Investigating the Effects of Intersection Control Types on Emissions Using Microsimulation Models and Field Measurements

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Abstract

Emission estimates are becoming critical metrics to evaluate the impacts of transportation projects such as modifications of the road geometry, updating of intersection signalization or technological improvements. To evaluate the impact of projects and policies, methods to evaluate emissions related to climate change and public health (through metrics such as air quality) have become more prevalent.

The general objective of this research is to determine the impact of traffic controls, in particular stop signs, in comparison to other intersection controls, on vehicular emissions. More specifically, the objective of the first project is to propose a microscopic modelling approach based on emission software tools to evaluate the impact on emission levels before and after the transformation of one-way stop to all-way stop intersections in an urban corridor. This case study used the EPA's emissions model MOVES, along with the traffic microsimulation model VISSIM, to evaluate the emissions impact of intersection modifications using a Montreal case study. Intersections in the network of interest were converted from one-way stop controlled to all-way stop controlled in a political move aimed at improving pedestrian and cyclist safety. This modification was analysed using the models and it was found that energy consumption as well as emission rates of CO, NO_x, NO, NO_2, atmospheric CO_2, PM_{10} – exhaust, PM_{10} – brake-wear, $PM_{2.5}$ – exhaust, and $PM_{2.5}$ – brake-wear increased after the stop signs were added, with growth range of 4.4% to 32%. The only pollutants whose rates decreased were $PM_{2.5}$ and PM_{10} due to tire-wear.

In the second portion of the research, a PEMS device was used with several test vehicles. These vehicles were driven throughout the network which was tested in the first portion of this research, along with several networks of a similar composition. Data was sorted based on type of intersection and compared. Results showed that within a 30m buffer of the intersection, a general pattern exists where intersections with stop in the minor approach generate the least emissions, followed by all-way stop intersections, then signalized intersections with emissions increases of approximately 50% and 20% between the types respectively. However, this pattern disappears when data is controlled for the number of seconds a vehicle spends within each type of intersections, with emission rates becoming relatively equal. Furthermore, the trajectories of these experiments were entered into MOVES in order to compare the model's predictions to the ground-truth data that was collected. It was found that MOVES estimates were inconsistent, with

the model providing a relatively accurate prediction of fuel consumption, over-predicting NO and NO_2, and under-predicting CO_2. A weak correlation was observed with absolute values ranging between 0.006 and 0.269.

Among the finding of this research we can highlight the fact that microsimulation models seem to introduce inaccuracies into the evaluation. Despite the safety benefits that stop signs can introduce, the addition of stop signs, and the subsequent required stop, significantly increases vehicular emissions related to climate change and human health issues. When upgrading intersections, or implementing other roadway modifications, the impacts on the environment and public health should be considered in the decision and design process. Furthermore, emission estimation tools such as MOVES should be further evaluated in the Canadian context to validate their accuracy and calibration.

Résumé

L'estimation des émissions est en voie de devenir un indicateur clé à l'évaluation des impacts engendrés par des projets de transport tels que les modifications à la géométrie des chaussées, la mise à jour de la signalisation routière aux intersections ou l'apport d'améliorations technologiques. Pour évaluer l'impact des projets et des politiques, plusieurs méthodes d'estimation des émissions portant sur le changement climatique et la santé publique sont devenues plus répandues (au travers de critères tels que la qualité de l'air).

L'objectif général de cette recherche est de déterminer l'impact des contrôles de la circulation, en particulier les panneaux d'arrêt, sur les émissions des véhicules, comparativement à d'autres contrôles aux intersections. De façon plus spécifique, l'objectif du premier projet est de proposer une approche de modélisation microscopique basée sur des outils informatiques pour évaluer l'impact, sur les niveaux d'émission dans un corridor urbain, avant et après la transformation des intersections contrôlées par des panneaux d'arrêt unidirectionnel à celles dotées de panneaux d'arrêt « toutes directions ». Cette étude de cas a utilisé le modèle d'émissions MOVES de l'EPA, ainsi que le modèle de micro simulation de la circulation VISSIM, pour évaluer l'impact des modifications des intersections sur les émissions à l'aide d'une étude de cas basée à Montréal. Les intersections se trouvant dans la zone d'étude ont été réaménagées en passant d'un arrêt unidirectionnel à un arrêt « toutes directions » dans le cadre d'une décision politique visant à améliorer la sécurité des piétons et des cyclistes. Cette modification a été évaluée à l'aide des modèles susmentionnés et il en ressort que la consommation énergétique ainsi que les taux d'émission de CO, NO_X, NO, NO_2, CO_2 atmosphérique, PM_{10} - gaz d'échappement, PM_{10} - usure des freins, $PM_{2,5}$ - gaz d'échappement et $PM_{2,5}$ – l'usure des freins ont augmenté à la suite de l'installation des panneaux d'arrêt, avec une hausse variant de 4,4% à 32%. Les seuls polluants dont les taux ont diminué étaient les $PM_{2,5}$ et les PM_{10} en raison de l'usure des pneus.

Dans la deuxième partie de la recherche, un dispositif PEMS a été utilisé avec plusieurs véhicules d'essai. Ces véhicules ont parcouru l'ensemble du réseau qui figure dans la première partie de cette recherche, ainsi que plusieurs autres réseaux de composition similaire. Les données ont été classées en fonction du type d'intersection et ont ensuite été comparées. Les résultats ont démontré qu'à l'intérieur d'une zone tampon de 30 m de l'intersection, on y retrouve une tendance générale avec laquelle les intersections contrôlées par un panneau d'arrêt dans

l'approche secondaire génèrent le moins d'émissions, suivies des intersections avec arrêt « toutes directions », puis des intersections signalisées avec des augmentations respectives en émissions allant de 20% à 50% entre chaque type. Toutefois, cette tendance disparaît lorsque les données sont contrôlées en relation avec le nombre de secondes qu'un véhicule passe dans chaque type d'intersection, les taux d'émission devenant ainsi relativement égaux. De plus, les trajets empruntés ont été incorporés dans le modèle MOVES afin de comparer les prévisions du modèle aux données in-situ qui ont été recueillies. Nous avons constaté que les estimations du modèle MOVES étaient incohérentes, le modèle offrant une prévision relativement précise de la consommation énergétique, tout en surestimant les émissions de NO et de NO_2 et à la fois sous-estimant les émissions de CO_2. Un faible degré de corrélation a été observé, avec des valeurs absolues comprises entre 0,006 et 0,269.

Une conclusion importante de cette recherche est que les modèles de micro simulation ajoutent des inexactitudes à l'évaluation. Malgré les avantages pour la sécurité que les panneaux d'arrêt peuvent introduire, l'ajout de panneaux d'arrêt et l'arrêt requis qui suit, augmentent considérablement les émissions des véhicules liées au changement climatique et aux problèmes de santé humaine. Lors du renouvellement des intersections ou de la mise en œuvre d'autres modifications de la chaussée, les impacts sur l'environnement et la santé publique doivent être pris en compte dans le processus de décision et de conception. De plus, les outils d'estimation des émissions comme MOVES devraient être évalués davantage dans le contexte canadien pour valider leur précision et leur étalonnage.

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Contribution of Authors

This thesis is the combination of papers written for conference presentations. My contributions to this research include conducting the collecting a portion of the data, preparing the data, analyzing the data, and writing the manuscript. My supervisor, Prof. Luis Miranda-Moreno, provided guidance, comments, and editorial revisions throughout the entire process. The co-authors of the publications helped in data collection, providing comments, and editing the papers. Additional members of the IMATs Lab at McGill assisted with data collection as well.

Chapter 3

Behan, M., Ledezma-Navarro, B., Miranda-Moreno, L.; 2019. Evaluating the safety and emissions impact of converting one-way stop intersections to all-way stop intersections

Presented at the following conferences:

The Science behind Hands on Sustainable Mobility; Karlsruhe, Germany – May 2019

TAC – ITS Joint Conference; Halifax, NS, Canada – September 2019

Chapter 4

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Presented at:

TRB Annual Meeting; Washington, D.C., United States – January 2020

I am the sole author of all additional chapters.

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1. Introduction

1.1. Context

Globally rising emissions of certain greenhouse gases (GHG) and presence of pollutants have caused a heightened awareness of air quality across the world. GHGs are compounds that are found naturally in the atmosphere and are mainly comprised of CO_2 and CH_4, with minor contributions from N_2O and ozone. Human activities are responsible for increasing the presence of these gases and therefore increasing their greenhouse effect on the planet. Air quality pollutants are studied for their negative impact on human health, and consist of airborne particulate in the form of particulate matter (PM) and ultra-fine particles (UFP) as well as gases such as CO, NO_x, and SO_2. Air pollution is linked to heart and lung related illnesses which may be serious or even fatal. The Government of Canada's report *Health Impacts of Air Pollution in Canada* reports that in Canada alone 14,600 deaths occur each year as a result of air pollution (Canada. Health Canada, 2019). The total cost of these air pollution related health issues amounts to \$114 billion per year in Canada alone (Canada. Health Canada, 2019). For the duration of this thesis, the term *emissions* will refer to both the GHGs and pollutants that are expelled from a vehicle's tailpipe.

Transportation is a significant contributor to climate change and public health impacts and generates about 25% of Canada's greenhouse gas emissions (Government of Canada, 2019). Cars and light trucks are responsible for approximately 13% of this total (Kumar Gupta *et al.*, 2008). Despite an increasing focus on active modes of transport, such as biking and walking, vehicle miles travelled (VMT) continue to grow ('Moving 12-Month Total Vehicle Miles Traveled', 2019) which in turn, increases annual emissions. From 1990 to 2017 in the US, VMT of cars and light trucks increased by 45.9% (US EPA, 2019). In Canada, passenger vehicles are responsible for approximately 21% of the transportation-related NO_x emissions (*Air pollution from cars, trucks, vans and SUVs - Canada.ca*, 2017). More stringent regulations are continuously applied to newly manufactured vehicles in an attempt to mitigate these growing emissions (US EPA, 2017), however, despite these regulations and the innovations in fuel efficiency and alternate sources of power, CO_2 emissions increased by 3.4% in 2018 (Rhodium Group, 2018).

Policies can be used to manage emissions in many ways from guiding land use to regulating technology. Two common types of policies are push and pull. Push policies make vehicle use less attractive through means such as tolling, taxes or parking costs. Pull policies entice drivers to switch to public transportation through means such as improved service or reduced fare programs (Nocera and Cavallaro, 2011). Additional standards regulate vehicle technology, like the US's Corporate Average Fuel Economy (CAFE) standards which regulate passenger vehicle fuel efficiency (*Corporate Average Fuel Economy | NHTSA*, 2019).

Emissions from transportation can be studied on the macroscopic or the microscopic scale. The following is summarized in *Figure 1*. The macroscopic scale is controlled by factors such as land use, policies, and vehicle technologies that impact an entire fleet or jurisdiction. For example, the London congestion charge requires a fee of £11.50 to drive within the designated zone on Monday through Friday during heavy traffic hours in order to reduce emission and traffic within London's central business district. This macroscopic change has wide-reaching effects since it impacts traffic at all road types contained in the zone and drivers of all vehicle types (with some exceptions and reductions for green vehicles and vehicles with nine or more seats).

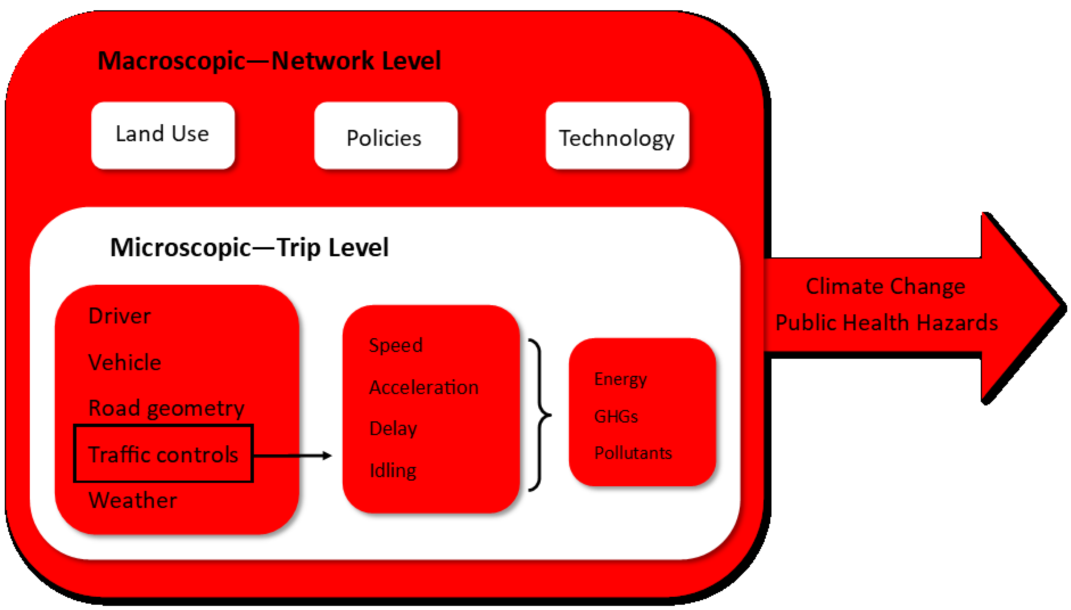

Figure 1: Organizational chart of emissions

There are also many factors that impact vehicular emissions on the microscopic level. These include driver behaviour, vehicle characteristics (make, model, age, etc.), roadway geometry, and weather patterns. De Vlieger et al. studied the impact of aggressive driving, among other factors, on vehicular emissions finding that aggressive driving can increase emissions by a factor of eight (De Vlieger, De Keukeleere and Kretzschmar, 2000). There are many physical characteristics of a vehicle that impact emissions. Mass is an important factor in vehicle efficiency; by reducing vehicle weight efficiency can be improved. Vehicle modifications that affect air resistance, such as roof racks and trailers, further deteriorate a vehicle's efficiency. Additionally, poor vehicle maintenance and aging of parts such as the catalytic converter contribute to higher levels of emissions (Fontaras, Zacharof and Ciuffo, 2017). Vehicular emissions are also affected by weather. Cold starts and idling, both common in cold winter months, cause an increase in emissions.

This research will focus on the traffic controls' impact on emissions, both GHGs and pollutants. The type of road can have a large emissions impact due to the characteristic traffic patterns such as speed, acceleration, delay/congestion, idling, and traffic controls present. Recently, emissions have become a metric by which to measure the benefit (or detriment) of roadway modifications. Such measures have been used to evaluate speed limits (Ghafghazi and Hatzopoulou, 2014), speed bumps (Ahn and Rakha, 2009; Ghafghazi and Hatzopoulou, 2014; Jazcilevich *et al.*, 2015), traffic circles (Ahn and Rakha, 2009; Ghafghazi and Hatzopoulou, 2015; Meneguzzer, Gastaldi and Arboretti Giancristofaro, 2018), and HOV lanes (Fontes *et al.*, 2014), among others. Generally, the literature suggests that devices which smooth traffic flow (traffic circles, HOV lanes) perform better than devices which generate more erratic driving patterns (speed bumps).

The two most common ways to study vehicular emissions are using models or portable emissions measurement systems (PEMS). Models commonly used are the US EPA's MOtor Vehicle Emissions Simulator (MOVES) or the EU's COPERT. These models are beneficial since they allow for the evaluation of a large study area or fleet using a relatively small budget and short amount of time. They also give the ability to test designs before they have been built. Most models can analyze a wide variety of pollutants and may be suitable to evaluate non-road vehicles such as watercraft. However, models are only as good as the information that is used to create them. They are usually tailored to a specific geographic location, which could effect their accuracy if used for a different region (depending on the ability to change inputs such as fleet mix, fuel make-up, driving habits and climate). Additionally, models are frequently built using data from lab tests, which has been found to have a growing disparity from real-world emissions (Pavlovic *et al.*, 2018). This disparity comes from running lab tests in ideal conditions such as minimal cargo weight, ideal temperature and humidity, and smooth drive cycles which rarely compare to real life.

PEMS offers a good alternative to emissions models, particularly for microscopic evaluations. PEMS allows for very specific analyses, using the exact network and fleet composition of interest. However, the use of PEMS comes with certain drawbacks. PEMS devices are expensive, costing around $40,000 CAD, and require frequent calibration. Depending on frequency of use, the device should be calibrated daily to monthly. Data collection is time consuming since each device can only be used to test one vehicle at a time and has a limited battery life. Without using a power source during testing, the battery on the main unit lasts a maximum of eight hours on one charge and the battery on the chiller lasts a maximum of five hours.

Fuel consumption can also be used to calculate an estimate of CO_2 emissions. This method allows for a low budget analysis since on-board diagnostic (OBD) loggers are widely available, universally compatible with vehicles, and capable of giving second by second readings of the engine functions necessary to perform these calculations.

1.2. Literature Gaps

This research strives to fill several gaps which currently exist in the literature. A large portion of the literature focuses on macroscopic emissions factors, while fewer studies evaluate the microscopic drivers of emissions, particularly involving types of intersection controls. Several studies have looked at the impact of traffic circles while a few others have looked at traffic signals. However, there is a particular gap surrounding the impact of stop controlled intersections. At the time of submission, no other studies were known to use a before and after approach to evaluate the emissions impact of all-way stops.

Most studies have used microsimulation studies to evaluate the impact of upgrading intersections (in particular for roundabouts) and changes in the type of traffic controls at the intersection or corridor level. Although models can be a powerful tool for analysis, their value cannot compare to that of field data. To our knowledge, no studies have looked at the impacts of adding stop signs using observed field measures.

Furthermore, a valuable avenue for research has been left untouched. There is a gap for comparative analysis between simulated emissions and real-world measures on the effect of traffic controls. The gap between real-life emissions and models calibrated based on laboratory measures makes this an even more important field of study.

1.3. Objectives

The general objective of this thesis is to evaluate the emissions impact of traffic controls in urban intersections using both ex-post microsimulation approach and a real-world measurement study. The specific objectives are as follows:

1. To develop a methodology to evaluate emissions impacts of converting one-way stop intersections into all-way stop intersections in an urban setting using video data collected in Montreal before and after an intersection modification project took place. The data collected from the videos was used to create a traffic model of the network using VISSIM. The outputs of this traffic model were used to create an emissions model using MOVES. Factors that were modeled include CO, NO_x, NO, NO_2, atmospheric CO_2, energy consumption, PM_{10}–exhaust, PM_{10}–brake-wear, PM_{10}–tire-wear, $PM_{2.5}$–exhaust, $PM_{2.5}$–brake-wear, and $PM_{2.5}$–tire-wear. The evaluation was limited to the emissions impact of non-commercial, light duty vehicles operating during daylight hours of weekdays.
2. To propose an alternative methodology based on real-world measures using 3DATX parSYNC Plus (a PEMS device), in conjunction with an OBD-II logger. This study was also conducted in Montreal using the same network as the first case study, in conjunction with other networks with similar characteristics. Using this system, CO_2, NO, NO_2, and fuel consumption were studied on three common vehicle models. This research focused on the difference between intersections with stop signs only at the minor approach(es), all-way stop intersections, and signalized intersections.

1.4 Contributions

Based on the gaps identified in the literature, the unique contributions of this work are as follows

- To provide methodologies to evaluate the impact of vehicular emissions using two alternative approaches and highlighting their strengths and weaknesses
- Demonstrating the use of these alternative approaches using case studies from Montreal, QC, Canada
- Evaluating the impact of the addition of stop signs on emissions through the use of a before and after study

- Use of PEMS to evaluate the impacts of the conversion of intersections with a stop in the minor approach, to all-way stop intersections and finally to signalized intersections on emissions
- Evaluation of MOVES ability to predict emissions using several types of data collection

1.5 Organization

This research is organized in the following way: Chapter 2 is a review of the existing literature surrounding the topics of emissions with a focus on modelling and PEMS as well as a generic overview of why the study of transportation related emissions is an important topic. Chapter 3 comprises the first Montreal case study which uses a modelling approach to evaluate the before and after effects of converting one-way stop intersections to all-way stop intersections. Chapter 4 discusses the second Montreal case study, where real-life emissions data was collected using a PEMS in conjunction with an OBD logger to compare different types of intersection control devices. Chapter 5 concludes this research by summarizing all relevant findings. The methodology presented in the two case studies is compared highlighting the strengths and weakness of each type of evaluation. Limitations of this research and avenues for future study are also included.

