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Evaluating the Safety and Emissions Impact of Converting One-Way-Stop Intersections to All-Way-Stop Intersections

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Abstract

Pedestrians and cyclists represent a large portion of sustainable transportation. In order to encourage the usage of these modes, we must ensure users are safe. This research will evaluate the safety and emissions effects on a connected network of the conversion of One-Way-Stop (OWS) intersections to All-Ways-Stop (AWS) intersections with a particular focus on these vulnerable users. For such purpose, a network of 22 intersections in a central borough of Montreal is evaluated through computer microsimulation. Ten of the 22 intersections are part of a before and after study where OWS were replaced with AWS. For the intersections that are part of the before and after study, users' trajectories were obtained from video data collected. From the second by second information of the video trajectories, speed values (mean, median, 15th percentile and 85th percentile), volumes, and turning ratios were obtained. In order to evaluate the effects of these modifications, the information from the video trajectories was used to calibrate two scenarios of a microscopic model in Vissim. One scenario represents the network before modifications were made, and the other represents the network following the implementation of additional stop signs. Manual traffic counts were used to gather data on intersections required for the microsimulation model where stop control treatments were not made. The outputs from these models were used to run analysis of surrogate safety measures between high-risk users and motorized vehicles using the FHA's Surrogate Safety Assessment Model (SSAM). Hazardous interactions between motorized vehicles were found to increase in all scenarios evaluated. Hazardous interactions between motorized vehicles and cyclists were found to decrease in medium and high hazard scenarios. An additional aspect of this research involves using data gathered in Vissim to evaluate the additional stop signs' impact on vehicular emissions. Preliminary results show an increase of all pollutants evaluated due to increased time vehicles spend braking and decelerating. Emissions of Primary Exhaust PM_{10} and $PM_{2.5}$ were found to increase nearly 30%. The EPA's Motor Vehicle Emissions Simulator (MOVES2014b) is being used to complete this portion of the analysis.

Introduction

The World Health Organization's *Global Status Report on Road Safety 2015* lists road traffic injuries as the leading cause of death among 15-29 year-olds (World Health Organization, 2015). Pedestrians and cyclists are particularly vulnerable to traffic injuries as they are not physically protected by a vehicle.

Surrogate safety measures are commonly used as a replacement for traditional incident based studies. Traditional methods of predicting collisions involve collecting several years of crash data which is not always available. In contrast, surrogate safety measures such as post encroachment time (PET) and time to collision (TTC), allow potentially dangerous sites to be evaluated before a crash has occurred. PET and TTC, illustrated in *Figure 1*, are measured in seconds, meaning that the closer to 0 the value is, the more dangerous the interaction. PET measures the difference in time between the time when the first vehicle exits the conflict point and the time when the second vehicle enters it. TTC measures the difference between the two vehicles' distance from the conflict point divided by the difference in their velocities.

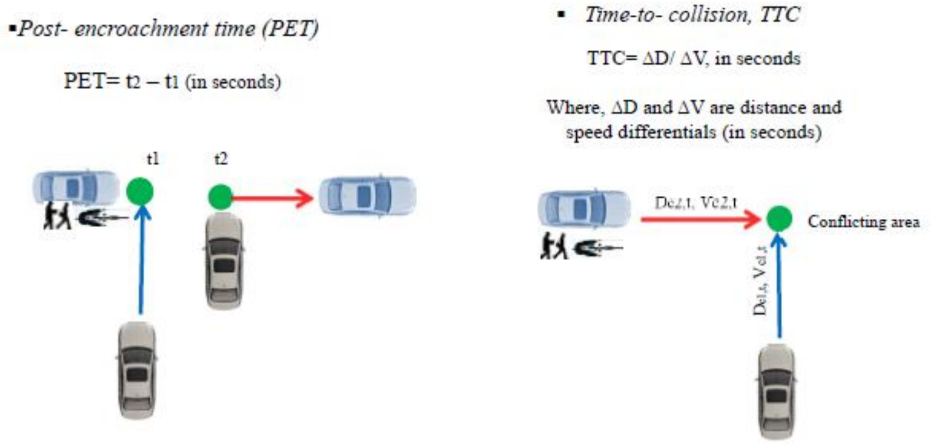

Figure 1: PET and TTC

Using stop signs to control traffic is a controversial topic. Adding stop signs offers cities a cheap and easy "solution" to many traffic problems and tend to be popular with the public. However, the Manual for Uniform Traffic Control Design provides guidance which includes the following requirements for installing multi-way stop signs:

- *Five or more reported crashes in a 12-month period that are susceptible to correction by a multi-way stop installation. Such crashes include right-turn and left-turn collisions as well as right-angle collisions.*
- *The vehicular volume entering the intersection from the major street approaches (total of both approaches) averages at least 300 vehicles per hour for any 8 hours of an average day, and*
- *The combined vehicular, pedestrian, and bicycle volume entering the intersection from the minor street approaches (total of both approaches) averages at least 200 units per hour for the same 8 hours, with an average delay to minor-street vehicular traffic of at least 30 seconds per vehicle during the highest hour* (Federal Highway Administration, 2015)

Often, municipalities modify this guidance since local roads rarely have the volume required to install multi-way stops (Cottrell, 1997). Additionally, some sources argue that additional stop signs cause traffic to speed up between stop signs, take other routes, and generally causing traffic violations to increase (Federal Highway Administration, no date).

While we concern ourselves with making the intersections physically safer for pedestrians and cyclists we must consider the impact additional stop signs will have on the air quality. For if pedestrians are made safer from crashes, but the quality of the air they are breathing is significantly decreased, did the modifications actually *improve* the conditions?

The addition of stop signs requires vehicles to accelerate and decelerate more within the network. Emissions of NO_X 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, like NO_x, 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). As of 2017, 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 create higher levels of PM. This is concerning for the health of individuals since it is difficult for individuals to limit their exposure to PM or even be aware of the levels of PM found in their neighborhood.

Literature Review

Surrogate Safety

Surrogate safety measures can be used in place of historical incident-based data. Two such measures are PET and TTC. These values are measured in seconds, so the larger the value, the safer the encounter. Prior to beginning an evaluation, a threshold value should be chosen to indicate a "hazardous conflict". J. Archer recommends a PET threshold value of 1 to 1.5 seconds (Archer, 2005). However, PET or TTC alone may not be enough to evaluate a conflict. Babu and Vedagiri recommend using critical speed as well (Shekhar Babu and Vedagiri, 2018). Peesapati et al. recommend including an exposure measure, such as AADT in the model (in addition to PET) to more accurately predict crashes (Peesapati, Hunter and Rodgers, 2018).

In a historically significant study, Lovell and Hauer re-evaluated safety improvement data from previous studies at intersections that were converted from two-way stop to AWS. They corrected for the bias in these previous evaluations by comparing the number of accidents that occurred in the after period with the number of accidents that *would have occurred* had the changes not been made. Their results still saw significant accident reduction at these locations (Lovell and Hauer, 1986).

Mohamed and Saunier outline a method for using video data along with tracking methods to evaluate surrogate safety indicators such as PET and TTC (Gomaa Mohamed and Saunier, 2017). Guo et al. performed a study comparing field-measured conflicts and conflicts found when the intersections were modeled in VISSIM and SSAM. Steps taken in calibration significantly impacted the model's ability to accurately predict conflicts (Guo *et al.*, 2019).

Stop Signs

The installation of AWS is a controversial topic. This control is popular because it is cheap and easy to install, however it may cause a reduction in compliance with traffic laws as well as encourage traffic to use other routes. In fact, AWS is sometimes used to reduce cut-through traffic (Cottrell, 1997). Cottrell's study evaluated the effectiveness of using stop signs as a residential traffic-management technique. Results showed that safety was not negatively affected despite the fact that frequently drivers only came to a rolling stop (Cottrell, 1997).

Retting et al. attempted to discover the cause of dangerous interactions at stop signs, citing that one third of the accidents occurring at stop signs result in injury. This research used data from four US cities and evaluated factors like whether or not the driver stopped, driver age, road geometry, and roadway conditions (Retting, Weinstein and Solomon, 2003).

