Microscopic modeling for atmospheric urban pollutant dispersion in dense urban road networks

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1. Introduction

Air dispersion modelling is typically conducted across large spatio-temporal scales. However, microscopic simulations are needed to investigate the effectiveness of strategies aiming at improving air quality in near-road environments. In this work, we developed a traffic simulation linked with an emission model, and a street-canyon model to simulate nitrogen dioxide (NO2) concentrations in near-road environments. Our study is set in Montreal, Canada where a small portion of the downtown road network is simulated. The network consists of 28 links and 10 intersections. First, we explain the criteria for selection of the traffic, emission, and air quality models according to their input data and scales. Next, we address the development of a modelling chain to link these models. Then, we investigate two approaches to vehicle behavior for emission modelling: one Eulerian which considers the behavior of a link in its entirety, the second considering the trajectory of each vehicle (Lagrangian). This study examines the performance of these approaches by validating modelled air pollutant concentrations against roadside measurements.

2. Materials and Methods

The study site is located in downtown Montreal and concentrations of NO2 were measured near the roadway at a fixed station located within our study site form March 16 to April 10, 2015. In order to validate simulated concentrations, hourly measured concentrations at a fixed station located within our study site were extracted for the simulation period.

2.1 Traffic simulation

Dynamic microscopic traffic models, of interest to this study, consider individual vehicle interactions with other vehicles and with the road network. We chose to work with the PTV VISSIM platform, a discrete, stochastic, time-step based microscopic model, with a psycho-physical car-following model The model can calculate instantaneously the location, speed, and acceleration of each vehicle on the road network. The traffic volumes, speed and location of individual vehicles were simulated with a time resolution of 1 second. Traffic was simulated for three different hours during the day: 8-9am, 12-1pm, and 4-5pm. For each 2 hours of monitoring, an average hourly traffic composition, turning movements, etc. was used to load the VISSIM network (Fellendorf and Vortisch, 2010). In order to allow for warm-up of the traffic simulation, each period of simulation spanned 4,500s, 900s for loading the network while output was extracted for the latter 3,600s.

2.2 Emission Modeling

The Project-Level scale of MOVES2014 (Koupal et al., 2002) was used to simulate emissions of NO and NO_2. Vehicle volumes, types and driving cycles were extracted for each link and each second from the traffic model. Data on weather, fuels, and road grade were also input, reflecting local conditions. Data on vehicle model years were obtained from the Société de l'Assurance Automobile du Québec (SAAQ) based on vehicle ownership records. Instantaneous emissions during the three simulation periods (8-9am, 12-1pm, and 4-5pm) were computed using the detailed vehicle and traffic information. We assumed that pollutant emissions exhibit a well-defined linear relationship with traffic volume in the remaining hours

of day. As such, a 24-hour traffic profile for our study network was obtained from the open data portal of the city of Montreal and used to extrapolate the emissions simulated for the three periods onto other hours of the day.

2.3 Dispersion Modeling

Various approaches are available for the dispersion of road emissions, these include (Sportisse, 2007): In this study two approaches are used Street-canyon models: Useful in situations where the atmospheric dispersion of pollutants is constrained by obstacles such as buildings.

The Street-canyon model SIRANE (Soulhac et al., 2011) was used to calculate ambient NO_2 concentrations using NO and NO_2 emissions as input. SIRANE is an operational urban dispersion model that adopts parametric relations for the pollutant transfer phenomena within and out of the urban canopy. This model provides the spatial and temporal evolution of concentrations for different pollutants, appropriate to the scale of a neighborhood or a city (from few hundred meters to ten kilometers).

SIRANE simulates each street with a box model and calculates the corresponding advective fluxes balance at intersections. This model accounts for three important transport mechanisms within the urban canopy to better estimate the effect of the complex street configuration in an urban area: 1) advective mass transfer along the street due to the mean wind along their axis, 2) turbulent mass transfer across the interface between the street and the overlying atmospheric boundary layer, and 3) advective transport at street intersections. Finally, a Gaussian plume model for atmospheric transport and dispersion above roof level completes the simulation at street level.