2. Literature Review

2.1. Emissions

2.1.1. Climate Change and Urban Mobility

Climate change is a key issue in today's world. Concentrations of GHGs are rising due to the impact of human activities such as agriculture, transportation and the oil and gas industry (Government of Canada, 2019). By offsetting nature's balance, we have seen changing weather patterns which have the power to drastically change humans' way of life. Extreme weather events pose the immediate risk of loss of life, but also impact life in the long term. Heavy flooding threatens infrastructure and droughts provide a water security risk. Shifting weather patterns also impact agriculture and livestock as well as contribute to the loss of ecological diversity (IPCC, 2015). In Canada, the average annual temperature has risen 1.7 °C since 1948 with a projected additional 1.8-6.3 °C by 2100 (Government of Canada, 2019). This could have a significant impact on the way of life for Canadians, particularly those living in northern communities where the changes will be more extreme.

Transportation is the second largest contributor of greenhouse gas emissions in Canada, accounting for about 25% of the nation's total (Government of Canada, 2019). Since transportation is a human created activity, we have the power to reduce transportation's impact on the environment through changes in policy, lifestyle adjustments and technological improvements. The IPCC recommends the use of fuel and vehicle taxes, congestion charges, fuel and vehicle standards, and investment in transit and human powered transport as ways to reduce the transportation industry's footprint on climate change (IPCC, 2014). These recommendations are hardly different from recommendations made 20 years earlier in *Sustainable transportation: a US perspective*. Recommendations in this paper include regulatory mechanism to control emissions, tax increases that would favor energy-efficient transport modes, support for new technologies and alternative fuels, and planning approaches that would lessen the need for automobile travel (Black, 1996). This begs the question whether we are doing enough. The recommendations have not changed despite GHG emissions in the transportation sector rising 43% between 1990 and 2017 (Government of Canada, 2019). Should we be searching for a fresh perspective to an old question?

In his paper, *Cities, mobility, and climate change*, David Banister approaches this problem from a city-planning perspective proposing designing cities in order to reduce the need to travel, implement transport policy and land use planning measures, and apply technological innovation. His work is focused on the idea that a significant, and growing, portion of the world's population lives in cities which we must retrofit in a way which balances existing infrastructure and green initiatives with the desires and needs of the population (Banister, 2011).

2.1.2. Public Health Concerns

There is often a focus on the detrimental effects that transportation GHGs play on the environment. While this is a major concern for our society, the effects of pollutants such as NO_x and PM on human health are often overlooked. Air pollution is the fifth highest cause of death world-wide, accounting for nearly 9% of all deaths in 2017 (Canada. Health Canada, 2019). Regular exposure to pollutants such as NO_x may lead to the development of cardiopulmonary diseases, lung cancer, and respiratory diseases. Caiazzo et al. attempted to quantify the premature deaths caused by each sector of pollution. They found that in 2005, road transportation accounted for 53,000 deaths related to $PM_{2.5}$ and 5,300 deaths related to ozone in the contiguous United States (Caiazzo *et al.*, 2013). In Canada, the annual economic cost of air pollution-related health impacts totaled $114 billion (Canada. Health Canada, 2019).

Long term exposure to street-level, transportation-generated Ultra Fine Particles (UFPs) has been studied through cohort studies for its connection to various health concerns. No associations were found between UFPs and lung cancer, COPD, or adult onset asthma (Weichenthal *et al.*, 2017). A possible link between postmenopausal breast cancer and NO_2 and UFPs was discovered (Goldberg *et al.*, 2017). In another similar study, a connection was found between outdoor UFP concentrations and incident brain tumors (Weichenthal *et al.*, 2019). The impact of carbonaceous ultrafine particles was studied on rodents, with the study finding that inhalation of the pollutant can cause pulmonary inflammation, which is worse in individuals with pre-existing conditions and with a larger effect when combined with ozone (Oberdrster, 2000). Weichenthal et al. developed a model to determine the exposure levels and predictors present in Canadian vehicle commuters. Their findings suggest that land use, road type and meteorology are important in determining the level of traffic-related air pollution (Weichenthal *et al.*, 2015). Hachem et al. compiled a summary of the existing literature on taxicab drivers' exposure to transportation related pollutants. Although the results widely varied due to study conditions, a need to further research these individuals' exposure to pollutants such as UFP and black carbon clearly exists since drivers spend a significant portion of their day exposed to these health hazards (Hachem *et al.*, 2019).

The United States and Canada are developed countries with sufficient health care as well as air quality standards and regulations in place. Developing countries may suffer far greater impacts from emissions depending on their health care, emissions regulations, and the size, age and maintenance of their vehicle fleet. World Bank Blogs published an article supporting the idea that countries with lower GDP per capita have higher concentrations of $PM_{2.5}$ (Morales Sarriera and Singh Sehmi, 2019).

2.1.3. Policies and Impacts

In an effort to reduce their footprint, many governments are experimenting with policies aimed at reducing emissions. These policies take on a wide range of shapes, from guiding land use (Hixson *et al.*, 2010), to encouraging modal shift (Nocera and Cavallaro, 2011), to even regulating vehicle technologies (Calef and Goble, 2007). There is often a disconnect between research and implementation, so UC Davis published a guide to assist in taking literature and efficiently applying it to policy (Salon, 2015).

Nocera and Cavallaro (2011) compared push and pull policies to reduce transportation-related CO_2 emissions. The push factors, designed to discourage the use of personal vehicles, included reduced speed and speed limit enforcement, use of commuter plans, raising parking costs and fuel taxes, increased vehicle ownership costs, use of congestion pricing and tolls, and capacity reductions. Measures aimed at pulling drivers to alternate modes of transportation included improvements to the rail system, telematics traffic management, liberalization of the market, and general improvements to the public transportation system including smoother transfers, park and ride facilities, smart card payments, intermodal centers, and efficiency (Nocera and Cavallaro, 2011).

Poudenx gives a review of policies used in different parts of the world. The Brazilian city Curitiba uses land use to reduce emissions. A combination of the axis layout of the city and creating separate spaces for express buses, slow traffic, and high-speed traffic allow for more efficient use of the transportation network. Singapore and Hong Kong increased the price of owning and driving a car, making it unaffordable for a large portion of the population. At the same time, they improved the public transit system to provide an alternate mode. In several European cities (Hamburg, Munich, Rhein-Ruhr, Vienna, and Zurich) a regional transit system was developed. Service was improved with better schedules, new parking facilities and higher frequency, while a marketing campaign was used to promote the improvements. In the North American cities of Houston and San Diego, large subsidies were used to improve public transit service and decrease fare costs (Poudenx, 2008).

Standards also exist at the federal level. In the US, CAFE standards regulate the fuel efficiency of vehicles (*Corporate Average Fuel Economy | NHTSA*, 2019). The National Ambient Air Quality Standards (NAAQS) are maintained through State Implementation Plans (SIPs). These plans help ensure that there are no new violations to the NAAQS (Houk, 2018).

2.1.4. Compliance & Testing Gap

In the US, the Environmental Protection Agency (EPA) is responsible for setting emission standards and defining test procedures, while states and local governments have the option to enforce stricter standards. The EPA monitors compliance with its regulations throughout vehicle production and post-production with five different types of tests: certification testing, confirmatory testing, in-use testing, production line testing, and fuel economy testing. All vehicles are required to receive a certificate of conformity ensuring compliance to the Clean Air Act before they can go to market.

Manufacturer compliance with the standards has been under scrutiny lately, following the scandal involving the Volkswagen Group. In 2015 was discovered that between 2009-2015, Volkswagen had installed programs on the computers of certain diesel vehicle models which would activate pollution control systems during testing, allowing the vehicles to pass the test. These control devices would become inactive during normal use of the vehicle, with the result that the vehicles would emit up to 40 times more NO_x during normal operation (Epa *et al.*, 2015). Despite the scandal costing Volkswagen over $30 million in legal fees and fines, as well as plummeting company stock values, further details involving the auto manufacturer continue to come to light. Most recently, it was discovered that Audi, part of the Volkswagen Group, continued to use the control devices on some vehicles for up to two years following the original discovery in 2015 (Ewing, 2019).

Partially as a result of the Volkswagen Group scandal, the EU has revamped their emissions testing to include on road tests as a supplement to laboratory testing. Another reason for these changes is the growing disparity between the values reported in these tests and the values generated from tests conducted on real-world use (Ligterink and Eijk, 2014). In the

European Union (EU), the gap between passenger cars' real-world CO_2 emissions and laboratory CO_2 emissions grew from 8% in 2001 to 39% in 2017 (Tietge *et al.*, 2018). A different set of research, also conducted in the EU, found that real-world emissions of NO_x were seven times higher than their associated lab tests (Mock and German, 2015). Lab tests are conducted in ideal conditions that are rarely replicated in real life. Vehicular factors contributing to the disparity include cargo and passenger weight, use of air conditioning or other electrical systems, engine operating range throughout testing, the addition of features (ex. roof rack or trailer), as well as age and maintenance of the vehicle. Furthermore, the test environment may have a large impact on the results, including air temperature, maintenance of roadways and traffic conditions (Fontaras, Zacharof and Ciuffo, 2017).

In their research, Pavlovic et al. summarized the existing studies which compared real life CO_2 emissions to lab tests, showing the trend of a growing gap between the two measurements. Their research found that in just five years the gap grew from 21% to a peak of 44%. Their findings are summarized in *Figure 2* which was taken from their paper entitled "Dealing with the Average Gap between Type-Approval and In-Use Light Duty Vehicles Fuel Consumption and CO_2 Emissions: Present Situation and Future Perspective" (Pavlovic *et al.*, 2018).

Authors	Year	Country	Real world – Certification value CO_2 shortfall
Weiss et al. (*1*)	2011	EU	21%
Mellios et al. (*2*)	2011	EU	25%
Fontaras and Dilara (*3*)	2012	EU	22.5%
Ligterink (*4*)	2013	Netherlands	30%
Mock et al. (*5*)	2014	EU	38%
Ligterink and Eijik (*6*)	2014	Netherlands	44%
Reynaert and Sallee (*7*)	2014	U.S.	41%
Tietge et al. (*8*)	2015	EU	40%
Zacharof et al. (*9*)	2015	EU	30%
Fontaras et al. (*10*)	2016	EU	40%
Duarte et al. (*11*)	2016	EU	24%

Figure 2: Comparison of real-world and type approval CO_2 emissions by Pavlovic et al.

2.1.5. Microscopic Determinants of Emissions

Emissions measurement is joining the ranks of metrics like network performance, safety, and cost as an important way to evaluate new technologies and roadway improvements.

Particularly, there is a growing body of research on the relationship between traffic-calming devices and vehicular emissions. Many experiments have found a growth in emissions following the installation of traffic-calming measures. Jazcilevich et al. examined the effect of a traffic bump, finding that it increased emissions particularly from diesel vehicles. The researchers quantified the cost of additional energy required by this calming measure and compared it to the lower cost of building a pedestrian bridge along with other solutions meant to protect vulnerable users (Jazcilevich *et al.*, 2015).

Another study by Ghafghazi and Hatzopoulou used origin destination matrices and traffic simulation models to calculate the effect of reduced speed limits, speed bumps and speed humps. Despite a reduction in vehicle kilometers traveled within the network, a small increase in emissions was detected (Ghafghazi and Hatzopoulou, 2014).

Using a numerical model, the addition of traffic signals on highways was studied as a potential method to reduce high speed crashes. Traffic signals result in all vehicles having an equal chance of being stopped by the light, not just vehicles violating the speed limit. Despite the fact that crashes were reduced by one third, emissions of CO, NO and HC grew by 15%, 10% and 40% respectively (Coelho, Farias and Rouphail, 2005). This raises the question of whether short term safety benefits are worth the long-term health detriments.

Using GPS data to extract driving behavior, Ahn and Rakha examined the effect of speed humps, traffic circles, and all-way stop intersections. Due to the smooth driving patterns they produce, traffic circles were found to perform the best, although all intersection controls included in the study did create an increase in emissions (Ahn and Rakha, 2009). Research by Meneguzzer et al. also supports roundabouts as an efficient intersection design. Their research found that emissions of CO_2 and CO were reduced when a signalized intersection was replaced with a roundabout (Meneguzzer, Gastaldi and Arboretti Giancristofaro, 2018). Another study on this topic found that roundabouts performed better than traffic signals, but stop-controlled intersections provided the best results in terms of emissions both network-wide and per intersection (Ghafghazi and Hatzopoulou, 2015).

Alternately, some roadway improvements have been shown to have a positive effect on emissions. Fontes et al. studied HOV and eco-lanes, finding that the increased occupancy of the vehicles (required by the use of HOV lanes) caused a drop in emissions (Fontes *et al.*, 2014). An analysis of Intelligent Speed Adaptation also studied using both modeling and real-world experiments. Both resulted in decreased in emissions with reductions up to 48% in some cases (Servin, Boriboonsomsin and Barth, 2006). Another study with positive results focused on signal coordination and its ability to reduce emissions. Both microsimulation traffic models and emission models were used to test the scenarios which resulted in the possibility of a 10-40% reduction (De Coensel *et al.*, 2012).

2.1.5.A. Emissions Models

The US EPA created MOtor Vehicle Emissions Simulator (MOVES) with the primary intended use for State Implementation Plan development and transportation conformity analysis. MOVES replaces its predecessor, the MOBILE Model. Both models can be used for analysis at the local, state, or national level, with MOVES also capable of project-level analysis. The Comprehensive Modal Emissions Model (CMEM) was developed prior to MOVES in order to fill the void of microscopic models. It is intended for use at the project- or corridor-level but has not received an update in more than 10 years. Virginia Tech developed the VT-Micro model using entirely publicly available data. Instead of being based on power-demand, as most models are, VT-Micro is a regression model from experimentation. The European Environmental Agency (EEA) developed their own model, COPERT. Despite these models' primary use in regulation conformity, they have found a growing role in research. Additional models found in the literature are MODEM, PHEM, VeTESS, ADVISOR, EMPA, TEE, and VERSIT+.

Emissions models are primarily a subject of two types of research. In the first, emissions models are used to evaluate transportation projects for their impact on the environment. For example, these models are used to evaluate a signalized intersection which was converted to a roundabout (Gastaldi *et al.*, 2014) and to compare various traffic calming measures (Ghafghazi and Hatzopoulou, 2014). In the second, emissions models are compared to each other and to field data to evaluate their ability to accurately model emissions (Nam, Gierczak and Butler, 2003; Fujita *et al.*, 2012).

Several more unique applications for emission models are demonstrated in this section. In the PhD thesis of Bin Liu, the MOVES model is simplified to reduce run times so that the model can be used more easily with traffic demand models and traffic simulation models (Liu, 2015). In a different study, MOVES is used to study bus transit emissions and the impact of network congestion, road grade, and passenger load and fuel type (Alam and Hatzopoulou, 2014).

The major drawback of using an emission model is the model's calibration for a particular location. Vehicle fleet characteristics such as age and vehicle mix play an important role in the generation of emissions so a model should accurately represent the fleet in order to provide accurate results. Additional factors such as climate and local driving habits may also reduce model accuracy.

2.1.5.B. Measuring

An alternate approach to quantifying emissions is to collect data from a portable emissions measurement system (PEMS). PEMS is a device that can be easily installed on any vehicle, with a collection tube inserted into the tailpipe and a sensor system in the vehicle's trunk. PEMS offers the unique advantage of allowing the testing of the exact desired fleet composition on the network of interest. Incredibly specific tests can be designed and executed.

PEMS has been used in research to measure fuel consumption-rate patterns (Wang *et al.*, 2008), emissions related to driving patterns (Luján *et al.*, 2018), vehicles' conformity with emission standards (Kousoulidou *et al.*, 2013) and to evaluate transportation improvement projects (Meneguzzer *et al.*, 2017; Gastaldi *et al.*, 2017). Additionally, research has been published that evaluates the accuracy of different PEMS units (Khan *et al.*, 2012), (Varella *et al.*, 2018). Geichaskiel et al. examine this problem in context of PEMS' new role in vehicle testing in the EU. In 2016 the Real Driving Emissions Test (RDE1), in combination with Worldwide Harmonized Light Vehicle Test Procedure (WLTP), replaced the previous New European Driving Cycle (NEDC). RDE uses PEMS on-road testing to supplement the existing laboratory tests (Giechaskiel *et al.*, 2018). Sandhu and Frey outline best practices in order to avoid inaccurate data and poor synchronization (Sandhu and Frey, 2013).

There are several disadvantages of using PEMS. The devices are expensive and require frequent calibration. Data collection can be time consuming since only one vehicle can be tested at a time making PEMS more suitable for tests at the microscopic level.

A cheaper alternative to measuring emissions is calculating them. On-board diagnostic (OBD) loggers can be used to track engine functions. OBD loggers are small, can be installed without any tools or training, and are widely available, costing only a fraction of the price tag of PEMS. Since 1996, it has been mandatory for all US vehicles to be compatible with OBD loggers which can receive information from the on-board computer. Among the measured parameters, vehicle speed, air-fuel ratio, intake airflow, and revolutions per minute (rpm) are particularly useful in calculating the emissions produced. An example of these calculations can be found in the work of Alessandrini et al. (Alessandrini, Filippi and Ortenzi, 2012).

A study in Montreal examined cyclists' exposure to ultrafine particles, fine particles, black carbon and carbon monoxide using TSI Model 3007 condensation particle counters, TSI Dust Trak monitors, Langan Enhanced CO Measurer Model T15n, and MicroAeth Model AE51 aethalometers. The findings showed that diesel vehicle traffic had a strong impact on exposure to black carbon, while separated cycle lanes had a small impact on cyclists' exposure to pollutants (Hatzopoulou *et al.*, 2013).

2.1.6. Research Gap

The study of vehicular emissions is a growing field of research but there are still many topics that have not been explored extensively. The microscopic contributors of emissions have not been explored in great depths, particularly the impact of different types of intersection controls. Although several studies have looked at the impact of traffic circles and a few others have looked at traffic signals, there are no known studies that directly look at the conversion of one-way stop intersections to all way stop intersections. The use of a before and after approach to evaluate the emissions impact of all-way stops is also believed to be unique to this study.

Several studies have used microsimulation studies to evaluate the impact of traffic improvement projects at the intersection or corridor level. Although models can be a powerful tool for analysis, their value cannot compare to that of field data. This research is unique for its use of PEMS to gather geographically specific data to evaluate the use of stop signs.

Finally, this research contributes to the literature with its comparative analysis between simulated emissions and real-world measures which is unique for its use on the effect of traffic controls. This allows the evaluating of the accuracy of models used in this situation.

3. Microsimulation to evaluate emissions

3.1. Introduction

Increased awareness over environmental issues has led many governments to promote active modes of transportation such as cycling or walking (Rojas-Rueda *et al.*, 2016). In order to reduce the use of personal vehicles many people are using these active modes, or combining them with public transportation. These active modes provide other benefits to users including a lower cost and improved personal health from an active lifestyle (Sallis *et al.*, 2004). The city may benefit through lower congestion on its roads and increased ridership on its public transportation system.

In order to create a safer environment for active transportation users, traffic calming and changes in traffic controls such as stop signs and traffic signals may be employed. This solution is popular with residents who see it as way to reduce motorized-traffic exposure, increase the comfort for non-motorized road users and slowing down traffic in local neighborhoods. Examples of traffic calming methods can include speed humps and speed tables, chicanes, or traffic circles. Implementing traffic calming measures has the ability to reduce speed in the intersection by as much as 33% (Ahn and Rakha, 2009). By requiring vehicles to reduce their speed, come to a complete stop, and yield to pedestrians and bicycles, intersection controls and traffic calming measures create a safer environment for active transportation users who are often also defined as at-risk users. However, by requiring vehicles to come to a complete stop, stop signs and other intersection controls increase the amount of acceleration and deceleration in driving, thereby increasing vehicular emissions. Speed bumps, speed bumps, and speed limits were tested for their impact on vehicular emissions using a modeling approach, finding increases in NO_x which varied from 5% to 160% (Ghafghazi and Hatzopoulou, 2015). Another study focused on the safety and emissions performance of two types of speed humps, speed tables and chicanes. Chicanes were determined to perform best in terms of traffic calming while the speed humps performed best in terms of emissions impact (Lee *et al.*, 2013).

Emissions of NO_x and NO_2 have been found to be linked to acceleration. NO_x is produced at a higher rate when vehicles accelerate and drive slowly, as is common in urban environments (Luján *et al.*, 2018). While greenhouse gas emissions, such as NO_x and NO_2, provide a serious threat to health, possibly more concerning is exposure to particulate matter (PM), more particularly, $PM_{2.5}$ and PM_{10}. PM is created from tire-wear and brake-wear and is also found in vehicular exhaust (Chung *et al.*, 2012). Currently, regulations on PM emissions only apply to emissions produced by vehicular exhaust, leaving no regulations on PM created from brake-wear and tire-wear (Caltrans, 2017). Since PM is largely produced from braking, it is directly related to vehicles' deceleration patterns; higher instances of braking generate higher levels of PM.