Simpson and Hummer attempt to find the crash reduction factors associated with converting two way stop intersections to AWS. They found that the method is beneficial for a wider range of traffic volumes than it is currently recommended for in North Carolina (the location of the study). Additionally, they found crash reduction factors as large as 77% (Simpson and Hummer, 2010).

Emissions

There is a limited amount of research on the impact of intersection redesign, traffic calming measures and traffic controls on vehicle emission and the studies that do exist contain varied results. Furthermore, emissions and air quality can be heavily effected by driver behavior, weather conditions, and non-vehicular emissions such as local manufacturing making it difficult to detect changes caused solely by modifications to the roadway (York Bigazzi and Rouleau, 2017).

Several studies have compared the performance of different traffic controls and calming measures by their impact on air quality as well as other performance measures. A study, performed by Lee et al., compared 3 m wide speed humps, 4 m wide speed humps, speed tables, and chicanes finding that the 4 m speed hump created the fewest emissions but had the least impact on speed reduction while the chicane created the most emissions, while also creating the greatest reduction in vehicle speed. Results showed that the emissions for CO_2 were 4% lower and $PM_{2.5}$ were 30% lower for the speed humps than for the chicane (Lee *et al.*, 2013).

MOVES, which is primarily used to prepare emissions inventories for State Implementation Plans and Transportation Conformity in the US, has been used in additional studies including by Xu et al. to study the difference between data from traffic radars and data from simulations (Xu *et al.*, 2018) and Papson et al. to analyze the effect of intersection congestion on emissions (Papson, Hartley and Kuo, 2012). Ghafghazi and Hatzopoulou explored air quality impacts from both isolated traffic calming measures and area-wide traffic calming measures using a combination of Vissim and MOVES. Their research found that NO_2 levels increased a maximum of 9.9% with the use of speed bumps while speed humps created smaller increase (Ghafghazi and Hatzopoulou, 2014).

Abou-Senna et al. compared several methods for calculating emissions, using the programs Vissim and MOVES as well as using hand calculations, for a 10 mile stretch of limited-access highway in Orlando, FL. They concluded that using operating mode distribution to calculate emissions provides the most accurate emission rates due to its focus on acceleration, deceleration and idling (Abou-Senna and Radwan, 2013).

At the time of submission, no studies were known to the authors that used MOVES to evaluate traffic controls.

Case Study: Montreal

A neighborhood within Montreal’s Villeray – Saint-Michel - Park-Extension borough has recently undergone improvements in an attempt to create a safer environment for pedestrians and cyclists. *Figure 2* represents the unsignalized intersections that were modified during the improvements. Prior to the changes, vehicles traveling on the major approaches were not required to stop, while vehicles on the minor approach were. The modifications introduced stop signs to all approaches and added crosswalks for pedestrian safety.