2.4 Modelling framwork

In summary, traffic simulation was conducted for three time periods: 8am to 9am, 12am to 1pm and 4pm to 5pm to estimate the position and kinematic parameters of the vehicles. Then second by second speeds of individual vehicles and links were used to calculate hourly emissions per road segment for the three periods. Using a daily traffic profile derived for the same network, the emissions of the three periods were interpolated in order to generate hourly emissions per road segment. To that end, two interfaces were developed to provide input data as driving cycles and vehicle categories with a time step of 1 second. In the Eulerian method, the vehicle speeds and volumes are averaged on each segment (20m). In the Lagrangian method, we consider the individual movement of each vehicle throughout the network and reconstruct link emissions. Hourly emissions were then dispersed using meteorological data for March 16 to April 10, 2015.

3. Results

The pollutant simulated in this study is NO2, a known marker for traffic-related air pollution. The results obtained for NO2 are more representative of model performance than the results for other pollutants that depend more strongly on background concentrations rather than local traffic. First we present results of emissions, estimated through the Eulerian and Lagrangian methods. Next the atmospheric dispersion simulations were conducted based on those emission rates and their results were validated against measured concentrations.

Emissions throughout the network were estimated using both the Eulerian and Lagrangian methods. Recall that we refer to the Eulerian method as the traditional method of inputting drive-cycles into the MOVES model by treating every link as the unit of analysis and inputting instantaneous speeds of the link itself. In contrast, in the Langragian method, we track every vehicle through the network and we input the instantaneous speeds of every vehicle as it crosses every link.

Given the emission results (using Eulerian and Lagrangian methods) and other input requirements of the atmospheric dispersion model, hourly concentrations of NO2 were simulated and compared with fixed-site measurements. It is important to note that when comparing our simulated NO2 concentrations with the ones measured at the roadside station, we are not accounting for the contribution of other sources and therefore would tend to underestimate measured concentrations. Therefore, using the results of a recent

source apportionment exercise (Borge et al., 2014), we adopted 69% as the proportion of measured NO2 concentrations reflecting the contribution of traffic. The rapid reactions between NO, NO2 and O3 were taken into account by the Chapman cycle. The hourly concentrations of NO2 based on Eulerian and Lagrangian emissions and observed concentrations are presented in Figure 1.

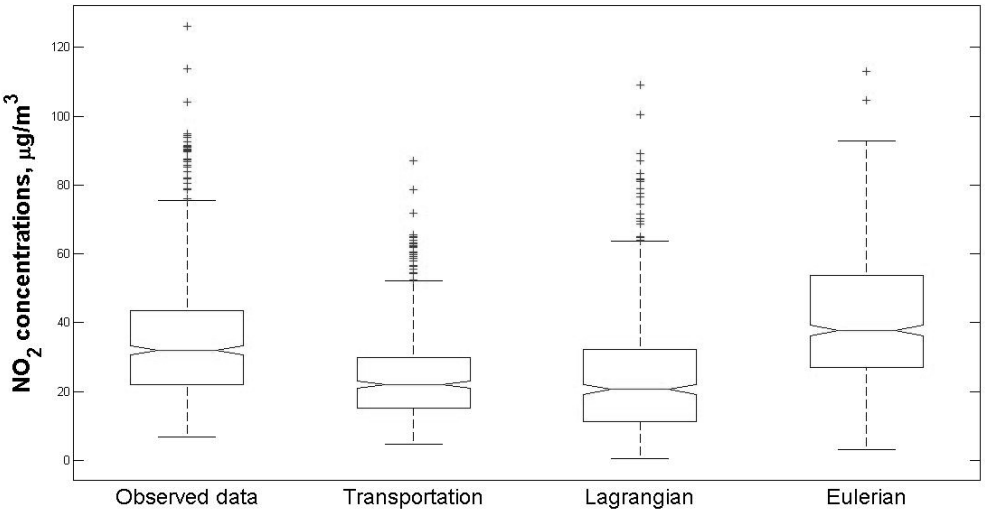
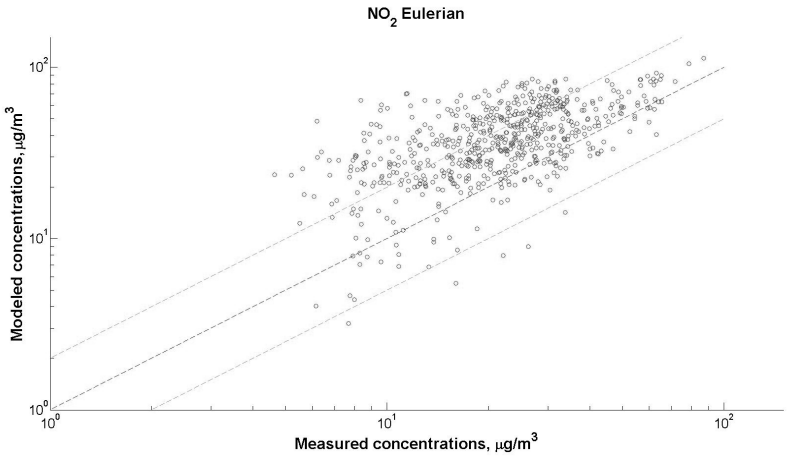