In 2010, exposure to $PM_{2.5}$ was ranked 11th in a list of factors contributing to disease (Clifford *et al.*, 2018). This is important because it is difficult for individuals to limit their exposure to PM or even be aware of the levels of PM found in their surroundings.

The purpose of this study is to examine the impact of requiring vehicles to stop at non-signalized intersections on the amount of emissions and pollutants they produce. This is evaluated using a case study of three intersections in Montreal, Canada that were modified from one-way stop intersections to three-way (or all-way stop) intersections. Before and after data from these intersections was used to calibrate a microsimulation model traffic model to evaluate the change in emissions created by requiring additional vehicles to stop upon approaching the intersection using an emissions model.

3.2. Methodology

Methodology steps can be seen in the flow chart in *Figure 3.* In order to evaluate the effects of the implementation of additional stop signs, first, video data was collected from the intersections of interest before and after the stop signs were added. Vehicle trajectories, speeds, volumes and turning ratios were obtained from the video data. Manual counts were used to gather data on intersections where changes were not made and video data was not available. Next, a small network of 22 intersections was modeled in VISSIM. One model was built with two scenarios, one to represent the network before modifications were made, and one to represent the network following the implementation of additional stop signs. Both scenarios consisted of 22 intersections, 10 intersections that were modified and had video data recorded, four that was modified but did not have video data recorded, four that underwent no change and four that were signalized and underwent no change. The results of the traffic simulation were then used as inputs for the EPA's Motor Vehicle Emissions Simulator (MOVES) which was used to calculate the change in emissions between the before and after scenarios. The network characteristics were defined in MOVES through inputs such as second-by-second speed data for each link, vehicle fleet age, meteorology data, and fuel composition, among others. MOVES is being used for this analysis since Canada does not have one agency solely responsible for environmental protection. Instead, the provinces share the responsibility with the Federal Government which frequently adopts the use of the US EPA's standards.

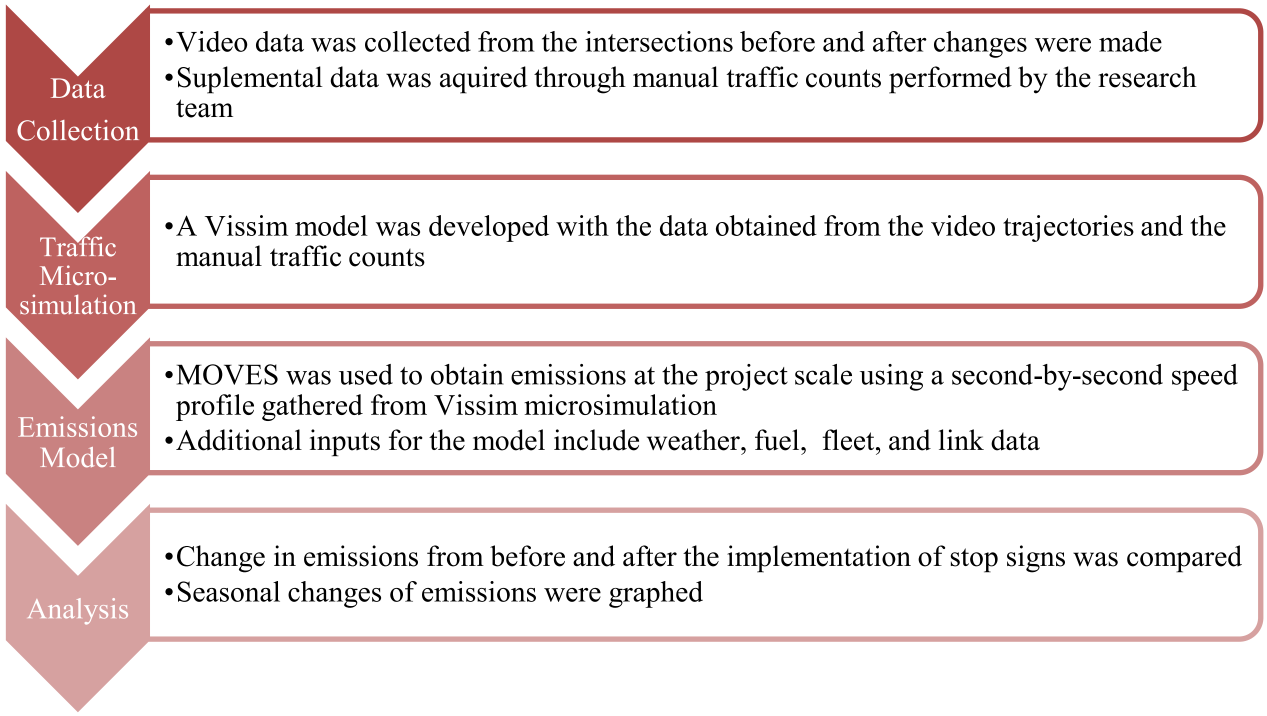

Figure 3: Methodology flow chart

3.2.1. Study Area

This study takes place in Villeray-Saint-Michel-Parc Extension, one of the central boroughs in the City of Montreal. In this borough, important projects have been implemented such as the intersection and street re-design in recent years. This includes the transformation of many one-way-stop intersections into all-way stop intersections. For this case study, the Rue Guizot and Rue de Liege corridors were selected since a few intersections have been recently re-designed from which data was collected before and after. The study focuses on ten intersections where video data was collected and the network that connects them. The study area can be seen on the map in *Figure 4*. Rue Guizot and Rue de Liege are the major roads of the network with single lane, bidirectional traffic and on-street parking. Rue St. Denis is the largest intersecting street, with multilane, bidirectional traffic and signalized intersections. Rue Lajeunesse is also signalized but is unidirectional. All other roads contained within the network are single lane and unidirectional. These roads have on-street parking on both sides. Most streets contain shared spaces for cyclists while Avenue Henri-Julien has a dedicated cycle lane. Prior to the modifications, each of the video-recorded intersections contained one stop sign that required traffic on the one-way street (or minor approach) to stop. Following modifications, each of these intersections requires an all-way stop (or three-way stop). Photos of the typical before and after intersection layouts can be seen in *Figure 5*.

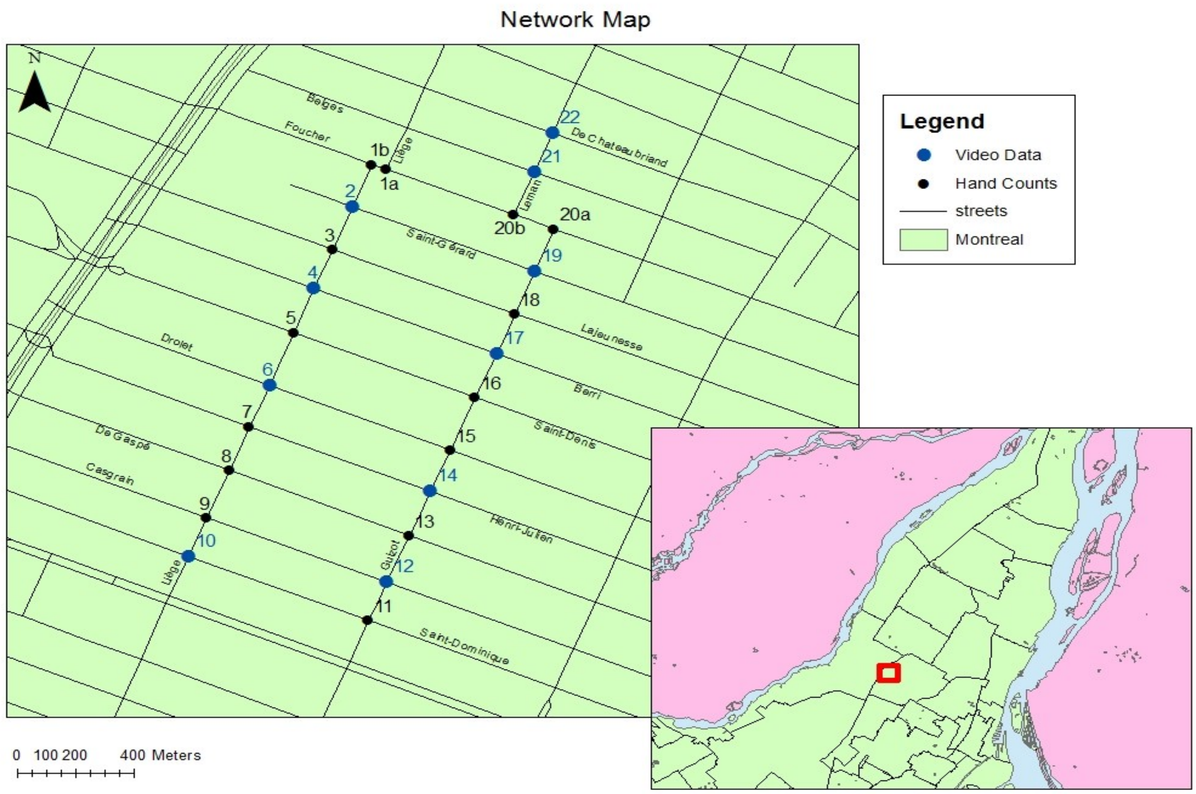

Figure 4: Study area map

Before Changes | After Changes

(a) Avenue Casgrain & Rue Guizot | (b) Avenue Casgrain & Rue Guizot

(c) Avenue Henri-Julien & Rue Guizot | (d) Avenue Henri-Julien & Rue Guizot

(e) Rue Berri & Rue Guizot | (f) Rue Berri & Rue Guizot

Figure 5: Typical intersection layouts before and after changes

3.3. Data

Anonymous video data is collected with normal action cameras due to their weather resistance, which are installed at each selected intersection. The video collected is processed to extract high-resolution road users' trajectories, which represent a continued position of the users captured around 15 times per second, with the help of a computer vision software. Trajectories of each road user are generated, which the software classified into seven categories: pedestrian, cyclist, car, motorcycle, bus, truck and unknown. A manual review is required to correct non-motorized users' trajectories; this process is accomplished using the tvaLib software.

This method of road users' data collection has several advantages over traditional sources of drivers' data collection:

- Instrumentation is unobtrusive for drivers, due to its externality.
- Road users are captured continuously with high-resolution data.
- All the users crossing the field of view of the camera are captured, minimizing the possibility of selection bias in the study. Personal information is not captured, faces and licenses plates are a certain distance that is indistinguishable to the computer algorithmic and human operators.
- Cameras are low cost and easy to install, making the data collection very cost-effective.

With the video data analysis, information related to traffic volumes and speed profiles were obtained for the analyzed intersections and used as inputs for the Vissim model. Data was collected during daytime hours of weekdays and details on its collection can be seen in *Table 1*.

Table 1: Data Collection Details

ID	Intersection Name	Method of Collection	Date of Collection BEFORE	Date of Collection AFTER
1a	Rue de Liege and Rue Foucher	Manual count	N/A	March 13, 2019
1b	Rue de Liege and Rue Foucher	Manual count	N/A	March 13, 2019
2	Rue de Liege and Rue Saint Gerard	Camera	September 29, 2016	October 25, 2017
3	Rue de Liege and Rue Lajeunesse	Manual count	N/A	February 22, 2019
4	Rue de Liege and Rue Berri	Camera	September 28, 2016	October 25, 2017
5	Rue de Liege and Rue Saint Denis	Manual count	N/A	February 22, 2019
6	Rue de Liege and Rue Drolet	Camera	September 28, 2016	October 25, 2017
7	Rue de Liege Henri Julien	Manual count	N/A	February 28, 2019

	Avenue			
8	Rue de Liege and Gaspe Avenue	Manual count	N/A	February 28, 2019
9	Rue de Liege and Casgrain Avenue	Manual count	N/A	February 28, 2019
10	Rue de Liege and Rue Saint Dominique	Camera	September 29, 2016	October 16, 2017
11	Rue Guizot and Rue Saint Dominique	Manual count	N/A	March 1, 2019
12	Rue Guizot and Casgrain Avenue	Camera	June 22, 2016	October 23, 2017
13	Rue Guizot and Gaspe Avenue	Manual count	N/A	July 6, 2018
14	Rue Guizot and Henri Julien Avenue	Camera	June 22, 2016	October 18, 2017
15	Rue Guizot and Rue Drolet	Manual count	N/A	July 5, 2018
16	Rue Guizot and Rue Saint Denis	Manual count	N/A	March 14, 2019
17	Rue Guizot and Rue Berri	Camera	September 27, 2016	October 25, 2017
18	Rue Guizot and Rue Lajeunesse	Manual count	N/A	March 1, 2019
19	Rue Guizot and Rue Saint Gerard	Camera	September 27, 2016	October 26, 2017
20a	Rue Guizot and Rue Foucher	Manual count	N/A	March 1, 2019
20b	Rue Leman and Rue Foucher	Manual count	N/A	March 1, 2019
21	Rue Leman and Avenue des Belges	Camera	September 27, 2016	October 23, 2017
22	Rue Leman and Avenue de Chateaubriand	Camera	September 26, 2016	November 1, 2017

3.4. Models

3.4.1. VISSIM

The Vissim model was built to represent the intersections which were modified as well as the supplementary, surrounding intersections. The model's first scenario represented the before period while the second scenario represented the after period. The only variations between the two scenarios of the model were the presence of the additional stop signs and the speeds. Traffic volume was not modified in order to prevent an unnecessary bias in the data. An image of the VISSIM model can be found in the Appendix. The intersections identified by a blue dot on the map in *Figure 4,* are the intersections which had video data recorded. Traffic data for both scenarios reflects the manual counts taken after changes were made. A combination of data from the video data and manual traffic counts were used as inputs for the model. Inputs can be seen in *Table 2*. The model included cars, trucks and cyclists. One run from before and one run from after were used to create the second-by-second speed profile input for MOVES. The model was run for a period of 4500 seconds with the first 900 seconds discarded to account for a warm-up period. Speed data was obtained from the video data when possible. Speeds for many of the additional intersections were approximated from similar stretches of roadway which were tracked on the video data. The speed limit for Rue St. Denis and Rue Lajeunesse were used as the input speed since no video data was available from streets of a similar composition.

Since data was collected over varying seasons, using different methods, and with the impact of construction, the traffic counts were not all compatible. In order to reconcile these differences, turning ratios for all intersections were considered as ground-truth and used to balance intersection volumes. Volumes were taken from the intersections with the highest confidence and the volumes were adjusted outward based on the turning ratio data. The intersections of Rue St. Gerard and Rue Guizot and Rue St. Gerard and Rue de Liege were chosen as the highest confidence intersections since they both had video data that was on a day with good weather, no construction, and had the highest volumes.

Table 2: Vissim Inputs Part A & B

	A. Speed (km/h)					
	Before			**After**		
	Car	**Truck**	**Bike**	**Car**	**Truck**	**Bike**
Casgrain	30	25	25	20	25	20
Gaspe	30	30	20	20	20	20
Henri-Julien	30	30	20	20	20	20
Guizot EB	30	30	20	20	20	20
St. Denis NB	50	50	20	50	50	20
Drolet	40	40	25	25	30	25
Berri	30	25	2	20	20	20
St. Denis SB	50	50	20	50	50	20
Guizot WB	30	30	2	20	20	20
Liege EB	30	30	2	20	20	20
Liege WB	30	30	20	20	20	20
Lajeunesse	50	50	25	50	50	25
St. Gerard	40	40	25	25	20	25
Foucher	30	30	20	20	20	20
Des Belges	30	30	20	25	25	25
De Chateaubriand	30	30	20	20	15	20
Leman	30	30	20	20	20	20
St. Dominique	30	30	20	20	20	20

	B. Volume		
	Car	**Truck**	**Bike**
Casgrain	210	8	4
Gaspe	49	1	4
Henri-Julien	141	2	7
Guizot EB	54	1	1
St. Denis NB	915	49	3

Drolet	62	18	13
Berri	60	3	2
St. Denis SB	652	20	14
Guizot WB	0	0	0
Liege EB	105	4	1
Liege WB	150	6	2
Lajeunesse	397	20	2
St. Gerard	6	1	2
Foucher	53	2	0
Des Belges	37	1	4
De Chateaubriand	63	2	6
Leman	110	5	0
St. Dominique	66	3	3

3.4.2. MOVES

The EPA's MOVES2014a program was used at the Project Scale with Link Drive Schedules (second-by-second speed profiles of each link) to calculate the emissions for this case study. When using the Project Scale, each run of the program calculates the emissions for one hour of one month. Per MOVES guidance files, the months January, April, July, and October were used to represent the seasonal weather and fuel changes of a year. One run was performed per month using "before" data and one run per month using "after" data. All evaluations were performed for the hour from 9:00 am to 10:00 am for the year 2017. This time and year was chosen since it was most representative of the data that had been collected. Meteorology data for 2017 was obtained from the Montreal/Pierre Elliott Trudeau International Airport's weather station via the Government of Canada's website (*Hourly Data Report for December 01, 2017 - Climate - Environment and Climate Change Canada*, 2017). Vehicle fleet age information was extrapolated from age data of light vehicles for the period of 2003-2012 and was assumed to be true for both the passenger cars and for the light trucks that were modeled (Miranda-Moreno, Luis; Zahabi, 2016). At the time of the study fuel data was not available for the province of Quebec so fuel data was imported from MOVES defaults for the US counties which border the province of Quebec.

3.5. Results

All results have been reported in grams of pollutant produced per hour of the typical 9:00-10:00 am hour of each month. The quantities of all types of pollutants produced hourly in each of the four months were summed and compared for their values before and after the addition of the stop signs. Additionally, the percent change was calculated and can be seen in *Table 3.* All pollutants and emissions were found to be produced in greater quantities after the stop signs were added to the intersections except for the production of PM from tire-wear. The greatest increases were from the production of brake-wear PM, followed by Atmospheric CO_2 and energy consumption.

Table 3: Grams of Pollutant Produced Per Hour

Pollutant	Before (kg per hour)	After (kg per hour)	% Change*
CO	9.362	9.886	5.60
NO_x	0.387	0.404	4.41
NO	0.323	0.337	4.41
NO_2	0.061	0.064	4.43
Atmospheric CO_2	1694.689	2072.626	22.30
Energy Consumption	23574363893	28831847416	22.30
Primary Exhaust PM_{10}	0.023	0.026	10.55
PM_{10} Brake-wear	0.238	0.314	31.54
PM_{10} Tire-wear	0.045	0.042	-6.32
Primary Exhaust $PM_{2.5}$	0.021	0.023	10.56
$PM_{2.5}$ Brake-wear	0.030	0.039	31.54
$PM_{2.5}$ Tire-wear	0.007	0.006	-6.32

*The percent change was calculated to the 10^{th} decimal place.

Emissions fluctuate throughout the year due to changes in temperature, humidity, and fuel formulation. These trends can be seen in *Figures 6-8* were the hourly emissions are plotted seasonally in addition to the temperature and humidity patterns used in the model. Emissions of CO, NO_x, NO, NO_2, and PM Exhaust were notably lower in the summer and fall months. When compared to the graph of the temperature data used in the models, they exhibit an inverse interaction. When the air temperature was cooler, emissions were produced at a higher rate. Other pollutants experienced a relatively consistent rate throughout the year. One notable trend seen throughout the graphs is a dip in the July emissions, particularly in the “after” period.