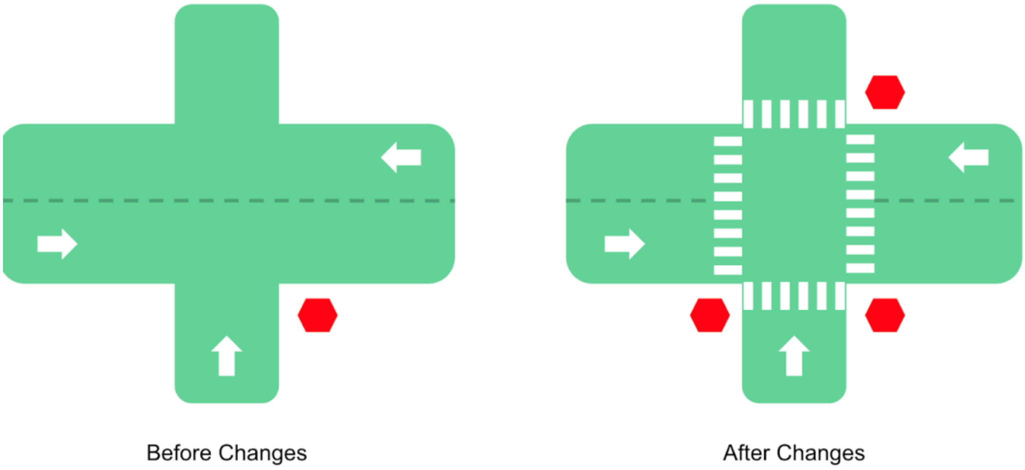

Figure 2: Intersection Diagram

This study is made up of data from a network of 22 intersections which can be seen in *Figure 3*. Eight of these intersections did not undergo any change; four are signalized, two were AWS prior to the study, and two contain unique intersection geometry. The remaining 14 intersections were modified according to the illustration in *Figure 1*. We have video data of before and after the modifications of 10 of these intersections. Intersections are labeled and numbered in *Table 1*. The intersections that were modified are neighborhood roads with low volumes and predominately local traffic.

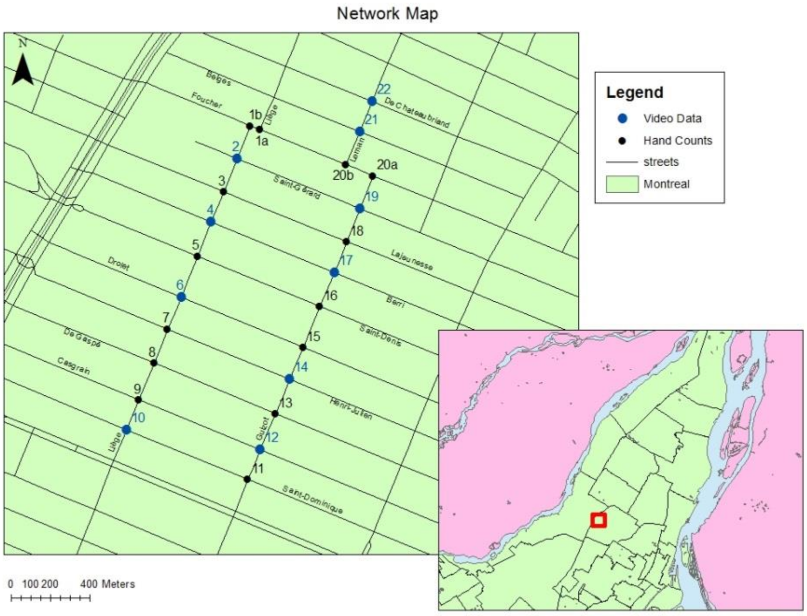

Figure 3: Network Map

Table 1: Intersection Details

Number	Major Road (E-W)	Minor Road (N-S)	Data Collection	Improved (Y/N)	Signalized (Y/N)
1	Rue de Liege	Rue Foucher	Manual	N	N
2	Rue de Liege	Rue Saint Gerard	Video	Y	N
3	Rue de Liege	Rue Lajeunesse	Manual	N	Y
4	Rue de Liege	Rue Berri	Video	Y	N
5	Rue de Liege	Rue St. Denis	Manual	N	Y
6	Rue de Liege	Rue Drolet	Video	Y	N
7	Rue de Liege	Henri Julien Ave.	Manual	Y	N
8	Rue de Liege	Gaspe Ave.	Manual	N	N
9	Rue de Liege	Casgrain Ave.	Manual	Y	N
10	Rue de Liege	Rue St. Dominique	Video	Y	N
11	Rue Guizot	Rue St. Dominique	Manual	Y	N
12	Rue Guizot	Casgrain Ave.	Video	Y	N
13	Rue Guizot	Gaspe Ave.	Manual	N	N
14	Rue Guizot	Henri Julien Ave.	Video	Y	N
15	Rue Guizot	Rue Drolet	Manual	Y	N
16	Rue Guizot	Rue St. Denis	Manual	N	Y
17	Rue Guizot	Rue Berri	Video	Y	N
18	Rue Guizot	Rue Lajeunesse	Manual	N	Y
19	Rue Guizot	Rue St. Gerard	Manual	Y	N
20	Rue Guizot	Rue Foucher	Manual	N	N
21	Rue Leman	Ave. des Belges	Video	Y	N
22	Rue Leman	Ave. de Chateaubraind	Video	Y	N

