic and provides ample scope to investigate dispersion of pollutants on a micro scale. However, AERMOD’s ability to only provide hourly averages proves to be a drawback when trying to compare pollutant patterns within the hour occurring due to difference in traffic volumes within the hour. Nonetheless, AERMOD generates contours that can be used to define regions with higher concentrations.

It is evident that the microsimulation of CO emissions exaggerates the effect of heavy vehicles and large concentrations of lighter vehicles on overall atmospheric concentrations of the pollutant, but the overall trend created with such simulations is surprisingly accurate. For the simple Gaussian plume model, after adding a factor to compensate for a lack of simulated ambient CO, the resulting simulation produces a trend nearly identical to that measured, with a particularly good correlation between 8:25 am and 8:45 am. Wind is observed to be a critical factor in the dispersion of pollutants. There is a large variation in modelled values depending on the wind speed and direction. The large variances in calculated CO concentrations are also concerning, since they indicate an oversensitivity within the modelling process that should be further investigated.

This modeling framework does not analyze other air pollutants such as NOx and particulate matter due to absence of observed concentrations for the given network area. Additionally, CMEM emissions model cannot calculate particulate matter emission factors on network links; as a result, the dispersion modeling methodology cannot be implemented. Finally, conducting the traffic survey over a larger area would give the opportunity to see whether the modelling process is accurate for more vehicles, and it could also help smooth out spikes in the calculated output.

Acknowledgements

This research was funded by the Ministry of Transportation of Ontario, the Toronto Atmospheric Fund, and the Department of Civil Engineering at the University of Toronto. The SOCAAR team at University of Toronto assisted with traffic counts and provided emissions data. They include Greg Evans, Tasko Olevski, Jessica Kok, Tara Stratton, Lisa Phin and Abby Eldib. Assistance was also provided by Glareh Amirjamshidi and Keith Cochrane.

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