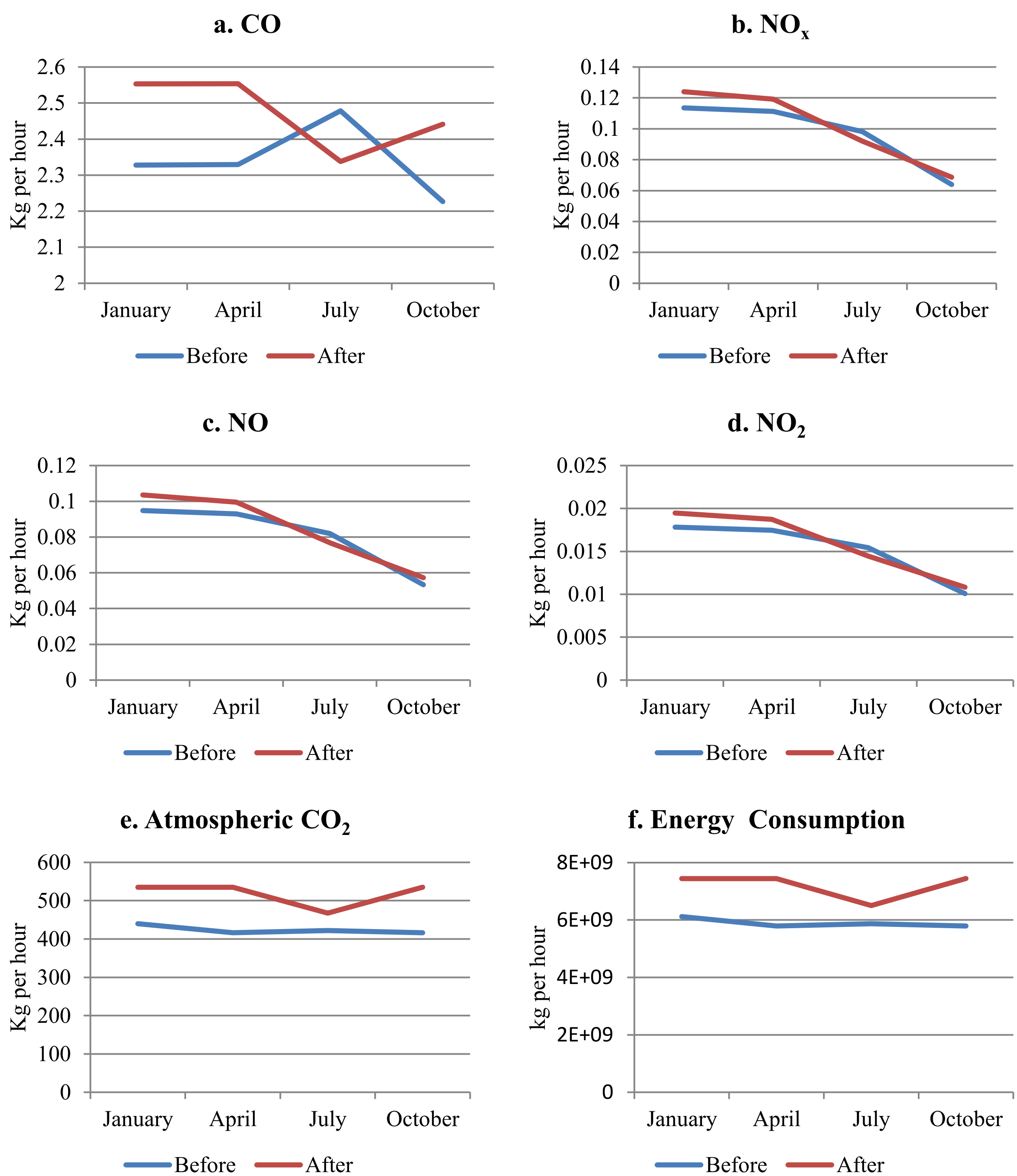

Figure 6: Seasonal variations in emissions and energy consumption (a) CO, (b) NO_X, (c) NO, (d), NO_2, (e) atmospheric CO_2, (f) energy consumption

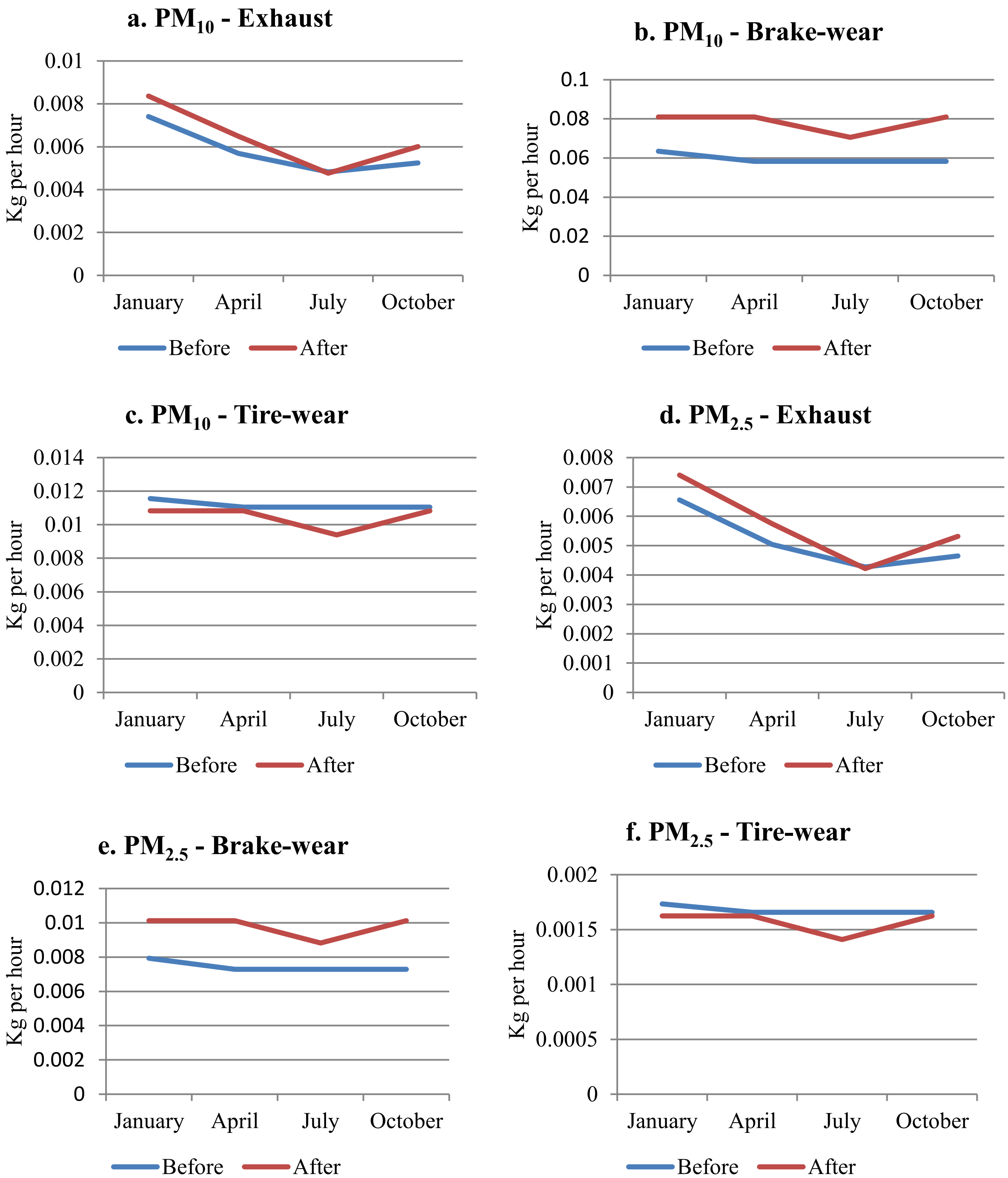

Figure 7: Seasonal variations in kg of particulate matter (a) PM10 – Exhaust, (b) PM10 – Brake-wear, (c) PM10 – Tire-wear, (d) PM2.5 – Exhaust, (e) PM2.5 – Brake-wear, (f) PM2.5 – Tire-wear,

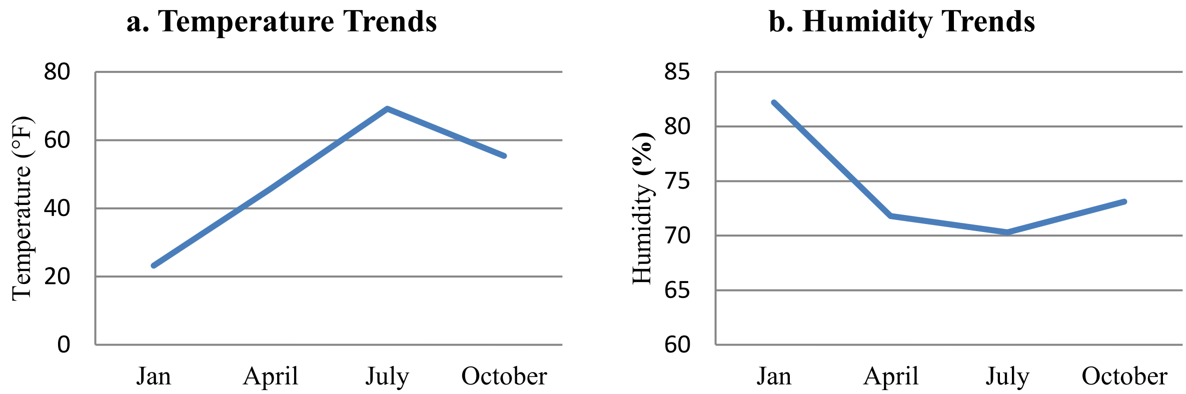

Figure 8: Seasonal variations in (a) Temperature Trends and (b) Humidity Trends

3.6. Conclusion

With the exception of tire-wear PM, emissions of all pollutants were found to be emitted in higher concentrations after the intersections were modified. The most significant increases were in the concentration of PM_{10} and $PM_{2.5}$ produced by brake-wear with a 31.54% increase, followed by the concentration of atmospheric CO_2 and energy consumption, both with a 22.3% increase. The increase in the amount of brake-wear pollutants is expected, due to the increased amount of time vehicles spend braking after the implementation of stop signs. There was a 17% increase in the number of required stops on the network due to the added stop signs. The fact that tire-wear emissions decreased is somewhat surprising, although it is possible that this is a result the overall lower driving speed in the network following the changes. In regards to the seasonal pattern displayed, existing literature shows that emission rates are particularly sensitive to cold temperatures (Suarez-Bertoa and Astorga, 2018) (Choi *et al.*, 2011), which explains the peak that is seen in January for many of the pollutants.

The increase in pollutants within the network is a negative result of this intersection modification. Although the implementation of stop signs might be perceived as beneficial due to the potential safety benefits, the long-term effects of air pollution are damaging to both health and the environment. These costs are not monetized as easily as things like vehicular damage leading them to be underrepresented in decision making.

3.6.1 Limitations and Future Research

Potential sources of error in this research are predominantly related to the limitations on the amount of video data collected and processed as well as the limitations of both modeling programs. Both are discussed in more detail below.

For this study, only one day (approximately 8 hours) of footage was recorded from before the changes and one day after the changes. The collection of this data is time consuming and limited by both the memory and battery capacity of the cameras. The cost and time associated with verifying the video trajectories is an additional burden which limits the amount of data that can be used for the analysis. In an ideal study, all intersections modeled in Vissim would have data collected from video trajectories (as opposed to the data gathered from manual traffic counts that was used in this study). The data would all be collected on the same day, or at least during the same season. An ideal model would represent traffic at peak hours of the day. This should not have a significant impact on the results of this study since the chosen network is within a residential neighborhood which likely doesn't exhibit significant peak traffic periods.

Another challenge that particularly effected the data collection for this study was construction. During a majority of the data collection period (both for videos and manual counts) construction was present within different parts of the neighborhood resulting in abnormally high counts in some areas and low counts in other areas. This construction was not consistent and shifted around the neighborhood making it even more difficult to obtain an unbiased traffic count.

Improvements in bike counts could also be made for future experiments. Due to the extreme weather patterns experienced in Montreal, biking changes significantly throughout the season. Since data was gathered over several seasons for this research, including winter where essentially no bikes were counted, the bike data from the videos was used as typical for the remainder of the network.

Accuracy of the models is the other significant challenge of this research. Additionally, the VISSIM model was built using default settings which allow for the input vehicle speeds in increments of approximately 5 km/h and therefore does not exactly represent the average vehicle speeds found from the video data. Furthermore, microsimulation does not account for the unpredictable actions and mistakes of human drivers. It assumes perfect compliance to traffic regulation which is often not seen in real life. A particular example of this is cyclists who rarely come to a complete stop at stop signs in real life while in the model they are represented with perfect compliance.

There was considerable difficulty calibrating this model due to its small size and the inputs from a large variety of sources and times (in addition to irregularities caused by construction). This represents a significant area for improvement within this experiment and others of a similar nature.

Similarly, the MOVES model creates a space for errors. MOVES was created for use in the United States, meaning that all its default data (fleet, weather, etc.) was built based on the typical data from the US. Actions were taken to replace defaults with local data. Additionally, the model uses speed bins to calculate emissions and if an input doesn’t fall within a bin the program places it in the nearest one causing the model to lose a small amount of accuracy. MOVES’ accuracy could possibly be improved by using operating mode distribution rather than a second-by-second speed profile to enter traffic data; however, this approach requires complicated inputs that are not easily gathered from microsimulation.

In order to avoid the complications that arise from modeling, future experiments could be designed to test emissions using alternative methods such as calculations from fuel consumption or directly through PEMS measurement.

4. PEMS to evaluate emissions

4.1. Introduction

Often, roadway design, intersection controls in particular, is overlooked as an influential factor on vehicular emissions. Urban transportation authorities implement traffic calming plans disregarding the long-term side effects of modifications to the network design.

Intersection controls are introduced to an intersection in order to improve the safety of its users, especially vulnerable segments such as cyclists and pedestrians. Popular intersection controls in North America include, but are not limited to stop signs, yield signs, traffic circles and traffic signals. These controls force vehicles to slow down or come to a complete stop before proceeding. The addition of such intersection controls forces vehicles to accelerate and decelerate more within the network. Frequent stop-and-go patterns not only lead to higher tire-wear and brake-wear PM emissions, but also is expected to increase GHG and NO_x emissions as well. Higher combustion chamber temperatures occur with higher acceleration rate and the temperature is the main root cause of NO_x generation in spark-ignition engines (Thoma, Allgöwer and Morari, 2010; Luján *et al.*, 2018).

However, intersection controls are rarely studied for the specific impact that they have on emissions. Often, studies rely on microsimulation and models to generate emissions estimates. In a study by Rakha et al. the emissions models MOBILE5a, MOBILE6, VT-Micro, and CMEM are compared for their ability to match EPA data (Rakha *et al.*, 2003). Ahn and Rakha also performed a study comparing intersections with no control, stop control, traffic circles and speed humps using a combination of driving cycles gathered from test drivers and the VT-Micro emissions model. They found that traffic circles produced smoother driving patterns and generated the least emissions (Ahn and Rakha, 2009). Similarly, Fernandes et al. used traffic data to build a VISSIM model along with several alternative scenario models containing varying intersection controls. Roundabouts, traffic lights, and stop signs were compared. When analyzed at the intersection level, stop controlled intersections generated less emissions than roundabouts, and roundabouts in turn generated less emissions than intersections controlled with traffic lights (Fernandes *et al.*, 2015).

The Motor Vehicle Emission Simulator (MOVES) developed by the U.S. Environmental Protection Agency (USEPA) covers a broad range of pollutants in addition to estimation of energy consumption. Several transportation consulting firms and governmental authorities in

Canada have been using MOVES to assess the energy and environmental impacts of different policies or network-treatment scenarios proposed during the development of transportation plans. Although the software provides options to adjust the model settings for the prevailing conditions of the area under study (in terms of energy sources, vehicle type, engine technology, fleet distribution, and meteorology), it is limited to the U.S. states and counties. On the other hand, the model is estimated based on a large sample of vehicles from the U.S. which is significantly different from Canadian fleet of vehicles. People are apparently more interested in smaller-size vehicles with higher fuel economy in Canada. Extreme weather conditions of Canada which are not comparable to any of the U.S. states is another crucial difference.

The last and the most important concern regarding usage of MOVES is the type of experiments conducted for collecting energy consumption and emissions data from target vehicles before estimating the models. The data is mainly collected through in-lab chassis dynamometer tests by performing the FTP-75 (Federal Test Procedure) driving cycles for urban driving simulation and the supplementary US06 test procedure (addresses the shortcomings of the FTP-75 test cycle in the representation of combined high speed and/or high acceleration driving behavior, rapid speed fluctuations, and driving behavior following start-up (United States EPA, 2019)). Studies such as Pelkmans and Debal's (Pelkmans and Debal, 2006) research through comparison of on-road and lab test results show the negative impact of controlled test environments on the quality of energy consumption and emissions estimations. Not only the dynamics of the vehicle–dynamometer combination differ in many respects from those of a vehicle on the road (Plint and Martyr, 2001), but also factors such as pavement quality, tire type, tire age, tire pressure, wind direction, rainfall, and existence of snow or ice on the road are disregarded in the lab.

This study has the objective to assess the energy and environmental impacts of different intersection treatments on annual transportation-source emissions and energy consumption by performing on-road experiments and collecting real-world data using a PEMS (portable emission measurement system) and a portable activity measurement set (PAMS). As the intersection treatments are expected to have significant impact on drivers' reaction when approaching an intersection and crossing it (different approach speeds and acceleration/deceleration patterns), we also assess the reliability of MOVES for future applications in similar studies. Comparing the MOVES estimates with the ground-truth measured by a PEMS in combination with an OBD-II logger (for energy consumption measurement), we could evaluate the general over-/under-estimation or even case-specific biases in MOVES output.

4.2. Methodology

We perform our study in three major steps. First, we conduct on-road experiments in central neighbourhoods of Montreal while PEMS and PAMS units are installed on the vehicles. Then, we perform an independent analysis on the collected data to compare the average and distribution of emission rates of vehicles while passing intersections with different control types. Finally, we consider the field experiment results as ground-truth and compare them with the MOVES estimations.

4.2.1 On-road Experiments

Portable Emissions Measurement System

As technology advances, small-size PEMS devices are becoming more affordable and being widely used to verify existing emissions models and standards, particularly in Europe (Kousoulidou *et al.*, 2013; Varella *et al.*, 2018). The 3DATX parSYNC Plus we used in our experiments is a lightweight integrated portable emissions measurement system which utilizes multiple miniaturized sensors capable of measuring concentrations of GHG and criteria pollutants such as PM, CO_2, NO, and NO_2 from both diesel and gasoline engines in real-time. The device uses electro-chemical sensors for NO_x measurement, non-dispersive infrared (NDIR) absorption technology for CO_2 measurement, and finally a multi-plex method of combining ionization, opacity-metering, and laser-scattering sensors data for PM concentration measurement. *Figure 9.a* shows the PEMS unit.

(a) (b)

Figure 9: (a) 3DATX parSYNC Plus portable emissions measurement system. (b) Veepeak OBD-II logger installed on a Ford Escape 2006

Portable Activity Measurement Set

On-board diagnostics (OBD) interface have been required in the United States for all cars and light duty trucks since 1996. OBD-II standard provides access to instantaneous operational parameters of the vehicle measured by different sensors and reported by ECU (Electronic Control Unit). Its original purpose is to determine if vehicle adhere to mechanical, energy consumption, and emission standards. There are over 200 parameters that can be measured through the OBD-II interface, although not all vehicle models are compatible with them all (Gardetto, Lindner and Bagian, 2005).

We use a wireless OBD-II logger in combination with a tablet. The OBD-II logger sends the desired parameters through Wi-Fi to the tablet where the data is combined with GPS location of the vehicle and logged into memory for future analysis. *Figure 9.b* shows the picture of OBD-II logger installed on the corresponding port under the steering wheel.

Study Area

For this study, we focus on a network in the Villeray borough of Montreal, Quebec. Many intersections within this neighborhood recently received treatment which converted them from a one-way or two-way stop intersection to an all-way stop intersection. Intersections within this network were separated into three categories: signalized, all-way-stop (AWS), and intersections with stops only in the minor approach (SMA). Signalized intersections are defined as those which are controlled in all directions by a traffic light. AWS intersections are defined as those in which a stop sign is placed at all approaches. SMA intersections are defined as those intersections where a stop sign controls only the minor approach or there is no signalization at all. Only SMA intersections where the researchers' trajectories approached the intersection from the direction where there was no stop sign were included in this analysis. The intersections included in this study contain three or four approaches and are within neighborhoods which are mostly residential. Some roads have parking along the curb and some roads have painted bike lanes adjacent to them. *Figure 10* contains a map showing the location of the vehicle trajectories.