Methodology

Methodology steps can be seen in the flow chart in *Figure 4.* 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 at intersections where changes were not made and video data was not available. Due to the variation in collection time and method a balancing method was used which will be described in more detail in the following section. Next, a small network was modeled in Vissim containing the 22 intersections that make up the network. One model was built, using two scenarios. One scenario represents the network before modifications were made and the other represents the network following the implementation of additional stop signs. The only differences between the models are the speeds of the vehicles and the presence of new stop signs. Volumes of vehicles were not varied between the two scenarios in order to avoid the bias this could introduce to the data. Both models consisted of 22 intersections, 14 intersections that were modified, ten of which had video data recorded, two that was already an all-way-stop intersection, four signalized and two unsignalized intersections that underwent no change. The results of the traffic simulation were then used as inputs for the FHW's Surrogate Safety Assessment Model (SSAM) and the EPA's Motor Vehicle Emissions Simulator (MOVES). SSAM was used to evaluate the PET and TTC data which is an indicator for the overall safety of the intersections. MOVES 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.

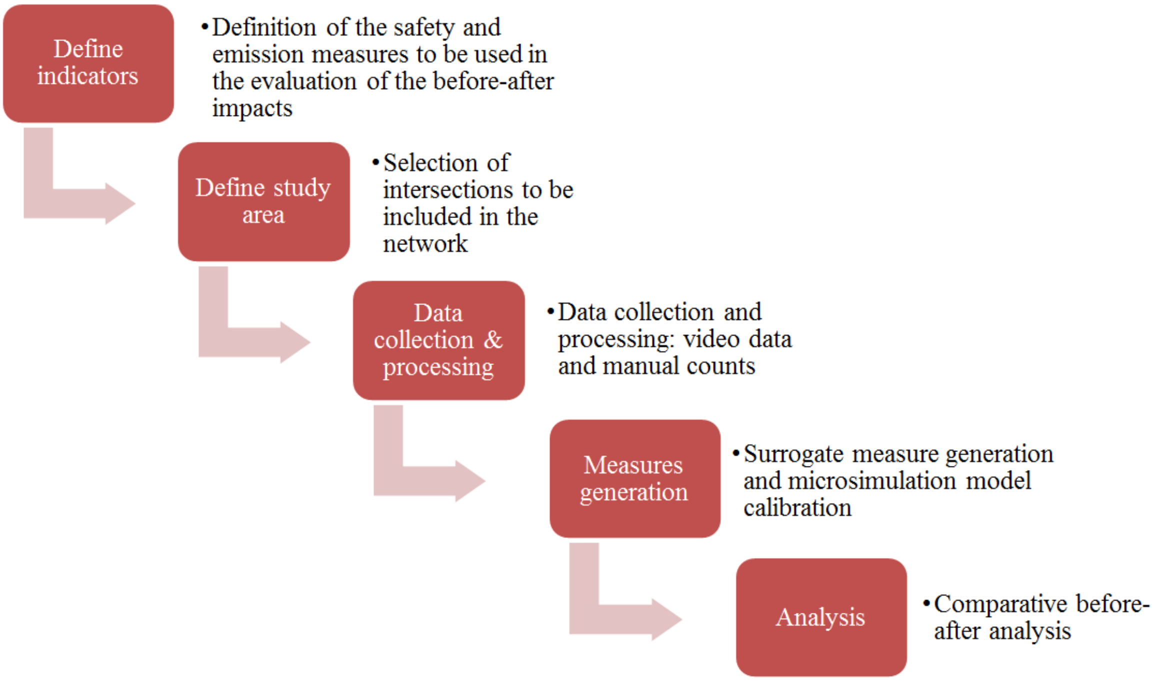

Figure 4: Methodology flow chart

<u>Traffic Data Collection</u>

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, using LUMINA. Each road user is represented with trajectories; 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 ten analyzed intersections and used as inputs for the Vissim model. Data was collected during day time hours of weekdays.