FIGURE 1. NO2 concentrations measured at the fixed station, measured concentrations scaled down to 69% to reflect the contribution of traffic, and simulated concentrations with Eulerian and Lagrangian emission methods

Scatter plots of simulated vs. measured concentrations are presented in Figure 2 for both the Lagrangian and Eulerian methods. The correlation between measured and simulated concentrations is 61% for the Eulerian method and 79% for the Lagrangian method. The fraction of predictions within a factor of two of observations are respectively 62% and 84% for Eulerian and Lagrangian methods. The better match between the measured concentrations and the simulated ones based on the Eulerian method is an artefact of the weakness of the Eulerian method, slightly overestimating emissions and thus leading to higher predicted concentrations. The comparison of the two methods for NO2 shows that RMSE, MNE, MNB, NME, and MFE decrease by 54%, 63%, 98%, 55%, and 46%, respectively when using Lagrangian method. These significant decreases of the errors for the Lagrangian method highlight the importance of explicitly considering the behaviour of vehicles to better simulate pollutant concentrations.



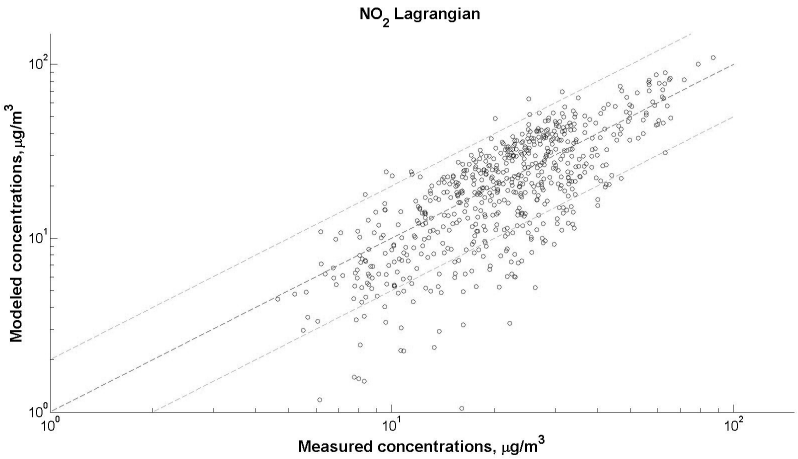


FIGURE 2. Comparison of concentrations modeled with the Eulerian method for emissions and the Lagrangian method with measured NO2 concentrations (reflecting the contribution of traffic)

Conclusion

In this study, a microscopic modelling chain is developed and applied to simulate near-road concentrations of NO2 in a dense urban network. These models are able to represent the dynamic phenomena occurring in the traffic flow. A microscopic dynamic (car-following) model of traffic is used to estimate the driving cycles required for modelling instantaneous emissions. Two interfaces were developed to link traffic and emission models with Eulerian and Lagrangian approaches of vehicle behaviour. The emission results were used in a street-canyon dispersion model to obtain the concentration of NO2 considering street geometry and spatially resolved building heights. The results of both methods were compared with roadside measurements of NO2.

The results of the chain modelling by Eulerian and Lagrangian methods were compared to roadside measurements and showed that the Lagrangian method improves the correlation coefficient significantly and reduces the discrepancy between simulated and measured concentrations. It is important to acknowledge that when a large network is considered, the Lagrangian method requires significant computational time.

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