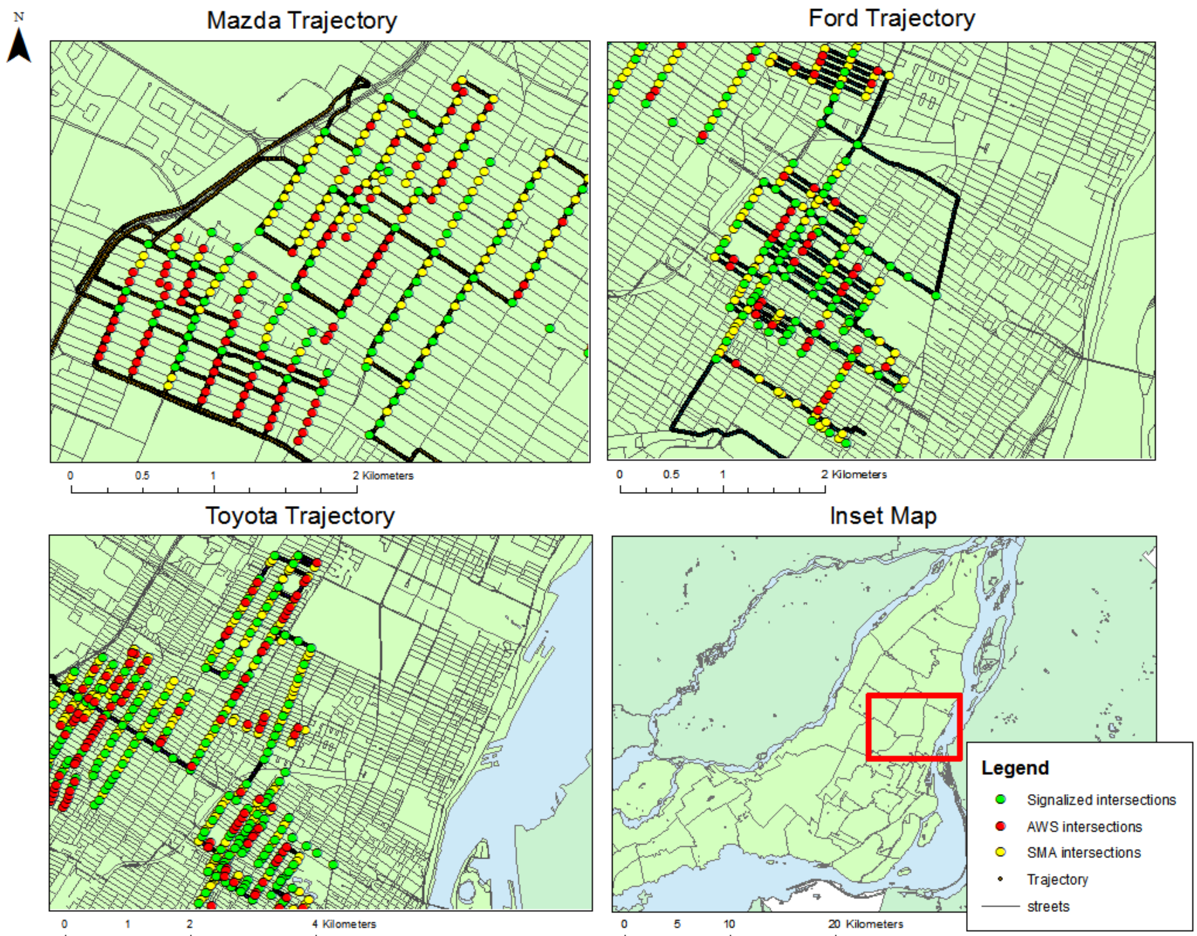

Figure 10: Trajectory map and the intersections under study

Data Collection

We drove three different vehicles through this network for a combined total of 8.5 hours. The vehicles were all outfitted with the OBD-II logger, PEMS, and dashboard camera for the duration of the tests. *Table 4* contains vehicle and trip specifications. We conducted all tests by the same driver in order to eliminate the possibility of error due to different driving habits.

Table 4: Test Vehicle Details

Make	Model	Year	Duration of Trip (hr)	Length of Trip (km)	No. of Intersections Included*		
					AWS	SMA	Sig.
Ford	Escape	2006	2.49	35.38	31	16	34
Mazda	3	2016	3.60	65.48	91	90	54
Toyota	RAV4	2016	2.62	41.46	36	52	80

* No. of intersections after data had been cleaned and undesirable intersections removed.

Engine speed (RPM), fuel rate, mass air flow, and wheel speed, in addition to the vehicle's GPS coordinates (including latitude, longitude, and altitude) in second-by-second manner are the major parameters we collect with the help of our PAMS set. The dashboard camera installed on the front windshield (facing towards the road) provides a secondary reference if there is a question regarding the intersection type that was traversed at a particular time during the test.

The complete PEMS setup installed on a 2016 Mazda 3 is shown in *Figure 11*. The intake hose is clamped into the tailpipe where it collects a sample from the exhaust gas generated by the vehicle (the pump vacuums exhaust with a flow of 2.5 l/min). This gas flows through the hose into the chiller. The purpose of chiller is to condense the water that is present in the exhaust gas, in order to remove it. The water is collected in a water trap, before the rest of the gas is sent to the main unit. The gas is finally expelled outside the vehicle through an exhaust hose. Following installation and prior to beginning each test, we zero out the measurements by letting the PEMS measure the ambient and clean air as a basis.

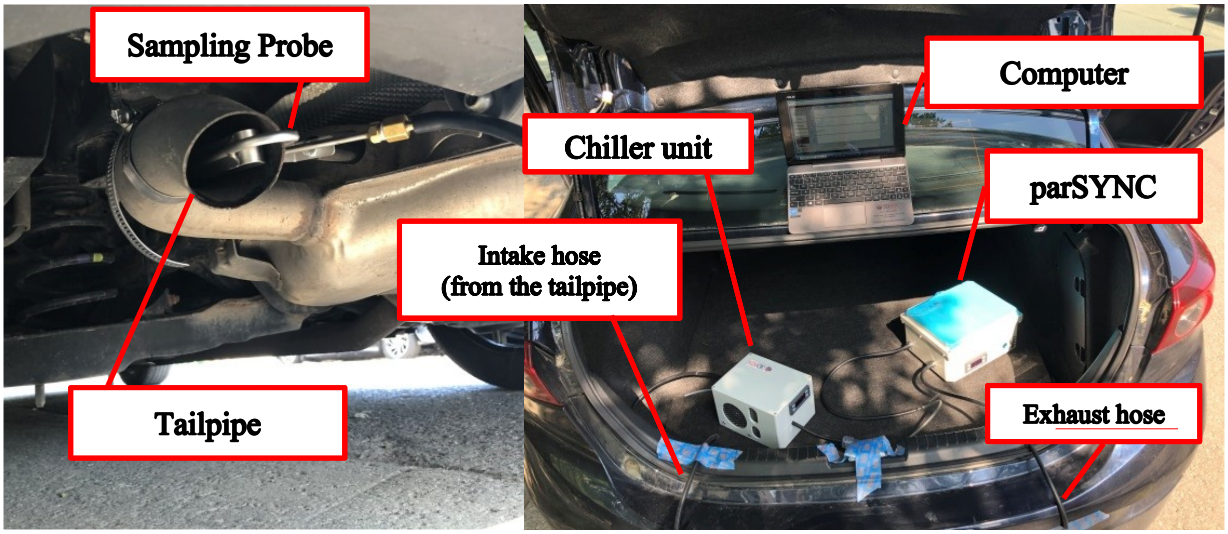

Figure 11: PEMS setup installed on a Mazda 3

Timestamps, synchronized to internet time servers prior to each test, are the only common parameter that allows alignment of dashboard camera, PAMS, and PEMS measurements.

4.2.2. Extracting Measures

Following the data collection, we take a data matching process to precisely align the output of the PAMS to the output of the PEMS. There is a variable time lag between the two sensors which can be accounted for by the amount of time it takes the exhaust to travel from the engine to the tailpipe. What the OBD-II logger logs is the real-time readings of engine interactions, while what PEMS unit measures at the same time is the result of past engine interactions. This lag depends on metrics such as the physical structure of the vehicle, engine technology, and the driving modes undertaken during the test. In order to match the time, we compare graphs of emissions vs. time and engine RPM vs. time. We choose the RPM as the most accurate representation of engine internal events. We select fifty random points and then determine the lag visually. The average of these 50 time lags gives us a rough estimate of the time lag for each vehicle. Once the datasets generated by PAMS and the PEMS are joined, we import the GPS measurements to ArcGIS software. We consider the group of data points that fell within 30 meters buffers generated around intersections to be one "event". Then, we separate the events by type (signalized, AWS, SMA) for analysis. Intersections where turns were made were removed from the analysis.

Since the PEMS reports CO_2 in percent concentration and NO_2 and NO in ppm, steps must be taken to convert these units into mass rate (kg/hr). We use Equations 1 and 2 for this purpose. The calculations are based on a thesis published by Graver (Graver, 2016).

$$CO_2\ Concentration\ (\%) = 10^4 * CO_2\ Concentration\ (ppm) \quad \text{(Eq. 1)}$$

$$Mass\ Rate = \frac{Concentration}{10^6} \times MAF \times \frac{1}{1000} \times \frac{Moleclar\ Weight\ of\ Air}{Molecular\ weight\ of\ Gas} \times 3600 \quad \text{(Eq. 2)}$$

In Equation 2, mass rate is in kg/h; concentration is in ppm; MAF (intake mass air flow rate of the engine) is in g/s; the division by 1000 is to convert grams to kilograms and multiplication to 3600 is to convert hours to seconds. The molecular weight of gases used in calculation can be seen in *Table 5*.

Table 5: Molecular weight of air and emissions used in calculations

	CO_2	NO_2	NO	Ambient Air
Molecular weight (g/mol)	44.01	46.01	30.01	28.97

4.2.3. MOVES Runs

Scale

For the special needs of this study, we execute MOVES at the project level domain. Each MOVES run estimates vehicular emissions for a specific hour in July 2019, when we conducted the three field experiments on the Mazda 3, Ford Escape, and Toyota RAV4. In total, we performed 12 runs covering 4 hours for each of the three vehicles. Moreover, we took the emissions “inventory” approach rather than “emissions rate” to estimate total mass of the emissions generated (and the energy consumed) while the test vehicles were within a designated buffer zone around each intersection.

Temporal Domain

To make the comparisons between signalized and non-signalized intersections feasible, we focus on local intersections which are negligibly affected by daily traffic volume variations. In addition, the time periods when we conducted the field experiments were mainly during mid-day off-peak. No significant change of traffic volume occurs in target neighbourhoods in that period. We use second-by-second driving schedules including speed and grade profiles instead of average speed and average grade values to improve the MOVES estimation accuracy. We log the instantaneous wheel speed through the OBD-II port and disregard GPS speed due to lower accuracy. However, for the grade estimation, we have no other choice rather than using GPS altitude.

Geographic Bounds and Meteorological Conditions

We choose the Franklin county in Vermont state as the closest U.S. county to the city of Montreal in terms of location and weather conditions. As mentioned earlier, this is one of limitations of generalizing MOVES to non-U.S. regions. The only solution is to select a similar county from U.S. and then fine tune the settings to improve the similarity. As the meteorological records show, there was no significant variation in temperature and humidity index during each of our tests. Thus, no further MOVES runs or adjustments on the output were required due to weather condition variations.

Every link in MOVES simulation is virtually defined as a set of continuous points corresponding to a buffer of 30 meters around the center point of the intersection. The number of data points depends on the speed profile at each intersection.

Vehicle and Fuel Specifications

Normally, MOVES gets traffic volume information for each links and combines it with fleet distribution information. However, we do a special type of simulation including only a single vehicle in each run. We include the age of our single vehicle which affects the choice of engine technology (by MOVES). Furthermore, we select regular gasoline (and define its corresponding chemical formulation) as the only available option for fuel.

Road Type

As we study only passage of vehicles through the local intersections, we choose the “urban unrestricted access” type for the roads. Although we have idling moments especially when the vehicles stop because of stop sign or traffic signal, we could not include those situations as virtual “Off-network” road segments. The reason is that we warm up the engine before beginning of each field experiment and no cold-start operation is monitored by the sensors.

Pollutants and Emission Processes

We choose criteria pollutants including NO, NO_2, and particulate matters ($PM_{2.5}$ and PM_{10}), the CO_2 as the major GHG emission, and energy consumption as the output of our MOVES runs. All the emissions correspond to running exhaust; thus, we ignore the cold-start and crankcase emissions. Regarding the particulate matters, we only compare the part emitted from tailpipe. We exclude brake-wear and tire-wear particulate matter emissions, although they form majority PM generated by road transportation.

4.3. Results

4.3.1. Energy and Emissions Analysis of Intersection Types

We use box plots to perform a visual descriptive analysis on the outputs. *Figures 12-15* show the total mass of emissions and fuel consumption in the three types of intersections in addition to maximum and minimum observations, first, and third quantiles found per event, separated by vehicle model. The Ford produced the highest level of emissions, and also consumed the largest amount of fuel. This is likely due to the age of the vehicle. This vehicle's outdated engine technology combined with the possibility of poor upkeep and maintenance lead it to burn more fuel than the newer, more fuel-efficient vehicles tested. Another possible root cause could be the catalytic converter losing its efficiency. Catalytic converters are installed in vehicles as part of the exhaust system and function to reduce the emissions of harmful gases by exposing the exhaust gas to a catalyst which causes it to undergo a chemical reaction, transforming the gas into a less dangerous gas before expelling it into the environment.

The emissions from the Toyota have less variation than the emissions produced by other vehicles. Although this is expected when compared to the older technology of the Ford, it is not intuitive when compared to the Mazda which is from the same model year. It is possible that this variation is caused by the Toyota's continuously variable transmission (CVT). CVT technology can allow vehicles to have higher fuel efficiency and lower emissions due to smoother gear transitions (Srivastava and Haque, 2009).

Signalized and AWS intersections follow a similar pattern with higher variability for signalized intersections. This is expected because signalized intersections do not always require vehicles to stop. However, when they do, acceleration and deceleration patterns for a signalized intersection are similar to an AWS intersection, generating similar levels of emissions.

CO_2 emissions and fuel consumption also follow a similar pattern. This is also expected as CO_2 is the primary GHG produced by vehicles. Interestingly, the amount of the CO_2 emitted does not comply with estimation formulas presented in literature or reported by the Canadian government (Resources Canada, 2014). A rough conversion rate between CO_2 and the regular gasoline is 2.29 kg/l. But according to *Figures 12-15* we observe average conversion rates of 1.159, 1.506, and 1.175 kg/l for the Ford, Mazda, and Toyota, respectively. It is possible this discrepancy is due to the fact that our calculations only come from intersection data, while the data from the Canadian government is from a full drive cycle. Still, this observation brings into question the official reported conversion rates, but also shows the impact of vehicle type, vehicle age, engine, transmission, and emission control (catalytic convertor) technology on amount of GHG emissions.

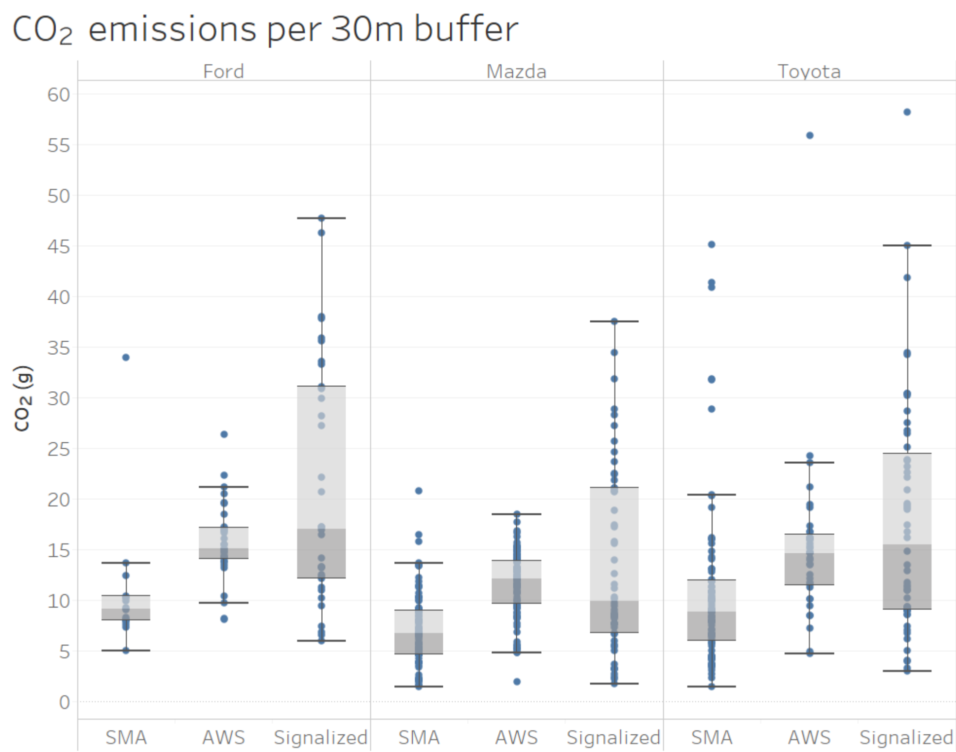

Figure 12: CO_2 emissions calculated per buffer area

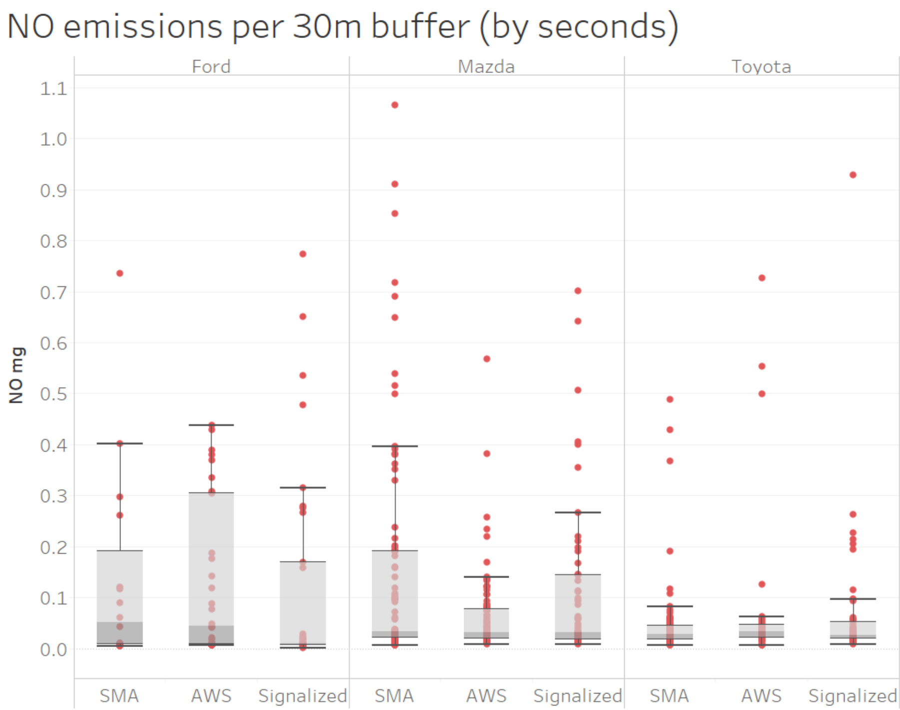

Figure 13: NO emissions calculated per buffer area

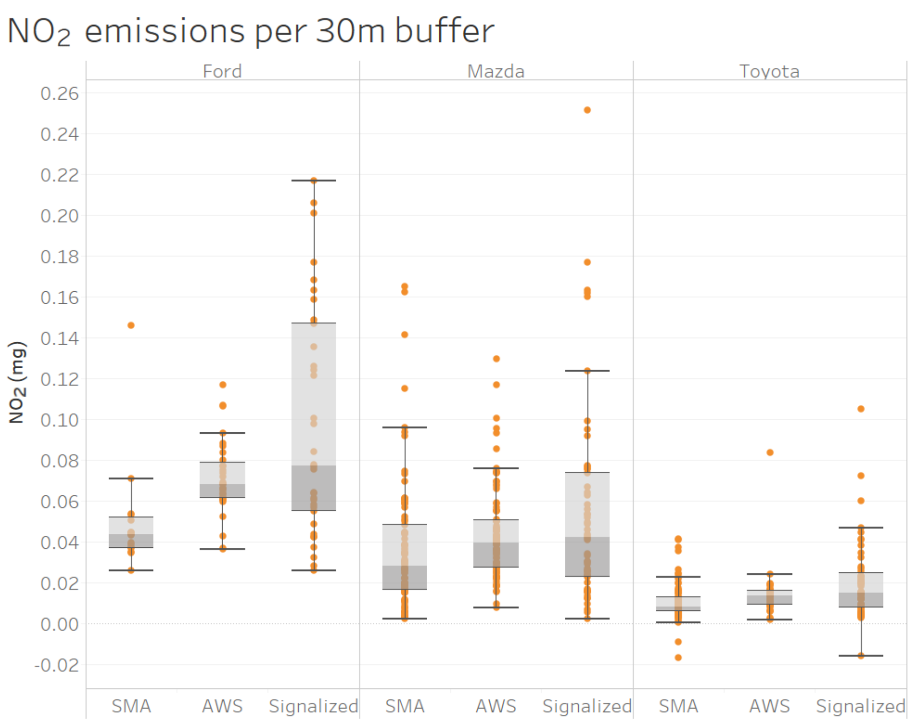

Figure 14: NO_2 emissions calculated per buffer area

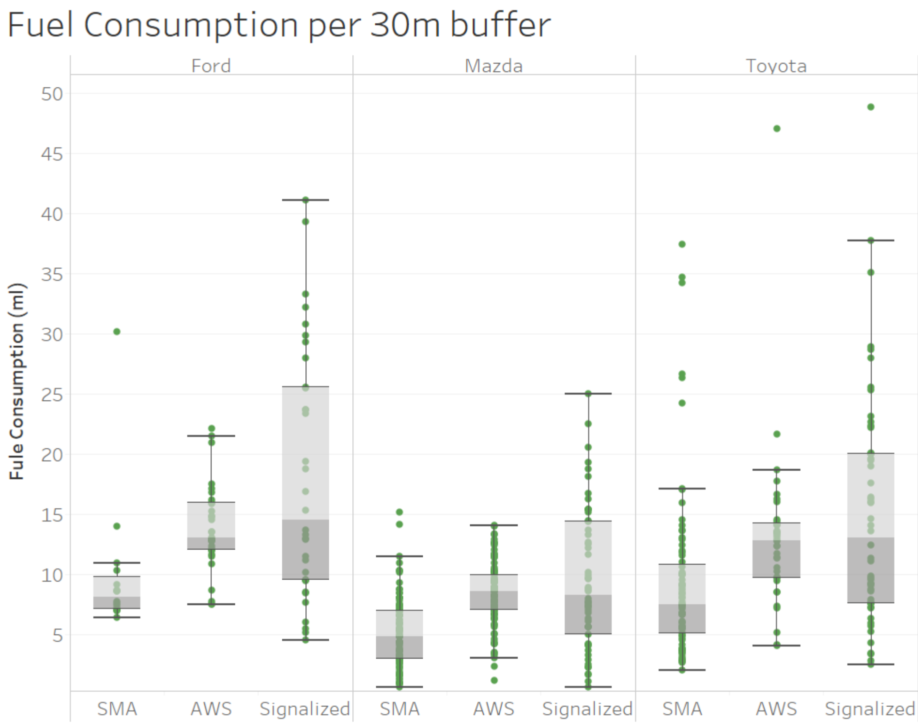

Figure 15: Fuel consumption calculated per buffer area

Next, we control the results for time by dividing the sum of emissions found in each buffer area by the number of seconds spent within that buffer. The results of the time-controlled mass rate of emissions can be seen in *Figures 16-19*. These figures no longer display the growth trend that was clear in *Figures 12-15*. The difference between these sets of figures suggests that time is a controlling factor in the amount of emissions generated within each intersection buffer for all the emissions. There is very little variation between the emissions generated by each test vehicle.