Vissim Model

A Vissim model containing two scenarios was built to represent the network – one for before the changes and one for after. The only things that vary between the two models are the speeds of the vehicles and the presence of additional stop signs. Traffic volumes were held constant to avoid bias. The volumes used in the model represent the volumes detected in the after period and were balanced using a method described in the following section.

During the study, illegal traffic movements were witnessed but were not included when the model was built. Vehicle speeds represent the 85th percentile speed as collected from the video data. The speed for roads with no video data was entered as the speed limit.

Since several of the manual counts were performed during winter months, the bicycle data was not representative of peak bike flows for the neighborhood. The typical method of using adjustment factors could not be used since many approaches had zero bikes counted. Therefore, three intersections were chosen as representative of the network – Intersection 4 for non-signalized intersections without bike lanes, Intersection 6 for non-signalized intersections with bike lanes and Intersection 16 for signalized intersections. These intersections were chosen for conditions which promote cycling (dry weather, warm season, etc.).

Each scenario was run 10 times using the same 10 random seed variables for each scenario.

Volume Balancing

Since data was collected using several methods, it was necessary to balance the volumes observed on the network. Each major approach was looked at individually, first in the eastbound direction, then in the westbound direction. The intersection of highest confidence was chosen as the starting point. Highest confidence was defined as an intersection where the data was collected via video and that had the highest volumes (since we do not want to under represent the traffic on our network). For both major approaches Rue Berri contained the highest volume (Intersections 4 and 17). Using the volume obtained at Rue Berri as ground truth, as well as the turning ratios obtained at all other intersections. Beginning with the volume observed at Rue Berri, and moving forward first in the direction of traffic (and later backwards from Berri), the volumes observed at other intersections were adjusted based on their turning ratios. This allows volumes to be consistent linearly along the east-west direction. Along Rue Guizot/Leman the volume increased 11% from the original to the adjusted value. Along Rue de Liege the volume increased 43% from the original to adjusted value (for cars).

The adjusted volumes were then used to calibrate the model. The average link volumes from the 10 random seed model runs were compared to the adjusted values found through this method.

SSAM and Surrogate Safety

The *.trj* files created from the VISSM model were used as inputs for the SSAM evaluation. TTC and PET were set at the maximum values for the runs and narrowed down later. Threshold values of both TTC and PET for the analysis are shown in *Table 2*. The conflict types “lane change” and “rear end” were included in the analysis.

Table 2: Threshold Values for TTC and PET

Low Hazard	Medium Hazard	High Hazard
≤ 5 sec	≤ 2.5 sec	≤ 1 sec

For comparison, results are also included from a surrogate safety analysis of similar intersections which was derived directly from the video data collected at these intersections. Conflicts were detected using the LUMINA tracking program to find instances of hazardous conflicts using PET.

MOVES

The EPA's MOVES2014b 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. 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*, no date). 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.

Results

Aspects of network performance were analyzed using the results generated in Vissim. The addition of stop signs within the network caused the average velocity of all users to decrease, the average acceleration of all users to increase, and the average delay to increase. These results can be seen in *Table 3* and *Figure 5*.

Table 3: Changes in Velocity and Acceleration

	Average Velocity (km/h)		Average Acceleration (m/s^2)	
	Before	**After**	**Before**	**After**
All	28.97	24.5	0.68	1.18
Car	29.4	24.9	0.71	1.2
Truck	30.09	26.23	0.39	0.68
Bike	16	11.42	0.26	1.36