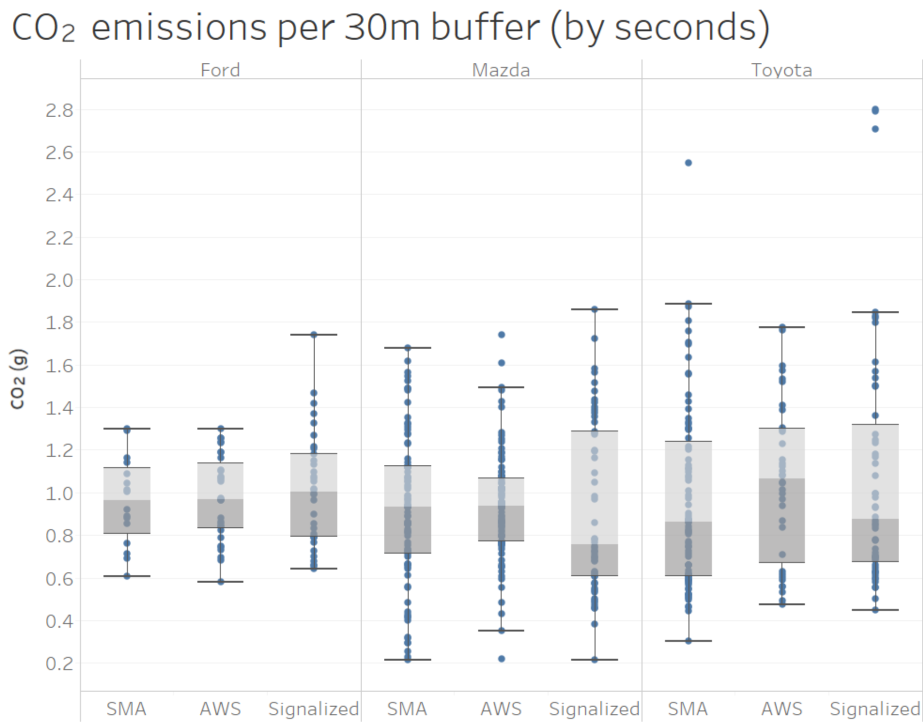

Figure 16: Mass rate of CO_2 emissions per buffer area controlled for the time spent within each buffer

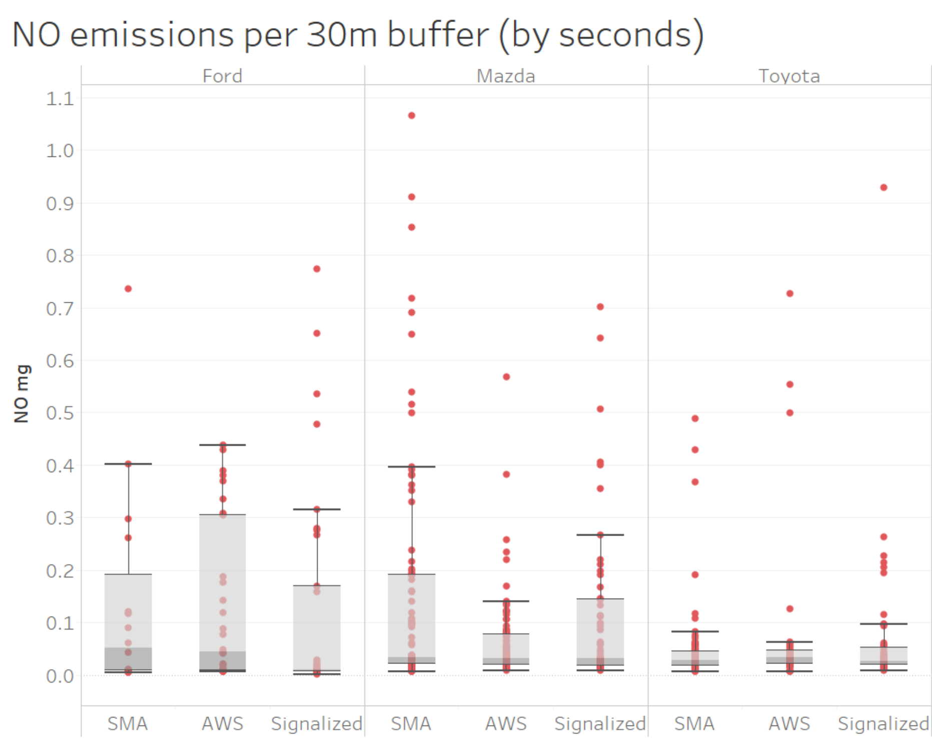

Figure 17: Mass rate of NO emissions per buffer area controlled for the time spent within each buffer

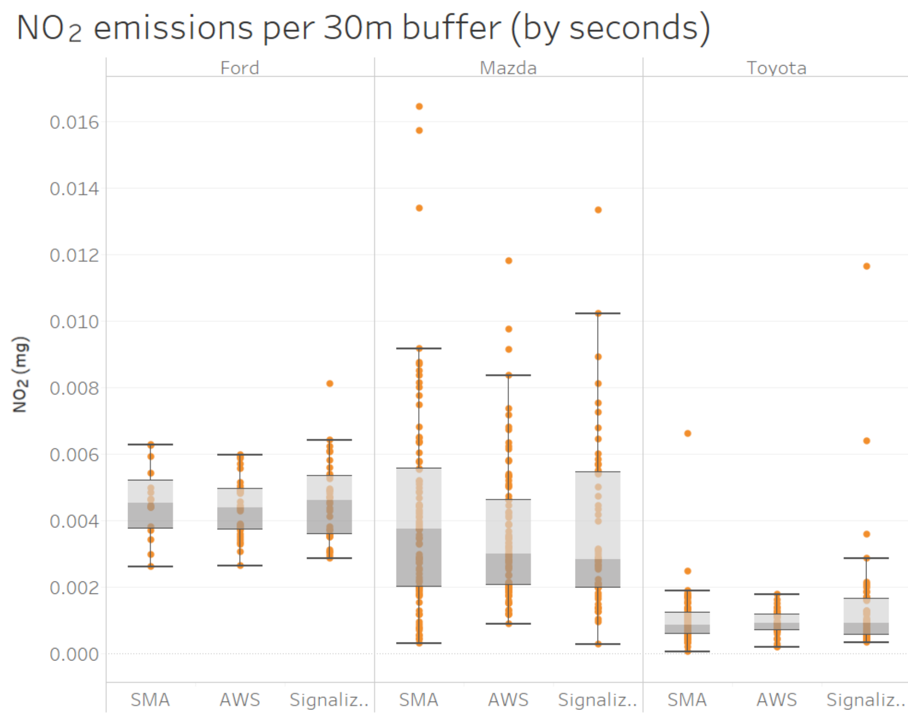

Figure 18: Mass rate of NO_2 emissions per buffer area controlled for the time spent within each buffer

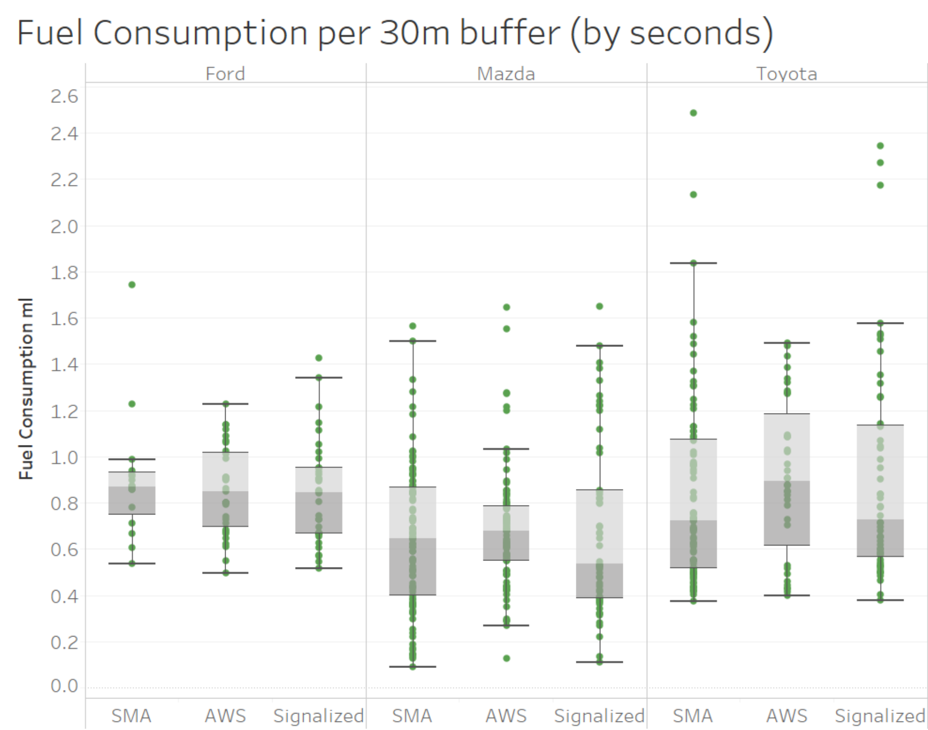

Figure 19: Mass rate of fuel consumption per buffer area controlled for the time spent within each buffer

4.3.2. Linear Model

Stata was used to build a linear regression model of the factors contributing to the emissions of CO_2, NO, NO_2, and fuel consumption. A model was built for each pollutant, beginning with the following factors: average RPM, average vehicle speed, number of seconds spent in the buffer zone (discreet), and type of car, type of intersection, start hour (categorical). However, average vehicle speed, start hour, and number of seconds spent in the buffer zone were removed from the model for being highly correlated to other values. *Table 6* shows the output of the model and *Table 7* shows the statistics of the categorical variables included in the model.

Table 6: Regression Data

	CO_2 (g)	**NO (mg)**	**NO_2 (mg)**	**Fuel Consumption (ml)**
Avg. RPM	-0.014	-0.000	-0.000	-0.010
	(0.000)	(0.467)	(0.000)	(0.000)
Toyota	-	-	-	-
Ford	0.352	1.936	0.057	0.823
	(0.723)	(0.000)	(0.000)	(0.318)
Mazda	-4.215	0.165	0.028	-0.498
	(0.000)	(0.597)	(0.000)	(0.000)
AW	-	-	-	-
SMA	-2.997	-0.122	-0.003	-2.445
	(0.000)	(0.720)	(0.374)	(0.000)
Signalized	3.274	0.024	0.014	2.362
	(0.000)	(0.947)	(0.000)	(0.001)
Constant	31.343	1.480	0.055	24.697
	(0.000)	(0.093)	(0.000)	(0.000)

Table 7: Model input statistics

	Frequency	Percent
Toyota	168	34.71
Ford	81	16.74
Mazda	235	48.55
AWS	158	32.64
SMA	186	38.43
Signalized	140	28.93

The general findings were in line with expected behavior. Increased RPM led to a decrease of emissions, which is probably due to smoother driving cycles achieved at higher RPMs. As for types of vehicles, the Ford increased emissions from the base case (Toyota) and the Mazda decreased CO_2 production and fuel consumption but increased NO and NO_x. Since the Ford was significantly older than the other two vehicles, it was expected to produce higher emissions while the Mazda and Toyota were both model year 2016 so their emissions should be similar. Finally, the all-way stop intersection was considered as the base scenario, with stop in the minor approach intersections decreasing all emissions and signalized intersections increasing all emissions.

4.3.3. PEMS/PAMS vs. MOVES Comparison

We compare the emissions captured by the PEMS/PAMS combination to MOVES estimates in order to determine MOVES' accuracy at modeling the emissions on a microscopic scale. The graphs in *Figures 20-23* plot the emissions compared by event. Points falling above the bisector line represent MOVES under-estimation and those falling below the bisector represent MOVES over-estimation. The correlation coefficient is included in on each graph. For all three vehicles, ground-truth emissions of CO_2 were greater than the MOVES estimate with the Ford having the lowest accuracy. For all three vehicles, MOVES over estimated the NO_x emissions, although NO predictions generally have a higher accuracy. This could be due to the larger scale at which NO is emitted by gasoline-engine vehicles, making prediction easier. NO_2 is the dominant NO_x emission in diesel-engine vehicles and we observe a limited amount of it in our measurements. The NO_x predictions for the Ford are more accurate than the other vehicles which may be due to the age of the vehicle. Its outdated engine technology generates higher emissions, causing the ground-truth to be closer to the model prediction. The Mazda has a slightly more accurate prediction of NO and NO_2 than the Toyota. This is also expected since *Figures 10-13* revealed that the Mazda had a higher emission generation than the Toyota. Fuel consumption was predicted by MOVES with the greatest accuracy, although for both the Ford and the Toyota, ground-truth emissions were higher than the model predictions. It is likely that the vehicles we tested are not well represented by the average fleet that is used in MOVES calculations, causing the disparity between its ability to predict fuel consumption and emissions. MOVES' inaccuracies in modeling the emissions do not come as a surprise. MOVES was created for use in the US and although it has been modified for our scenario, this run is outside of the model's intended use. Furthermore, MOVES is intended primarily for use in State Implementation Plan (SIP) conformity analysis and using it as the microscopic level also likely decreases its accuracy.

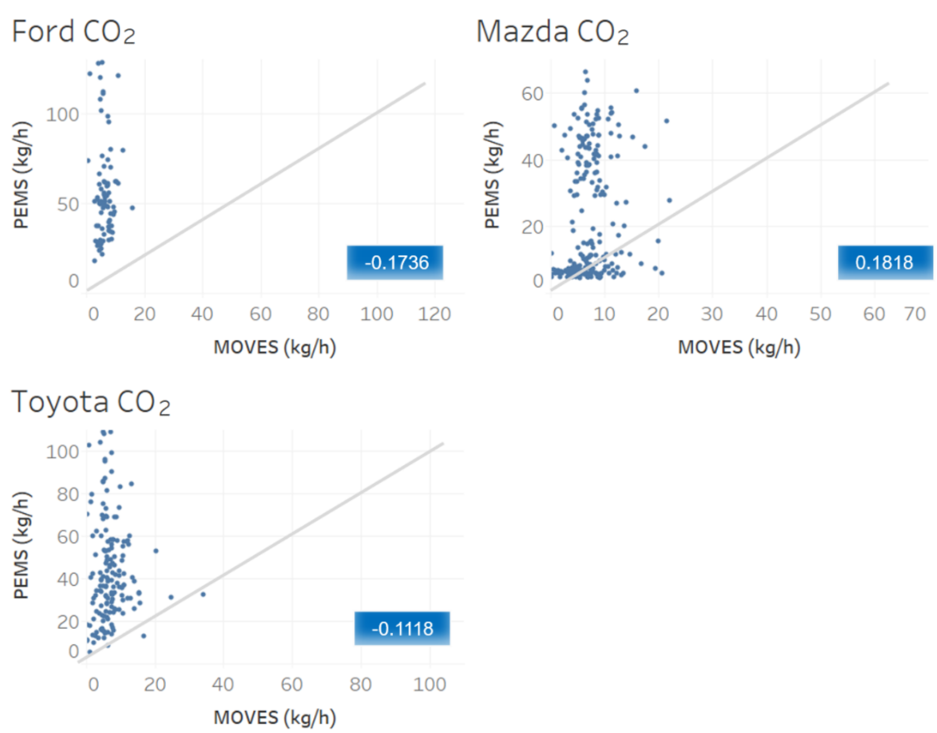

Figure 20: Comparing CO_2 emissions estimated by MOVES to ground-truth PEMS/PAMS data

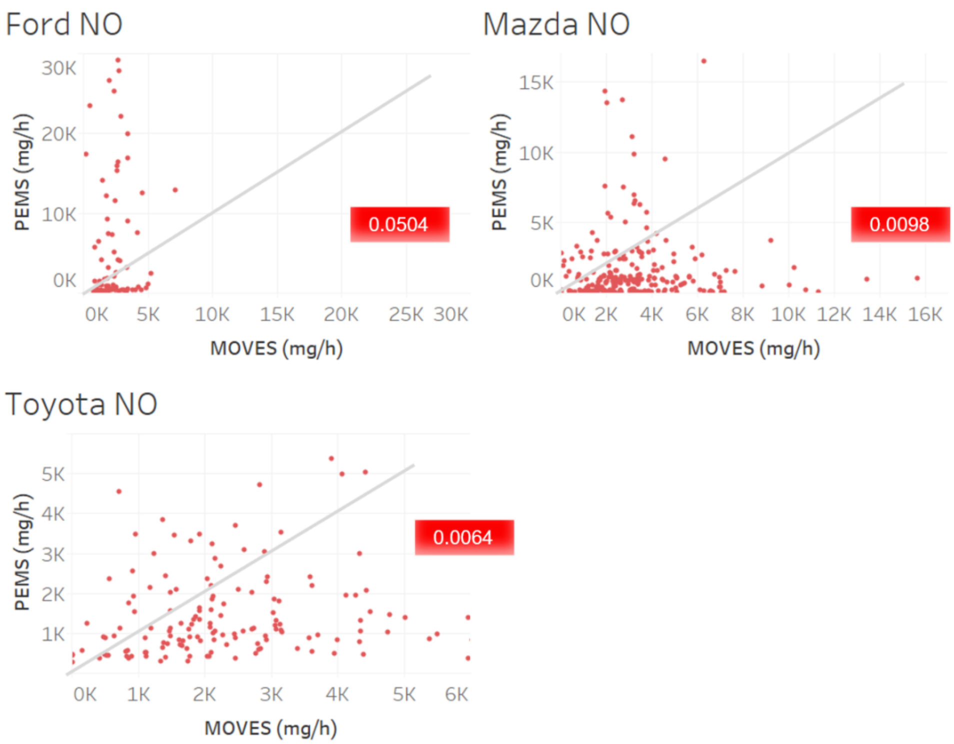

Figure 21: Comparing NO emissions estimated by MOVES to ground-truth PEMS/PAMS data

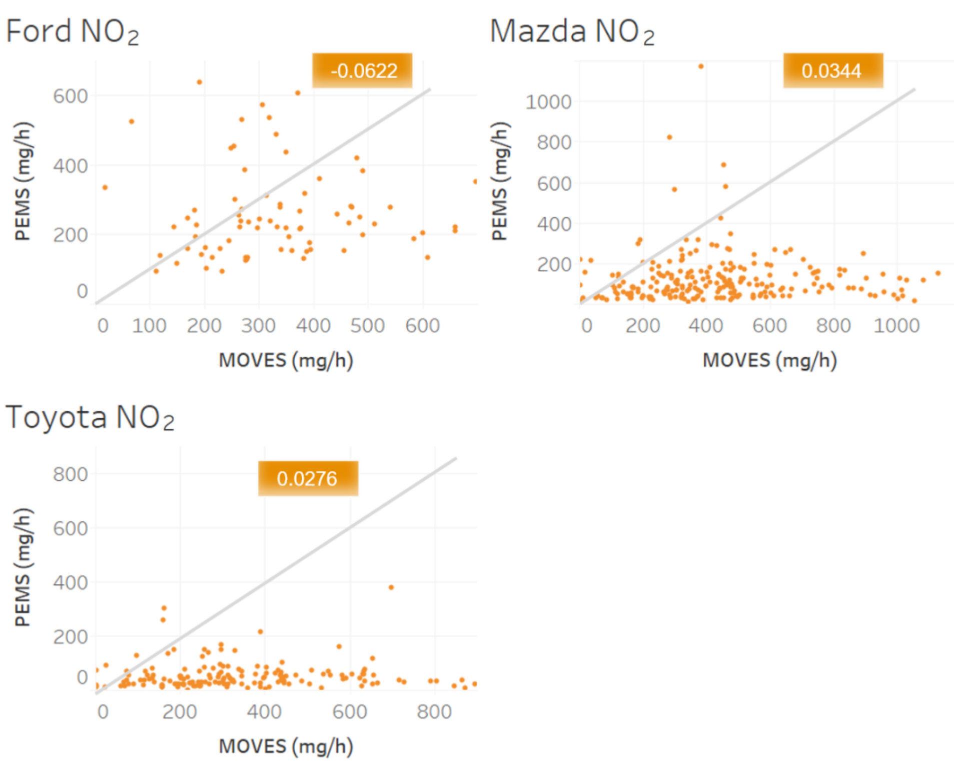

Figure 22: Comparing NO_2 emissions estimated by MOVES to ground-truth PEMS/PAMS data

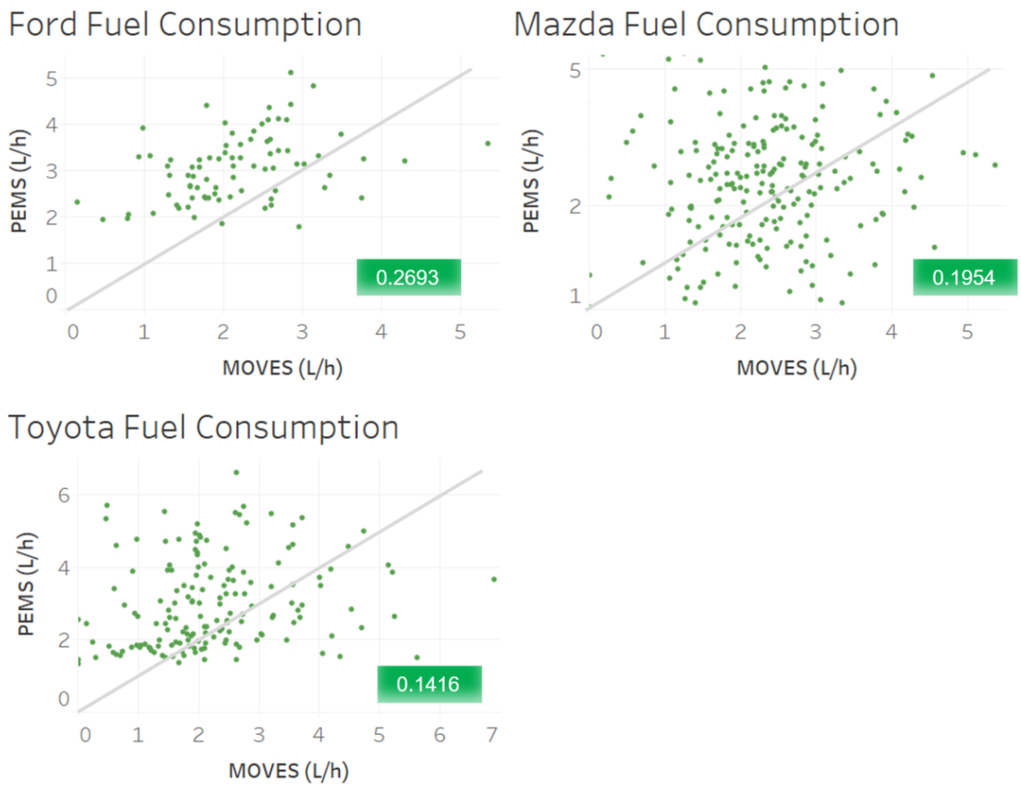

Figure 23: Comparing fuel consumption estimated by MOVES to ground-truth PEMS/PAMS data

4.4. Conclusion

This work investigates the impact of the three main categories of traffic controls in the city of Montreal. From the three categories, it is not surprising that SMA intersections produced the least emissions, followed by AWS intersections, and finally signalized intersections. We can use this as an argument that converting SMA intersections to either AWS or signalized intersections is detrimental to the environment and the people living in the area. However, when controlled for the time spent within each intersection, this pattern disappears, leaving essentially no variation for CO_2 and fuel consumption, while NO_2 and NO show that SMA intersections generate the most pollution followed by, signalized and then AWS.

A regression model was built for CO_2, NO, NO_2, and fuel consumption, to attempt to explain the factors contributing to the rates of emission generation. Factors included in the models were average RPM, and type of car, and type of intersection. Increased RPM led to a decrease of emissions, which is probably due to smoother driving cycles achieved at higher RPMs. As for types of vehicles, the Ford increased emissions from the base case (Toyota) and the Mazda decreased CO_2 production and fuel consumption but increased NO and NO_x. Finally, the all-way stop intersection was considered as the base scenario, with stop in the minor approach intersections decreasing all emissions and signalized intersections increasing all emissions.

A comparative analysis between real-world data and MOVES emission estimates was carried out. Using MOVES to model emissions at the microscopic level for intersection analysis has also shown to be very different to those obtained from PEMS results. When the ground-truth data collected from the PEMS was compared to the MOVES outputs, the results were inconsistent. MOVES overestimated NO_2 and NO emissions while underestimating CO_2 emissions. Although the pattern between vehicles remained the same, the model's accuracy did not. Furthermore, MOVES was able to predict fuel consumption with greater accuracy than any emissions. These discrepancies are most likely a result of the average vehicle fleet that MOVES uses to generate its emissions and how closely each of our test vehicles is represented by this average fleet.

There are several limitations in this study. The dataset used for our calculations was small and only considered a sample of three test vehicles. Accuracy of results could be improved by collecting from additional vehicles for longer periods of time. MOVES is another limiting factor of this research. The model was developed for use in the US and although inputs were modified to reflect the local conditions in Montreal, it functions with reduced accuracy.

An additional limitation encountered in this study involved the collection of PM data. The PEMS used for this research is capable of collecting data on PM emissions, but the results from the field tests showed data with an upward drift which made the data unusable. A future project could be undertaken to correct this data and include it within the analysis.

There is a wide range of future studies that could be conducted using this methodology. Firstly, a larger data set could be collected using a wider range of vehicles on similar test networks. Additionally, more variables such as vehicle types, weather, drivers (with different driving habits), and time of day and road condition could be evaluated. This expanded data set could be used to determine the influence of these additional factors on the generation of emissions. MOVES is just one of many emissions models currently being used. Data collected from PEMS could then be compared to various emissions models in order to determine their accuracy.

5. Concluding Remarks

The objective of this research is to determine the impact of stop signs, in comparison to other intersection controls, on vehicular emissions. Two methodologies were explored, the first using a microsimulation and modeling approach to evaluate before and after data, and the second using a PEMS device to capture real-life data in order to analyze and compare the emissions generated at varying types of intersection controls.

The findings of this research support the claim that the addition of stop signs significantly increases vehicular emissions. This was confirmed through two separate Montreal case studies using different methodologies. When comparing modeled emissions with field measures of emissions, this research also revealed a large gap between the two approaches, raising concerns over the use of microscopic emissions modeling tools that are calibrated for other conditions.

More specifically, the before and after study using MOVES and VISSIM revealed that emissions increased as much as 31% in the case of $PM_{2.5}$ and PM_{10} from brake-wear with significant increases for the emission rate of atmospheric CO_2 and energy consumption as well. Tire-wear was the only measured factor to decrease during the study.

The real-world study results showed that within a 30m buffer of the intersection, a general pattern exists where intersections with a stop in the minor approach generate the least emissions, followed by all-way stop intersections, then signalized intersections with emissions increases of approximately 50% and 20% between the types respectively. However, this pattern disappears when the data is controlled for the number of seconds a vehicle spends within each type of intersection, with emission rates becoming relatively equal between intersection types. This finding is important because it suggests that intersections should be designed efficiently so that vehicles spend as little time as possible within the intersection. When the performance of vehicle models is compared there is also not a significant difference, particularly when evaluating CO_2 and NO. There is a more apparent pattern in NO_2 emissions, with the Ford generating the most, followed by the Mazda and Toyota respectively. Due to the age of the Ford used in this research, this is expected. Fuel consumption was similar for the Ford and Toyota, but lower for the Mazda, which is likely explained by the fact that the Mazda was physically smaller than the other two vehicles.

Finally, when comparing PEMS data to MOVES, there are significant inconsistencies, with the model over-predicting some emissions while under-predicting others. The data from both sources were matched by intersection. Overall, weak correlation was observed for all comparisons, with absolute values ranging between 0.006 and 0.269. MOVES under-predicted emission rates of CO_2 for all vehicles, although more severely for the Toyota and Ford. When comparing emissions of NO, a clear pattern does not exist. The Ford and Mazda both experience a heavy portion of their data over-predicted by MOVES, with some intersections severely under-predicted. The Toyota experienced a more even distribution of over and under-prediction. Emissions of NO_2 were over-predicted by MOVES for both the Mazda and Toyota, with a fairly even distribution for the Ford. MOVES predictions were most accurate for fuel consumption.

This study highlights the need for public education regarding the emission hazards that can be generated by intersection redesign. Casualties of air pollution don't receive nearly as much attention as those caused by traditional traffic safety failures, allowing the former to go unnoticed. Education and awareness of this problem can help guide future research, and eventually policies, to be created with long-term health and safety benefits in mind. Additionally, this study raises questions of how to evaluate policies. Environmental implications should be taken into account when adding stop signs on a large scale in urban areas. It is recommended that environmental and human health impacts due to emissions be considered, in addition to traditional safety metrics, when design guidelines are created. Furthermore, our research findings highlight concerns over the use of a microsimulation modeling approach. We recommend further model validation and calibration when using MOVES or alternatively the development of impact analysis approaches based on field measurements.

Models are an extremely useful tool to analyze large amounts of data that represent an area or time span that is too large to easily measure. However, what is gained in speed is lost in accuracy as models are only as valuable as the data that was used to build them, in addition to their calibration. Emissions models are often built for a specific location, making their use outside of that region less desirable. This was the case with our research. We encountered considerable difficulty in calibrating the microscopic transportation model. The results from this model, which were taken with a low confidence level, were entered into another model, this time for emissions. However, adjustments had to be made to the model's default to account for the fact that this analysis took place in Canada, while the model was built for the United States. The combination of these issues decreases the researchers' confidence in the results from the modeled portions of the study. Furthermore, performing MOVES runs were time consuming.

Each run took approximately 15 minutes, with additional time to set up the files. Future researchers interested in using this tool for their analyses should build a program to automatically initiate runs, allowing for more efficient use of time.

There are many limitations to this research which can be addressed as part of future research. First, this study is limited to a relatively small urban area within the city of Montreal. This study should be replicated using other cities and more data. For example, more traffic data and a larger vehicle fleet could be used to improve the analysis.

Time and funding restricted the amount of video data that could be processed and used for the before and after experiment. Additional footage would improve the quality of results. Similarly, the collection of PEMS data from a wider range of vehicle models could be used to improve the results of this study. PM data could be included in the PEMS analysis if action was taken to correct the upward drift found in the data that rendered it unusable for this project. Future research could also look into the seasonal variation of emissions.

Second, the field measurements from which we drew our conclusions are limited. Therefore, more comparative analysis between field and estimated measurements using additional vehicle models and networks should be implemented to confirm the gaps found in this research. Ways to calibrate emissions estimation models such as MOVES to the Canadian urban environments should be further explored.

Third, the statistical analysis done in this work is exploratory. Alternative statistical modeling to investigate the impact of traffic controls should be investigated in order to take into account spatial and temporal dependencies. The controls of geometric factors and traffic conditions should be integrated into the analysis to better estimate the impact of traffic controls. Before and after studies using field measures should also be implemented.