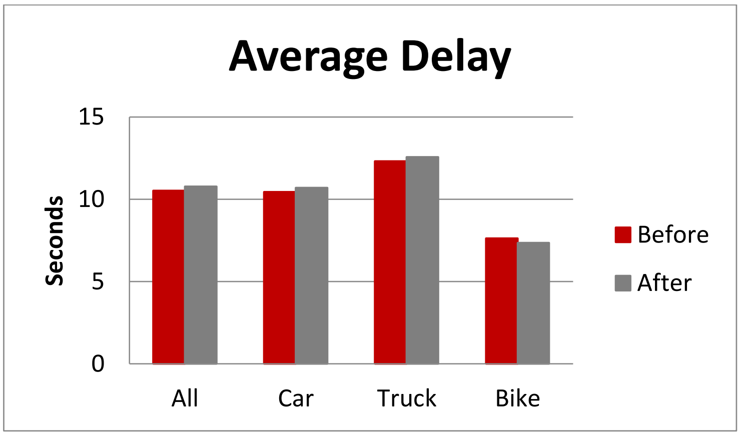

Figure 5: Average Delay per User

The surrogate safety analysis using SSAM was first performed for interactions between vehicles. Low, medium, and high hazard conflicts increased for both TTC and PET as seen in *Figure 6*. Next, the analysis was performed for interactions between bicycles and vehicles. Low hazard conflicts increased for both TTC and PET but medium and high hazard conflicts decreased. These results can be seen in *Figure 7*.

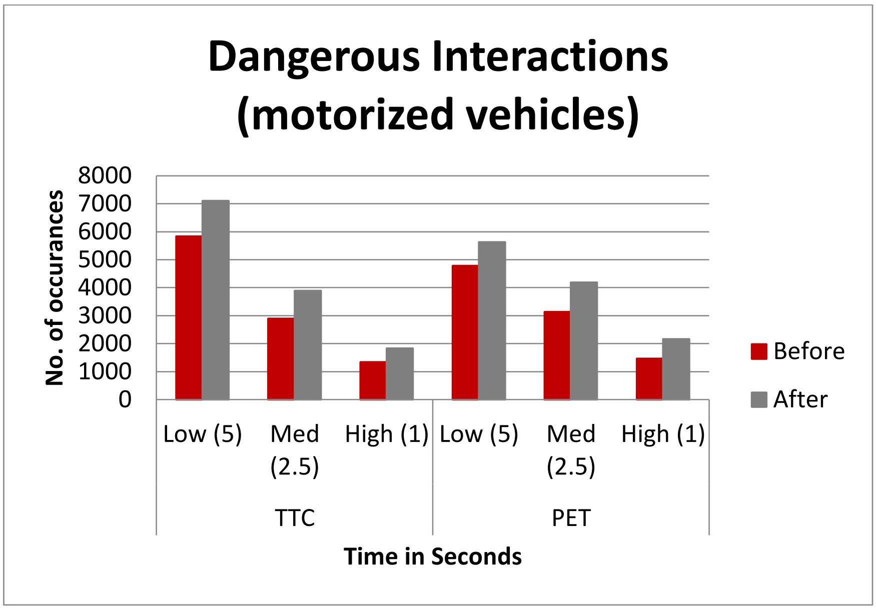

Figure 6: Surrogate Safety Measures (Motorized Vehicles)

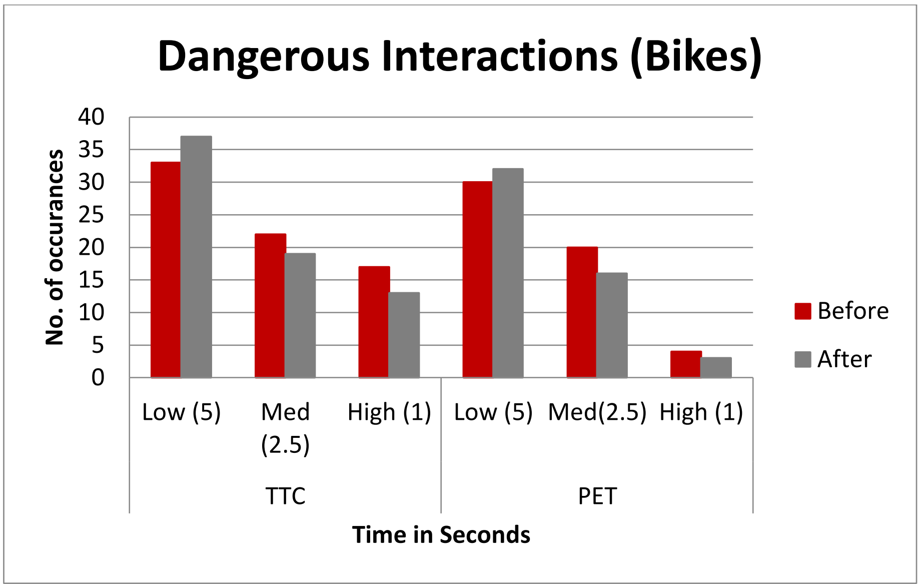

Figure 7: Surrogate Safety Measures (Bikes)

The emissions analysis is currently only available for a portion of the network containing six intersections. The analysis for the complete network is currently a work in progress. All of the pollutants measured experienced an increase with $PM_{2.5}$ and PM_{10} from primary exhaust experiencing the greatest increase. Results can be seen in *Table 4.*

Table 4: Emissions

Pollutant	Before (grams per hour)	After (grams per hour)	% Change
CO	455.65	484.27	+6.28
NO_X	8.90	9.56	+7.47
NO	7.42	7.97	+7.46
NO_2	1.41	1.51	+7.51
Primary Exhaust PM_{10}	1.21	1.55	+28.94
PM_{10} Break-wear	14.37	18.11	+26.08
PM_{10} Tire-wear	1.77	1.80	+1.82
Primary Exhaust $PM_{2.5}$	1.07	1.38	+28.94
$PM_{2.5}$ Break-wear	1.80	2.26	+26.08
$PM_{2.5}$ Tire-wear	0.27	0.27	+1.82

The summary of the impacts can be visualized in *Table 5*. The impacts can be neutral, positive and negative depending of the indicators and mode.

Table 5: Conclusion Summary

<table>
<tr><th></th><th colspan="2">Safety</th><th colspan="2">Traffic operations</th><th colspan="2">Emissions</th></tr>
<tr><th></th><th>Intersection</th><th>Corridor</th><th>Speeds</th><th>Delays</th><th>NOx</th><th>PM</th></tr>
<tr><td>Bicycles</td><td>=</td><td>=</td><td>+</td><td>+</td><td rowspan="2">-</td><td rowspan="2">-</td></tr>
<tr><td>Vehicles</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
</table>

+ positive impact, - negative impact, = neutral impact

Conclusions & Future Work

This project contains a lot of intricacies and components. Research on these topics is still ongoing, as is work on improving calibration. The network performance saw a slight decrease, particularly for vehicle users. However, this was expected as the additional stop signs will cause users to brake more frequently, therefore increasing their acceleration and decreasing their overall velocity. The safety analysis performed in SSAM showed an increase in conflicts for all levels of hazard between motorized vehicles and for low hazard conflicts between bicycles and motorized users. The number of high and medium hazard conflicts between bicycles and vehicles decreased. However, when a user stops at stop sign and allows another user to cross the intersection may trigger SSAM to note this encounter as a conflict, wrongly inflating the value of hazardous conflicts.

MOVES results show an increase of nearly 30% of some PM emissions. It should be noted that although inputs have been modified for local scenarios, MOVES was created for use in the United States and may not fully represent the local driving conditions.

Plans for future work on this topic include running real world driving tests by driving vehicles along this network, as well as along a control network using a car outfitted to gather emissions data. This data can then be compared to the data generated from the models.

Shortcomings in this research include having a limited amount of video data to base the models on, as well as the presence of construction in nearby areas during certain days of data collection. Using video data, microsimulation models will be calibrated for speed distributions. The calibration and validation of bicycle models is also an important aspect for future work. The microsimulation models for bicycle behaviors need also to be adjusted to more closely match the real conditions. Due to the large seasonal variation in traffic volume for cyclists, the most accurate representation would include using counts taken during the same season the analysis plans to replicate. Furthermore, the Vissim model assumes cyclists follow all the road rules such as coming to a complete stop at an intersection with a stop sign, which is not always the case. Improvements such as these would increase the accuracy of the results.

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