Appendix

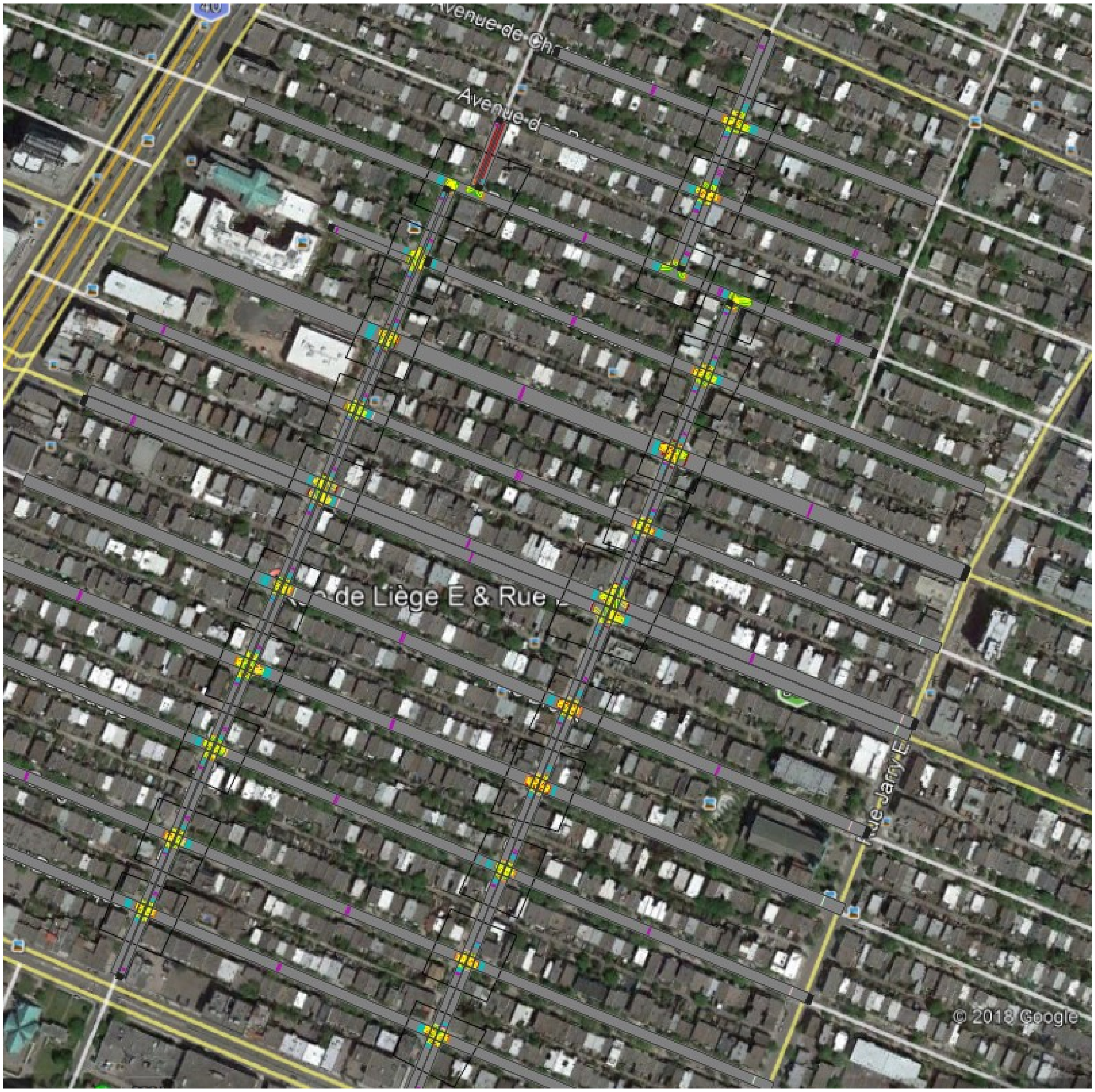

Figure 24: Image of the VISSIM network

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA
1	# FuelCalculationMethod = MassAirFlow																										
2	Time	Latitude (	Longitude	Vehicle s	Total fuel	Fuel rate	Engine RF	Intake air	Mass air f	Commanc	Fuel leve	Barometr	Catalyst t	Catalyst t	Fuel/Air c	Relative t	Ambient	Intake ma	Mass air f	Accelerat	Trip Dista	Trip Fuel	Trip Fuel	Trip Durat	Altitude (	GPS Speed (km/h)	
3	07-08-201	45.53997	-73.6272	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	52.00277	2.844	
4	07-08-201	45.53999	-73.6272	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	52.30569	2.916	
5	07-08-201	45.54	-73.6272	0	10.66821	0	752.75	58	2.86	0	71.37255	101	306.3	0	1.006104	0.392157	38	0	2.660041	-4.16E-15	0	0	0	0	52.53408	0.864	
6	07-08-201	45.54	-73.6272	0	10.66903	0.472734	683	58	1.43	0	71.37255	101	305.8	0	1.006104	2.352941	38	16.66516	2.413561	-4.16E-15	0	0.000371	0	0.066679	52.53408	0.864	
7	07-08-201	45.54	-73.6272	0	10.66944	0.528933	694.75	58	1.6	0	71.37255	101	305.4	0	1.006104	2.745098	38	20.55055	2.534279	-4.16E-15	0	0.000552	0	0.081796	52.53408	0.864	
8	07-08-201	45.54	-73.6272	0	10.66973	0.561992	698	58	1.7	0	71.37255	101	305	0	1.006104	2.352941	38	21.46568	2.466567	-4.16E-15	0	0.000684	0	0.095965	52.53408	0.864	
9	07-08-201	45.54	-73.6272	0	10.66973	0.561992	698	58	1.7	0	71.37255	101	305	0	1.006104	2.352941	38	21.46568	2.466567	-4.16E-15	0	0.000684	0	0.095965	52.53408	0.864	
10	07-08-201	45.54	-73.6272	0	10.66973	0.561992	698	58	1.7	0	71.37255	101	305	0	1.006104	2.352941	38	21.46568	2.466567	-4.16E-15	0	0.000684	0	0.095965	52.53408	0.864	
11	07-08-201	45.54	-73.6272	0	10.66973	0.561992	698	58	1.7	0	71.37255	101	305	0	1.006104	2.352941	38	21.46568	2.466567	-4.16E-15	0	0.000684	0	0.095965	52.53408	0.864	
12	07-08-201	45.54	-73.6272	0	10.66973	0.561992	698	58	1.7	0	71.37255	101	305	0	1.006104	2.352941	38	21.46568	2.466567	-4.16E-15	0	0.000684	0	0.095965	52.53408	0.864	
13	07-08-201	45.54	-73.6272	0	10.67223	0.938857	773	58	2.84	0	71.37255	101	303.2	0	1.006104	3.921569	38	35.69333	3.877109	-4.16E-15	0	0.001814	0	0.168242	52.53408	0.864	
14	07-08-201	45.54	-73.6272	0	10.67275	0.889269	765.75	59	2.69	0	71.37255	101	302.8	0	1.006104	3.921569	38	30.5279	3.655128	-4.16E-15	0	0.002046	0	0.187438	52.53408	0.864	
15	07-08-201	45.54	-73.6272	0	10.67275	0.889269	765.75	59	2.69	0	71.37255	101	302.8	0	1.006104	3.921569	38	30.5279	3.655128	-4.16E-15	0	0.002046	0	0.187438	52.53408	0.864	
16	07-08-201	45.54	-73.6272	0	10.67332	0.892575	766	59	2.7	0	71.37255	101	302.4	0	1.006104	4.313725	38	31.0249	3.917487	-4.16E-15	0	0.002304	0	0.227164	52.53408	0.864	
17	07-08-201	45.54	-73.6272	0	10.67468	0.935551	749	59	2.83	0	71.37255	101	301.5	0	1.006104	3.921569	38	32.50808	3.830546	-4.16E-15	0	0.002919	0	0.240359	52.53408	0.864	
18	07-08-201	45.54	-73.6272	0	10.67513	0.899187	753	59	2.72	0	71.37255	101	301	0	1.006104	3.921569	38	31.95367	3.851003	-4.16E-15	0	0.00312	0	0.262499	52.53408	0.864	
19	07-08-201	45.54	-73.6272	0	10.67595	0.922328	756.25	59	2.79	0	71.37255	101	300.6	0	1.006104	3.921569	38	32.6019	3.867624	-4.16E-15	0	0.003488	0	0.277852	52.53408	0.864	
20	07-08-201	45.54	-73.6272	0	10.67641	0.938857	754	59	2.84	0	71.37255	101	300.2	0	1.006104	3.921569	38	33.04354	3.770425	-4.16E-15	0	0.0037	0	0.292605	52.53408	0.864	
21	07-08-201	45.54	-73.6272	0	10.67641	0.938857	754	59	2.84	0	71.37255	101	300.2	0	1.006104	3.921569	38	33.04354	3.770425	-4.16E-15	0	0.0037	0	0.292605	52.53408	0.864	
22	07-08-201	45.54	-73.6272	0	10.67688	0.846293	750	59	2.56	0	71.37255	101	299.3	0	1.006104	3.921569	38	29.87461	4.006134	-4.16E-15	0	0.003912	0	0.333502	52.53408	0.864	
23	07-08-201	45.54	-73.6272	0	10.67688	0.846293	750	59	2.56	0	71.37255	101	299.3	0	1.006104	3.921569	38	29.87461	4.006134	-4.16E-15	0	0.003912	0	0.333502	52.53408	0.864	
24	07-08-201	45.54	-73.6272	0	10.67882	1.279358	747.5	59	3.87	0	71.37255	101	298.9	0	1.006104	0.392157	38	45.40288	3.228205	-4.16E-15	0	0.004786	0	0.352061	52.53408	0.864	
25	07-08-201	45.54	-73.6272	0	10.68007	0.985139	760.5	59	2.98	0	71.37255	101	298.2	0	1.006104	4.313725	38	35.78443	4.14865	-4.16E-15	0	0.005351	0	0.382192	52.53408	0.864	
26	07-08-201	45.53999	-73.6272	0	10.68062	0.975221	759.5	59	2.95	0	71.37255	101	297.9	0	1.006104	3.921569	38	34.13159	4.056878	-4.16E-15	0	0.005596	0	0.395851	55.86551	0.972	
27	07-08-201	45.53999	-73.6272	0	10.68062	0.975221	759.5	59	2.95	0	71.37255	101	297.9	0	1.006104	3.921569	38	34.13159	4.056878	-4.16E-15	0	0.005596	0	0.395851	56.52847	0.936	
28	07-08-201	45.53998	-73.6272	0	10.68062	0.975221	759.5	59	2.95	0	71.37255	101	297.9	0	1.006104	3.921569	38	34.13159	4.056878	-4.16E-15	0	0.005596	0	0.395851	57.11081	2.448	
29	07-08-201	45.53997	-73.6272	2	10.68283	1.30911	767.75	59	3.96	0	71.37255	101	296.8	0	1.006104	5.098039	38	45.87764	5.147995	0.343864	0.000449	0.006641	1479.703	0.448462	56.97433	1.584	
30	07-08-201	45.53997	-73.6272	0	10.68376	1.295887	765	59	3.92	0	71.37255	101	296.5	0	1.006104	5.098039	38	44.92622	5.129556	0.258338	0.000449	0.007063	1573.855	0.463502	56.97433	1.584	
31	07-08-201	45.53997	-73.6272	0	10.68442	1.295887	769.25	59	3.92	0	74.5098	101	296.1	0	1.006104	5.098039	38	45.08772	5.070629	-0.08553	0.000449	0.007358	1639.541	0.48036	56.97433	1.584	
32	07-08-201	45.53997	-73.6272	0	10.68521	1.276052	762.75	59	3.86	0	74.5098	101	295.8	0	1.006104	5.098039	38	44.15231	5.027783	-4.15E-15	0.000449	0.007718	1719.819	0.493998	56.97433	1.584	
33	07-08-201	45.53997	-73.6272	0	10.68521	1.276052	762.75	59	3.86	0	74.5098	101	295.8	0	1.006104	5.098039	38	44.15231	5.027783	-4.15E-15	0.000449	0.007718	1719.819	0.493998	56.97433	1.584	
34	07-08-201	45.53997	-73.6272	0	10.68521	1.276052	762.75	59	3.86	0	74.5098	101	295.8	0	1.006104	5.098039	38	44.15231	5.027783	-4.15E-15	0.000449	0.007718	1719.819	0.493998	56.97433	1.584	
35	07-08-201	45.53999	-73.6272	0	10.68721	1.276052	745	59	3.86	0	74.5098	101	295	0	1.006104	5.490196	38	44.52857	5.334125	-4.15E-15	0.000449	0.008619	1920.486	0.541155	56.54306	1.98	
36	07-08-201	45.53999	-73.6272	1	10.68808	1.421509	743.25	59	4.3	0	74.5098	101	294.6	0	1.006104	5.098039	38	50.78622	5.152655	0.04762	0.001259	0.009096	722.532	0.55691	56.54306	1.98	
37	07-08-201	45.53999	-73.6272	3	10.6886	1.30911	750.25	59	3.96	0	74.5098	101	294.4	0	0.991372	5.098039	38	46.88068	5.030653	0.370536	0.001976	0.009408	476.1416	0.571396	56.54306	1.98	
38	07-08-201	45.53998	-73.6272	4	10.68907	1.311788	771.25	59	3.91	0	74.5098	101	294.2	0	0.991464	5.490196	38	45.85687	5.259116	0.482763	0.002941	0.009722	330.5565	0.584947	54.87771	4.356	
39	07-08-201	45.53998	-73.6272	4	10.68907	1.311788	771.25	59	3.91	0	74.5098	101	294.2	0	0.991464	5.490196	38	45.85687	5.259116	0.482763	0.002941	0.009722	330.5565	0.584947	54.87771	4.356	
40	07-08-201	45.53996	-73.6272	6	10.68952	1.549847	911.75	59	4.62	0	74.5098	101	293.8	0	0.987133	5.882353	38	52.70848	5.8027	0.509421	0.004266	0.010066	235.9879	0.632005	54.9349	9.252	
41	07-08-201	45.53992	-73.6273	9	10.69092	1.735224	994.75	59	5.15	0	74.5098	101	293	0	0.988719	5.882353	38	49.701	6.330942	0.491186	0.011621	0.011484	98.82214	0.647528	54.66897	11.844	

Figure 25: Sample raw data from PEMS

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC
1	Timestam	Date	Time	Bag#	Scattering	Ionization	Opacity (\	PM (æg/r	PN (#/cm	Cb	Cs	Ci	Co	PSN	PSN_limit	Pass/Fail	NO2 (V)	NO2 (ppm	NO (V)	NO (ppm)	CO2 (V)	CO2 (%)	CO (V)	CO (%)	Temperat	ErrorCode	Scattering	Ionization	Opacity (\
146																													
147	35913	########	########	0	-0.00073	0.080914	0.012741	212.8	507269.6	0	20	1	20	0.321141	0.5	Pass	0.008374	0.89	0.004086	10.79	3.086056	16.74	N/A	N/A	35.3	0	0.117607	5.654799	7.226863
148																													
149	35914	########	########	0	0.000052	0.058056	0.013034	265.8	638403	0	20	1	20	0.319774	0.5	Pass	0.007398	0.79	0.004965	13.11	3.086154	16.74	N/A	N/A	35.3	0	0.118389	5.677656	7.22657
150																													
151	35915	########	########	0	0.000247	0.055907	0.012643	281.3	674828.6	0	20	1	20	0.313718	0.5	Pass	0.007691	0.82	0.006333	16.73	3.085959	16.74	N/A	N/A	35.3	0	0.118584	5.679805	7.22696
152																													
153	35916	########	########	0	-0.00044	0.075639	0.013327	244.8	585014.5	0	20	1	20	0.333449	0.5	Pass	0.007886	0.84	0.007017	18.53	3.086154	16.74	N/A	N/A	35.3	0	0.1179	5.660074	7.226277
154																													
155	35917	########	########	0	0.00015	0.087556	0.013131	340	806158.9	0	20	1	20	0.353181	0.5	Pass	0.006909	0.74	0.009068	23.95	3.085959	16.74	N/A	N/A	35.3	0	0.118486	5.648157	7.226472
156																													
157	35918	########	########	0	-0.00024	0.090877	0.013229	299.1	709540.2	0	20	1	20	0.350641	0.5	Pass	0.006909	0.74	0.010045	26.53	3.086349	16.74	N/A	N/A	35.3	0	0.118096	5.644836	7.226374
158																													
159	35919	########	########	0	-0.00063	0.087653	0.013522	247.8	588794.2	0	20	1	20	0.345464	0.5	Pass	0.0073	0.78	0.010045	26.53	3.086056	16.74	N/A	N/A	35.3	0	0.117705	5.648059	7.226081
160																													
161	35920	########	########	0	-0.00063	0.086286	0.013034	239.2	568728.6	0	20	1	20	0.334328	0.5	Pass	0.007007	0.75	0.010631	28.08	3.086447	16.74	N/A	N/A	35.3	0	0.117705	5.649427	7.22657
162																													
163	35921	########	########	0	-0.00024	0.08189	0.013522	284.1	676513.1	0	20	1	20	0.347515	0.5	Pass	0.006519	0.7	0.010631	28.08	3.085861	16.74	N/A	N/A	35.4	0	0.118096	5.653822	7.226081
164																													
165	35922	########	########	0	-0.00053	0.08736	0.013327	256.8	610448.1	0	20	1	20	0.343217	0.5	Pass	0.006421	0.69	0.010729	28.34	3.086154	16.74	N/A	N/A	35.4	0	0.117803	5.648352	7.226277
166																													
167	35923	########	########	0	-4.6E-05	0.080718	0.013131	301.4	717345.9	0	20	1	20	0.342436	0.5	Pass	0.006812	0.73	0.011412	30.14	3.086642	16.74	N/A	N/A	35.4	0	0.118291	5.654994	7.226472
168																													
169	35924	########	########	0	-0.00073	0.079839	0.013425	218.6	521587.7	0	20	1	20	0.333742	0.5	Pass	0.006812	0.73	0.012194	32.21	3.086056	16.74	N/A	N/A	35.4	0	0.117607	5.655874	7.226179
170																													
171	35925	########	########	0	-4.6E-05	0.069973	0.013425	282.8	676015.2	0	20	1	20	0.337552	0.5	Pass	0.007007	0.75	0.01151	30.4	3.086838	16.74	N/A	N/A	35.3	0	0.118291	5.665739	7.226179
172																													
173	35926	########	########	0	-0.00053	0.075346	0.013425	233.3	557876.8	0	20	1	20	0.333156	0.5	Pass	0.007007	0.75	0.011315	29.88	3.086252	16.74	N/A	N/A	35.3	0	0.117803	5.660367	7.226179
174																													
175	35927	########	########	0	-0.00112	0.074564	0.01362	162.7	389051.8	0	20	1	20	0.32456	0.5	Pass	0.007398	0.79	0.010924	28.85	3.086349	16.74	N/A	N/A	35.4	0	0.117216	5.661148	7.225984
176																													
177	35928	########	########	0	0.000052	0.073001	0.013718	304.7	726968.5	0	20	1	20	0.348394	0.5	Pass	0.006519	0.7	0.010729	28.34	3.086545	16.74	N/A	N/A	35.4	0	0.118389	5.662711	7.225886
178																													
179	35929	########	########	0	0.000247	0.070364	0.013522	321.6	766659.2	0	20	1	20	0.345757	0.5	Pass	0.006616	0.71	0.010338	27.3	3.086447	16.74	N/A	N/A	35.3	0	0.118584	5.665348	7.226081
180																													
181	35930	########	########	0	-0.00063	0.077592	0.01362	228.3	545246.8	0	20	1	20	0.337356	0.5	Pass	0.006616	0.71	0.010142	26.79	3.087228	16.75	N/A	N/A	35.4	0	0.117705	5.65812	7.225984
182																													
183	35931	########	########	0	-0.00044	0.083649	0.013425	262.4	624684.2	0	20	1	20	0.343412	0.5	Pass	0.005737	0.61	0.008384	22.14	3.086838	16.74	N/A	N/A	35.4	0	0.1179	5.652064	7.226179
184																													
185	35932	########	########	0	-0.00122	0.089119	0.013718	182.1	430458.4	0	20	1	20	0.339115	0.5	Pass	0.005639	0.6	0.009068	23.95	3.08674	16.74	N/A	N/A	35.4	0	0.117119	5.646594	7.225886

Figure 26: Sample raw data from OBD-II logger

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1	Site ID	Site Name	Period	Date	Approa	Directi	UserNu	Date	Time	ID	EpochT	EpochT	mean	avg	15th	85th	User Ty
1062	13979	Guizot-Casgrain	after	20171023	East	N/A	1	20171023	91000	10878	1.51E+09	1.51E+09	11.1	11.14	4.61	18.87	car
1063	13979	Guizot-Casgrain	after	20171023	East	N/A	1	20171023	91000	28436	1.51E+09	1.51E+09	7.93	4.73	0.42	20.71	car
1064	13979	Guizot-Casgrain	after	20171023	East	N/A	1	20171023	91000	31467	1.51E+09	1.51E+09	14.97	10.91	6.78	22.49	car
1065	13979	Guizot-Casgrain	after	20171023	East	N/A	1	20171023	91000	52832	1.51E+09	1.51E+09	19.53	23.75	10.11	27.74	car
1066	13979	Guizot-Casgrain	after	20171023	East	N/A	1	20171023	91000	79518	1.51E+09	1.51E+09	19.48	20.31	9.14	31.76	car
1067	13979	Guizot-Casgrain	after	20171023	East	N/A	1	20171023	91000	92418	1.51E+09	1.51E+09	20.22	17.01	3.87	34.49	bus
1068	13979	Guizot-Casgrain	after	20171023	East	N/A	1	20171023	91000	105020	1.51E+09	1.51E+09	15.95	15.41	5.3	25.06	truck
1069	13979	Guizot-Casgrain	after	20171023	East	N/A	1	20171023	91000	114575	1.51E+09	1.51E+09	7.95	6.37	3.66	13.31	car
1070	13979	Guizot-Casgrain	after	20171023	East	N/A	1	20171023	91000	132769	1.51E+09	1.51E+09	13.05	12.54	6.69	19.8	car
1071	13979	Guizot-Casgrain	after	20171023	East	N/A	1	20171023	91000	144328	1.51E+09	1.51E+09	10.87	7.22	1.93	23.46	car
1072	13979	Guizot-Casgrain	after	20171023	East	N/A	1	20171023	91000	148248	1.51E+09	1.51E+09	19.19	21.97	10.84	26.75	car
1073	13979	Guizot-Casgrain	after	20171023	East	N/A	1	20171023	91000	175998	1.51E+09	1.51E+09	12.47	11.83	6.52	18.09	car
1074	13979	Guizot-Casgrain	after	20171023	East	N/A	1	20171023	91000	181505	1.51E+09	1.51E+09	11.35	13.81	0.78	19.4	car
1075	13979	Guizot-Casgrain	after	20171023	East	N/A	1	20171023	91000	194046	1.51E+09	1.51E+09	17.83	13.95	7.09	29.05	car
1076	13979	Guizot-Casgrain	after	20171023	East	N/A	1	20171023	91000	215289	1.51E+09	1.51E+09	10.01	10.09	5.33	15.56	car
1077	13979	Guizot-Casgrain	after	20171023	East	N/A	1	20171023	91000	255047	1.51E+09	1.51E+09	16.02	12.81	6.26	27.04	car
1078	13979	Guizot-Casgrain	after	20171023	East	N/A	1	20171023	91000	274252	1.51E+09	1.51E+09	11.37	7.13	1.15	27.06	car
1079	13979	Guizot-Casgrain	after	20171023	East	N/A	1	20171023	93604	7892	1.51E+09	1.51E+09	19.62	18.73	7.53	34.86	car
1080	13979	Guizot-Casgrain	after	20171023	East	N/A	1	20171023	93604	29250	1.51E+09	1.51E+09	11.84	9.72	7.44	17.38	car
1081	13979	Guizot-Casgrain	after	20171023	East	N/A	1	20171023	93604	48278	1.51E+09	1.51E+09	15.89	15.39	8.45	22.29	car
1082	13979	Guizot-Casgrain	after	20171023	East	N/A	1	20171023	93604	49103	1.51E+09	1.51E+09	9.7	9.7	9.7	9.7	car
1083	13979	Guizot-Casgrain	after	20171023	East	N/A	1	20171023	93604	55545	1.51E+09	1.51E+09	13.04	12.67	9.15	18.09	car
1084	13979	Guizot-Casgrain	after	20171023	East	N/A	1	20171023	93604	56546	1.51E+09	1.51E+09	3.73	0.74	0.21	7.34	car
1085	13979	Guizot-Casgrain	after	20171023	East	N/A	1	20171023	93604	75576	1.51E+09	1.51E+09	11.76	9.4	5.45	19.53	car
1086	13979	Guizot-Casgrain	after	20171023	East	N/A	1	20171023	93604	86405	1.51E+09	1.51E+09	17.92	14.11	9.73	28.35	car
1087	13979	Guizot-Casgrain	after	20171023	East	N/A	1	20171023	93604	97718	1.51E+09	1.51E+09	15.42	15.9	6.96	25.23	car
1088	13979	Guizot-Casgrain	after	20171023	East	N/A	1	20171023	93604	132957	1.51E+09	1.51E+09	11.06	9.48	6.47	17.31	car
1089	13979	Guizot-Casgrain	after	20171023	East	N/A	1	20171023	93604	150988	1.51E+09	1.51E+09	14.91	11.89	7.28	23.89	car
1090	13979	Guizot-Casgrain	after	20171023	East	N/A	1	20171023	93604	166321	1.51E+09	1.51E+09	13.31	14.23	7.3	17.95	car
1091	13979	Guizot-Casgrain	after	20171023	East	N/A	1	20171023	93604	170346	1.51E+09	1.51E+09	17.53	11.84	4.24	33.77	car
1092	13979	Guizot-Casgrain	after	20171023	East	N/A	1	20171023	93604	185507	1.51E+09	1.51E+09	2.44	0.11	0.06	0.55	car
1093	13979	Guizot-Casgrain	after	20171023	East	N/A	1	20171023	93604	203338	1.51E+09	1.51E+09	22.65	22.6	10.64	35.83	car
1094	13979	Guizot-Casgrain	after	20171023	East	N/A	1	20171023	93604	221329	1.51E+09	1.51E+09	16.25	15.24	7.73	25.79	car
1095	13979	Guizot-Casgrain	after	20171023	East	N/A	1	20171023	93604	246030	1.51E+09	1.51E+09	17.97	11.76	5.64	36.81	car
1096	13979	Guizot-Casgrain	after	20171023	East	N/A	1	20171023	93604	248856	1.51E+09	1.51E+09	14.67	13.28	7.29	23.67	car
1097	13979	Guizot-Casgrain	after	20171023	East	N/A	1	20171023	93604	266022	1.51E+09	1.51E+09	4.05	4.17	1.67	8.04	car
1098	13979	Guizot-Casgrain	after	20171023	East	N/A	1	20171023	100209	10111	1.51E+09	1.51E+09	17.36	13.47	8.15	27.05	car
1099	13979	Guizot-Casgrain	after	20171023	East	N/A	1	20171023	100209	47628	1.51E+09	1.51E+09	12.21	10.91	7.62	17.11	car
1100	13979	Guizot-Casgrain	after	20171023	East	N/A	1	20171023	100209	61829	1.51E+09	1.51E+09	12.19	15.51	2.41	21.09	car

Figure 27: Sample raw data from video analysis

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